PLUTONIUM
WORKING GROUP REPORT

on
ENVIRONMENTAL, SAFETY AND HEALTH
VULNERABILITIES ASSOCIATED WITH THE
DEPARTMENT’S PLUTONIUM STORAGE

VOLUME II, APPENDIX A:
PROCESS AND PROTOCOL

U.S. DEPARTMENT OF ENERGY
SEPTEMBER 1994
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# VOLUME II - APPENDIX A

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INTRODUCTION

This appendix contains documentation prepared by the Plutonium ES&H Vulnerability Working Group for conducting the Plutonium ES&H Vulnerability Assessment and training the assessment teams. It has the following five parts:

A.1 The "Project Plan" describes the genesis of the project, sets forth the goals, objectives and scope, provides definitions, the projected schedule, and elements of protocol.

A.2 The "Assessment Plan" provides a detailed methodology necessary to guide the many professionals who have been recruited to conduct the DOE-wide assessment. It provides guidance on which types and forms of plutonium are to be considered within the scope of the assessment (in-scope versus out-of-scope), and lays out the assessment methodology to be used by both the "Site Assessment Teams" (SATs) and the "Working Group Assessment Teams" (WGATs).

A.3 The memorandum from the Project to Operations Office Managers provides the protocol and direction for participation in the assessment by external stakeholders (individuals or organizations) and members of the public; and the guidance for the physical inspection of plutonium materials in storage.

A.4 The memorandum from the Project to the assessment teams provides guidance for vulnerability screening criteria, vulnerability evaluation and prioritization process, and vulnerability quantification for prioritization, for use by both the SATs and the WGATs to assist the Working Group in prioritizing vulnerabilities across the DOE complex.

A.5 The "Team Training" manual was used at the training session held in Colorado Springs on April 19-21, 1994 for all members of the Working Group Assessment Teams (about 100 people) and for the leaders of the Site Assessment Teams (about 30 individuals). The session covered the scope of the project, the assessment methodology, and numerous technical topics needed to carry out the assessments at all DOE sites. The goal was to provide the same training to all of the individuals who would be conducting the assessments, and thereby provide consistency in the conduct of the assessments and uniformity in reporting of the results. The training manual in Section A.5 includes supplemental material provided to the attendees after the meeting.
A.1

DOE Plutonium ES&H Vulnerability Assessment

Project Plan
DEPARTMENT OF ENERGY
PLUTONIUM ES&H VULNERABILITY ASSESSMENT

PROJECT PLAN

April 25, 1994
MEMORANDUM FOR SECRETARIAL OFFICERS AND OPERATIONS OFFICE MANAGERS

FROM: HAZEL R. O'KEEFE

SUBJECT: DEPARTMENT-WIDE INITIATIVE FOR CONTROL AND DISPOSITION OF SURPLUS FISSILE MATERIALS

With the end of the Cold War, significant quantities and forms of nuclear materials have become excess to national defense needs in both the United States and Russia. Underscoring the concern about nuclear proliferation, the President has directed an Interagency Working Group to initiate a comprehensive review of long-term options for plutonium disposition. The Department of Energy must play a leading role in this effort in view of its responsibilities for management and disposition of surplus nuclear materials. However, the organizational responsibilities and structure of the Department are not well suited to address the cross-cutting nature of surplus nuclear materials.

To address the urgency of this issue, I am creating a Department-wide project reporting directly to the Under Secretary. This project will have line responsibility for developing departmental recommendations and for directing implementation of decisions concerning disposition of excess nuclear materials. The objective is to provide for safe, secure and environmentally sound control, storage and ultimate disposition of surplus fissile materials. The project will carry out its responsibilities in a manner that promotes effective nonproliferation policies and sets an example for other nations to follow. It will coordinate the Department's participation on nuclear materials matters being addressed by the President's Interagency Working Group. It will operate in an open and transparent manner and will assure stakeholder participation in the decision-making process.

The materials of interest include plutonium and highly enriched uranium from the disassembly of nuclear weapons; separated nuclear materials previously in the weapons production pipeline; and weapons-usable quantities which may result from future stabilization and waste processing operations.

The Department-wide project will initially be comprised of experienced staff, including at least one full-time participant from the following organizations: Defense Programs; Environmental Restoration and Waste Management; Policy, Planning and Program Evaluation; Environment, Safety and Health; Intelligence and National Security; Nuclear Energy; and Civilian Radioactive Waste Management.

In addition to these core participants, other program offices may be called upon to assign qualified people to assist this activity. The Department-wide project will control funds authorized and appropriated for this effort and it will work closely with the programs, laboratories and field offices. Proceeding in this way, I expect the project will begin immediately identifying actions needed to effectively control and dispose of surplus nuclear materials. The project will have the breadth and range to develop consensus and effectively integrate surplus nuclear materials control and disposition efforts across the Department.

Bob DeGrasse, Special Assistant in the Office of the Secretary, will lead efforts to organize the Department-wide project. I ask you to provide him your full cooperation and support.
MEMORANDUM FOR TARA O'TOOLE, M.D., M.P.H.
ASSISTANT SECRETARY,
ENVIRONMENT, SAFETY & HEALTH

FROM: HAZEL R. O'LEARY

SUBJECT: VULNERABILITY ASSESSMENT OF FISSILE MATERIALS STORAGE

President Clinton recently directed an Interagency Working Group to initiate a comprehensive review of long-term options for the disposition of plutonium that will be surplus in the post-Cold War era. The Department of Energy plays a leading role in this effort. On January 24, 1994, we initiated a Department-wide project to develop options and recommendations and direct implementation of decisions concerning disposition of surplus fissile materials.

In order to establish a foundation for decision making, project staff, including staff from the Office of Environment, Safety and Health, have outlined a plan to conduct a comprehensive assessment of the environment, safety and health vulnerabilities associated with the entire inventory of plutonium in storage outside of intact nuclear weapons. While not all fissile material in storage is surplus, this vulnerability assessment will serve as the information base to identify interim corrective actions and options for the safe management of surplus fissile materials.

I would like your office to take the lead in coordinating this vulnerability assessment. It should:

- encompass all forms and isotopes in the inventory of plutonium under Department's custody or control except plutonium in intact nuclear weapons;
- build on existing data and assessments to the maximum extent appropriate;
- include participation of cognizant secretarial offices, operations offices, and management and operating contractors, external stakeholders such as Nuclear Regulatory Commission, Environmental Protection Agency, National Academy of Sciences, International Atomic Energy Agency, Defense Nuclear Facilities Safety Board, the Congress, State representatives and public interest groups; and
be completed by September 30, 1994.

I understand that staff have developed an initial cost estimate of approximately $4.0 million for this assessment. The funding to support this assessment will be made available from the Nuclear Materials Disposition Project. This estimate is based on the expectation that cognizant secretarial offices, operations offices, and management and operating contractors will support their portion of the assessment effort from within their current operating funds. Funding and schedule arrangements should be coordinated with Bob DeGrasse at 6-7550.

I appreciate your support of this important task and I intend to separately write to the operations office managers and Secretarial Officers whose support will likewise be important to the Department's success.

cc: Bill White, S-2
    Charles B. Curtis, S-3
    Bob DeGrasse, S-1
The Secretary of Energy
Washington, DC 20585

March 15, 1994

MEMORANDUM FOR SECRETARIAL OFFICERS
MANAGERS, OPERATIONS OFFICES

FROM: HAZEL R. O'LEARY

SUBJECT: VULNERABILITY ASSESSMENT OF FISSILE MATERIALS STORAGE

President Clinton recently directed an Interagency Working Group to initiate a comprehensive review of long-term options for the disposition of surplus plutonium. This effort is part of a broader framework for the United States' efforts to prevent proliferation of nuclear weapons. As a result, on January 24, 1994, we initiated a Department-wide project to develop options, recommendations, and direct the implementation of decisions concerning the disposition of surplus fissile materials.

In order to establish a foundation for decision making, we need a comprehensive understanding of the environment, safety and health issues surrounding our entire inventory of fissile materials in storage outside of intact nuclear weapons. While not all fissile material in storage is surplus, this vulnerability assessment will serve as the information base to identify interim corrective actions and options for the safe management of surplus fissile materials. I have requested the Office of Environment, Safety and Health to assume the primary responsibility to perform this assessment. Although The Office of Environment Safety & Health is designated as the focal point for this Secretarial initiative, I expect full participation and support from the program offices, operations offices, and management and operating contractors to gather information and conduct assessments.

The fissile materials vulnerability study should involve external stakeholders such as Nuclear Regulatory Commission, Environmental Protection Agency, National Academy of Sciences, International Atomic Energy Agency, Defense Nuclear Facilities Safety Board, the Congress, State representatives, and public interest groups. Operations offices should take the lead to involve local stakeholders in working group meetings or assessments, while The Office of Environment Safety & Health will coordinate the involvement of other Federal agencies. The vulnerability assessment of plutonium will start in March 1994 and be completed by September 30, 1994.

As a first step, The Office of Environment Safety & Health will establish a Plutonium Vulnerability Assessment Working Group to formulate and execute a plan to accomplish the objectives of this project. Materials of interest include all isotopes and
forms in the inventory of plutonium, including process residues, pits from disassembly of nuclear weapons, and separated plutonium previously in the weapons production pipeline; however, plutonium housed inside intact nuclear weapons is excluded from this vulnerability assessment.

You are requested to authorize the management and operating contractors and laboratories to designate three or four individuals possessing the best technical knowledge of the subject and facilities at their sites to participate as Working Group members. Operations offices should also designate at least one management contact to fully participate in this effort.

I recognize that the environment, safety and health vulnerabilities at many of our sites are well characterized, assessed, and controlled. Furthermore, this study represents an additional burden on already strained resources in light of our other initiatives. Although this study involves new assessments by you, your contractors, and the Working Group, we will build on existing work to the extent appropriate and create a Department-wide assessment to serve important national and international needs. In light of the significance of this study, I trust that you will support it and assure its success.

The first Working Group meeting is scheduled for March 28-30, 1994 at the Holiday Inn, Gaithersburg, MD (Phone 301-948-8900). The Office of Environment Safety & Health will coordinate arrangements for this meeting. Sarbes Acharya (301-903-2419) is the Office of Environment Safety & Health Project Leader for this effort.

cc: B. White, S-2
C. Curtis, S-3
T. O'Toole, EH-1
B. DeGrasse, S-1
WORKING GROUP

PROJECT PLAN

Department of Energy
Plutonium ES&H Vulnerability Assessment Project

April 25, 1994
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1.0 OBJECTIVE AND SCOPE

The objective of the Plutonium ES&H Vulnerability Assessment Project is to conduct a comprehensive assessment of the environmental, safety and health (ES&H) vulnerabilities arising from the Department's storage and handling of its current plutonium holdings. The term "ES&H vulnerabilities" is defined for the purpose of this project to mean conditions or weaknesses that could lead to unnecessary or increased radiation exposure of workers, release of radioactive materials to the environment, or radiation exposure of the public. The assessment will identify and prioritize ES&H vulnerabilities, and will serve as an information base for identifying interim corrective actions and options for the safe management of fissile materials.

- encompass all forms and isotopes in the inventory of plutonium under the Department's custody or control, except plutonium in intact nuclear weapons;
- build on existing data and assessments to the maximum extent appropriate;
- include participation of cognizant secretarial offices (CSOs), operations offices, management and operating (M&O) contractors, and external stakeholders, such as the Nuclear Regulatory Commission, Environmental Protection Agency, National Academy of Sciences, International Atomic Energy Agency, Defense Nuclear Facilities Safety Board, the Congress, State Representatives, and public interest groups; and

The final report will be issued under the signature of the Assistant Secretary, Environment, Safety and Health, to the Secretary of Energy.

Although the Office of Environment, Safety and Health (EH) will lead the project, a broad-based Working Group composed of M&O contractor personnel, DOE operations office staff, Headquarters program office staff, and expert consultants will be involved in the assessment process.

This Project Plan serves to organize and implement the project by defining the scope, outlining roles and responsibilities, coordinating project management, and serving as an information resource document for the Working Group and others.

Attachment 1 contains details about plutonium materials included in the scope of the Plutonium ES&H Vulnerability Assessment Project. This assessment is intended to take a "snap-shot" of the Department's plutonium holdings and associated ES&H vulnerabilities as of the May–June, 1994, timeframe. It is the goal...
of this project to present as much information as possible about ES&H vulnerabilities of plutonium at DOE sites in an unclassified form. Classified information will be presented in classified appendices to the various reports of this project.

2.0 BACKGROUND

President Clinton recently directed an interagency working group to initiate a comprehensive review of long-term options for the disposition of surplus plutonium. This effort is part of a broader framework of the United States' efforts to prevent the proliferation of nuclear weapons. The Department of Energy plays a leading role in this initiative. On January 24, 1994, the Secretary of Energy initiated the Department-wide Nuclear Materials Disposition Project reporting directly to the Under Secretary (Reference 1). The project purpose is to develop options and recommendations and to direct implementation of decisions concerning the disposition of surplus fissile materials.

To establish a foundation for decision making, the Nuclear Materials Disposition Project identified the need for a comprehensive assessment of the ES&H vulnerabilities of the DOE inventory of plutonium other than plutonium in intact nuclear weapons. The vulnerability assessment will provide an essential information base needed to identify interim corrective actions and options for the safe management of fissile materials.

The Secretary has requested the Office of Environment, Safety and Health to assume the primary responsibility for conducting the ES&H vulnerability assessment of plutonium (Reference 2). This assessment covers the handling, processing, and storage of all isotopes and forms of plutonium, and will identify associated ES&H vulnerabilities. Although EH is designated as the focal point for the vulnerability assessment, the Secretary has also directed the program offices, operations offices, and M&O contractors to fully support and participate in the assessment process (Reference 3).

In response to the Secretary's directive, the Assistant Secretary for Environment, Safety and Health will conduct the vulnerability assessments of plutonium in a manner similar to that of the recently completed Department-wide spent nuclear fuel ES&H vulnerability assessment (Reference 4).

The Assistant Secretary for EH established the Plutonium ES&H Vulnerability Assessment Project, which has been structured to include the following elements:

(1) Working Group
   DOE-wide resource group

(2) Support Group
   Small group of near full-time personnel from the Working Group for project management and implementation

(3) Site Assessment Teams
   Teams of M&O contractor & operations office personnel to conduct self-assessment of ES&H vulnerabilities for their own sites

(4) Working Group Assessment Teams
   Teams for independent verification and validation of ES&H vulnerabilities

The composition and responsibilities of these elements are described in the following sections of this Project Plan.

The first meeting of the Working Group was held in Gaithersburg, Maryland, on March 28–30, 1994.

3.0 PROJECT MANAGEMENT PLAN

The following sections explain the approach to be followed to organize and execute the Plutonium ES&H Vulnerability Assessment Project.
3.1 Overview of Project Management

EH has drawn upon its recent experience with the spent nuclear fuel vulnerability assessment to organize this Plutonium ES&H Vulnerability Assessment Project. For the spent fuel study, the collaboration of appropriate DOE elements and involvement of the Defense Nuclear Facilities Safety Board (DNFSB) facilitated the project and ensured acceptance of the study's results and recommendations by the entire DOE complex. This project will include involvement of the DNFSB, the Nuclear Regulatory Commission, Environmental Protection Agency, National Academy of Sciences, International Atomic Energy Agency, Congress and State Representatives, and public interest groups.

The Working Group serves as the DOE-wide resource group. It consists of DOE Headquarters and operations office personnel and M&O contractor personnel with responsibility for plutonium operations and storage facilities. It also includes independent expert consultants. The Working Group provides guidance to the project through Working Group meetings and reviews the assessment results, as outlined in later sections of this Project Plan. Other agencies and external stakeholders will be involved in the Working Group process.

Due to the size of the Working Group, a small assembly of individuals serving as a subset of the Working Group, the Support Group, will carry out implementation of the project under the guidance of senior DOE-EH management. The Support Group will be responsible for the preparation of drafts of the various products required (Project Plan, Assessment Plan, Final Report, etc.); conduct Working Group meetings; conduct Working Group Assessment Team training and site visits; and otherwise run the daily operations of the project. The areas of expertise represented in the Support Group include plutonium chemistry, metallurgy, processing and storage, health physics, nuclear safety, criticality, operations, safeguards and security, training, and other disciplines essential to identifying and characterizing plutonium ES&H vulnerabilities.

The key project planning documents are the Project Plan and the Assessment Plan. The Project Plan describes project objectives, scope, management, responsibilities, implementation approach, deliverables, milestones, and schedule. The Assessment Plan describes the methodology to assess ES&H vulnerabilities. The essential disciplines of those who will assess vulnerabilities, the types and locations of plutonium to be assessed, the characteristics important to vulnerability identification, and the process and guidelines to be used in characterizing and prioritizing vulnerabilities are defined in these plans.

The following section identifies the roles of the Working Group, Site Assessment Teams, and Working Group Assessment Teams in managing this project.

3.2 Work Breakdown Structure

Figure 3-1, the Work Breakdown Structure, shows the division of this project into five chronological tasks.

Task 1: Planning

The purpose of Task 1 is to organize and define the project. Each subtask is described as follows.

1.a Project Organization. Prior to the first Working Group meeting, EH identified the disciplines needed in the Support Group, located and enlisted personnel with appropriate qualifications, and organized the Support Group meetings necessary to generate the Project Plan and Assessment Plan.
Figure 3-1
PLUTONIUM ES&H VULNERABILITY ASSESSMENT PROJECT
WORK BREAKDOWN STRUCTURE

Task 1 Planning
- 1.a Project organization
- 1.b Plutonium characteristics
- 1.c Planning meetings
- 1.d Working Group organization
- 1.e Facility dry runs
- 1.f Team qualifications
- 1.g Past experiences
- 1.h First Working Group meeting
- 1.i Project and Assessment Plans

Task 2 Training
- 2.a Team membership
- 2.b Team training

Task 3 Assessment
- 3.a Site Assessment Teams assessment
- 3.b Working Group assessment team verification and validation
- 3.c Assessments of smaller sites

Task 4 Analysis
- 4.a Data assembly
- 4.b Vulnerability characterization and summary
- 4.c Prioritization
- 4.d Second Working Group meeting

Task 5 Reporting
- 5.a Data collection and organization
- 5.b Report writing
- 5.c Draft report distribution
- 5.d Final report
- 5.e Management briefings
1.b Plutonium Characteristics. The Support Group met to gather information on essential material characteristics of plutonium in all expected forms and to lay the groundwork for the project.

1.c Planning Meetings. The Support Group developed drafts of the Project Plan and the Assessment Plan.

1.d Working Group Organization. The Support Group communicated with DOE elements and developed a comprehensive list of potential Working Group participants representing the CSOs, operations offices, M&O contractors, and expert consultants. Working Group designees and representatives of several external stakeholder organizations were invited to the first Working Group meeting, which was held on March 28–30, 1994.

1.e Facility Dry Runs. Prior to the Working Group meeting (March 28–30, 1994), small teams of the Support Group visited two DOE sites with large plutonium holdings to test a draft version of the Assessment Plan.

1.f Team Qualifications. Members of the Support Group developed qualification requirements for Working Group Assessment Team members (Attachment 3), including disciplines needed for the various teams. Lists of Working Group Assessment Team members have been developed after a review of qualifications of individuals who signed up to serve on these teams, other individuals from the DOE complex, and independent expert consultants needed for these teams. The list of Working Group Assessment Team members for each team is provided in Attachment 4.

1.g Past Experiences. The Support Group is currently collecting and reviewing historical occurrences involving plutonium processing, handling, and operations from the Occurrence Reporting and Processing System/Safety Performance Measurement System and other DOE records and reports. These occurrences will be compiled for use by the Working Group, Site Assessment Teams, and Working Group Assessment Teams. This compilation will provide a perspective of past problems with operations and storage of plutonium. The subtask also involves assembly of any existing vulnerability or risk studies of plutonium sites, facilities, operations or storage.

1.h First Working Group Meeting. Participants in the first Working Group meeting were provided with drafts of Project Plan and Assessment Plan. These drafts were discussed at the Working Group meeting on March 28–30, 1994. After presentations on these plans to the entire Working Group, breakout groups conducted in-depth evaluations of the plans and made revisions.

1.i Project and Assessment Plans. The Support Group reviewed and incorporated all Working Group inputs into the Project Plan and Assessment Plan. These documents were then sent to all Working Group participants, DOE sites, and operations offices for a final review. Comments resulting from the final review have been incorporated as appropriate.

Task 2: Training

The purpose of Task 2 is to identify, select, enlist, and train Working Group Assessment Team members and Site Assessment Team leaders in the assessment process.

2.a Team Membership. The Support Group will notify all team members; deliver training packages (Project Plan, Assessment Plan, and Question Set);
and establish the schedule and place of training.

2.b Team Training. All Working Group Assessment Team members and Site Assessment Team leaders will assemble for a 3-day training session, for “team building” and specific assessment process training.

Task 3: Assessment

The purpose of Task 3 is to perform the assessments.

3.a Site Assessment Team Assessment. The Project and Assessment Plans will be sent to each site that has plutonium holdings. The site management will assemble an appropriate Site Assessment Team consisting of DOE operations office and M&O contractor personnel. At the start of the Site Assessment Team work, the Working Group Assessment Team leaders will meet with the respective Site Assessment Team to review the scope and organization of the site assessment process. The Site Assessment Teams will complete the responses to the Question Set (which is part of the Assessment Methodology) and analyze their plutonium operations and storage for potential ES&H vulnerabilities. Electronic templates may be used for standardized reporting of question set responses and vulnerabilities. The Site Assessment Teams will complete their initial assessment by drafting Site Assessment Team reports (see outline in following column).

ES&H vulnerabilities identified by the Site Assessment Teams are expected to be in a form that is sufficiently complete to allow the Working Group Assessment Teams to identify, validate, and organize vulnerabilities (Task 3.b) using the Vulnerability Assessment Process described in Attachment 5. The data from the Site Assessment Team Assessment will be entered into a data base using off-the-shelf PC software and formats provided by the Support Group.

Each Site Assessment Team will complete its report after the Working Group Assessment Team visits the site and reviews, verifies, and validates the site’s draft report.

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• Responses to Question Set (each facility)
• Vulnerability Assessment Forms
• References

3.b Working Group Assessment Team Verification and Validation. Working Group Assessment Teams, having been trained under Task 2, will schedule visit(s) to each site. The Site Assessment Team will present its draft report to the Working Group Assessment Team which will review the draft report. Both teams will engage in discussions of the plutonium operations and storage conditions and participate in a walkdown of the storage and operations facilities. The Working Group Assessment Team will review and prepare Vulnerability Assessment Forms and prepare a draft report (see outline below). These will be discussed with
3.c Assessment of Smaller Sites. Some DOE sites have been identified as having small quantities of plutonium that are not in sealed-source forms. These sites will complete the Question Set from the Assessment Plan, but are not initially expected to be subject to a site visit. The length of responses and the level of detail for smaller sites should be commensurate with the quantity and form of materials, barrier/containment integrity, safety analyses and history, and the site's evaluation of potential ES&H vulnerabilities. The Support Group will review the responses and make determinations concerning the adequacy of the site response and the need for a site visit. Those DOE sites initially identified as having only out-of-scope material will be sent a letter asking that this information be confirmed.

Task 4: Analysis

The purpose of Task 4 is to compile the field data from Task 3, summarize and integrate the results, remove potential team bias, use consistent bases and terminology across all sites, characterize and prioritize potential ES&H vulnerabilities, and present the results to the Working Group.

4.a Data Assembly. The Support Group and Working Group Assessment Team leaders will assemble all field data (Site Assessment Team reports, Working Group Assessment Team reports, Vulnerability Assessment Forms, self-assessment reports of sites not visited, historical data, prior studies, and the database) and prepare for the second Working Group meeting.

4.b Vulnerability Characterization and Summary. The Support Group and Working Group Assessment Team leaders will review all vulnerabilities to remove team bias (that is, tendencies of a team to judge vulnerabilities either more or less severely than the average of all teams). Vulnerabilities will then be characterized using consistent terminology.

The Support Group will develop and use a relational database to organize, store, analyze, and report data and information collected from the sites. The database will be created in standard, off-the-shelf PC software. Data and information will be extracted from the Site Assessment Team reports, Working Group Assessment Team reports, and Vulnerability Assessment Forms, and will be entered into the database following the site visits.

4.c Prioritization. The Support Group will rank the vulnerabilities and provide narrative discussions of the rationale used. The results of prioritization will be presented and discussed at the Second Working Group meeting (4.d).
4.d Second Working Group Meeting. Working Group Assessment Team leaders will present the results of each site visit. A Support Group member will present the results of the site assessments of all other plutonium sites not visited by teams. The Working Group will review the adequacy of the assessments and the vulnerability characterization and prioritization and identify individuals to prepare the report.

Task 5: Reporting

The purpose of Task 5 is to summarize and organize the results of Task 4 and then draft the Plutonium ES&H Vulnerability Assessment Report.

5.a Data Collection and Organization. The Support Group will prepare the results of Task 4 in suitable forms for communication (i.e., bar charts, pie charts, text boxes, other graphics, and narratives).

5.b Report Writing. The Support Group (assisted by other Working Group members and expert consultants) will assemble the draft final report using the outline shown below.

```
FINAL REPORT OUTLINE
- Executive Summary
- Vulnerability Characterization
- Vulnerability Prioritization

APPENDICES
- Site Team Reports
- Working Group Assessment Team Reports
- Assessment Planning Documents

CLASSIFIED APPENDIX (if necessary)
- Classified appendices from the various site reports
- Classified appendix of Final Report
```

5.c Draft Report Distribution. A draft of the final report and results will be sent to Working Group participants for review and comment.

5.d Final Report. The Support Group will revise the draft final report to resolve comments and will issue the final report of the Plutonium ES&H Vulnerability Assessment Project.

5.e Management Briefings. EH and the Support Group will conduct briefings for DOE managers, as appropriate.

3.3 Responsibilities

The responsibilities for this project have been divided among four elements, as described below.

1. The Working Group is a DOE-wide group of designated Headquarters, operations offices, and M&O contractor personnel and expert consultants. The Working Group guides the conduct of the project, including review of the draft planning documents, the vulnerability assessments, the vulnerability prioritization, and the final report.

2. The Support Group is a subset of the Working Group. The Support Group is responsible for preparing drafts of the planning documents, conducting the day-to-day operations of the project, and preparing the draft final report.

3. The Site Assessment Teams consist of M&O contractor and DOE operations office personnel. The Site Assessment Teams are responsible for performing site assessments, responding to the questions provided by the Working Group in the Assessment Plan, presenting this information to the Working Group Assessment Teams, assisting in the identification and characterization of plutonium holdings and vulnerabilities at the site, and
preparing the Site Assessment Team self-assessment reports.


Figure 3-2 is provided to assist readers in understanding the relationships of these elements.

3.4 Classified Information Security

A goal of this project is to present as much information as possible for each site in an unclassified form. Some information for some sites is currently classified. If it is necessary to present such information, it will be contained in classified appendices or attachments to the reports. The handling of classified information and site accommodation for classified work are described in Attachment 6.

The Working Group meetings are unclassified, and no discussion or presentation will disclose or reveal classified information.

3.5 Schedule

The project schedule is shown in Figure 3-3. While this schedule is firm, changes will be considered on a case-by-case basis only.

The respective Working Group Assessment Team leaders and Support Group staff will attend the start of the Site Assessment Team work at each site to review the scope and methodology of the project. For each site, the Site Assessment Team report (Task 3.a) is due in draft form 1 week before the start of the Working Group Assessment Team visit for preliminary review by Working Group Assessment Team members.

3.6 Department Coordination

The DOE Working Group process is a crosscutting approach for identifying issues important to the entire Department complex. It is based on the principle of mutual cooperation among multiple DOE Headquarters program and operations offices, M&O contractors, national laboratories, expert consultants, and external stakeholder representatives. It requires significant senior management attention, commitment from responsible DOE and M&O organizations, and an openness to share information.

The Working Group process is committed to identifying and assessing weaknesses and vulnerabilities at DOE sites, which will provide the basis for corrective actions. The Working Group process also demonstrates that the Department can marshal tremendous technical expertise when its elements work together as a team, and that it is possible to rapidly assemble valuable and credible information in a manner that is useful to decision makers and the public.

At specific project stages, program office Directors and other senior Departmental staff will be briefed by Support Group and management representatives. This will minimize "surprises" and will facilitate the formulation of action plans by the program offices responsible for corrective action. This Project Plan includes provisions for this level of communication and briefing.

One of the goals of this project is to involve external stakeholders. These groups include other government agencies, the Congress, the states, and public interest groups. In accordance with DOE policy and the desire for a consistent approach, DOE will provide guidelines for stakeholder involvement and participation during the course of this project.
<table>
<thead>
<tr>
<th>Working Group</th>
<th>Site Assessment Teams</th>
<th>W.G. Assessment Teams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Develops vulnerability assessment methodology and process, including Question Set.</td>
<td>Collect facility data. Complete responses to Question Set.</td>
<td>Receive training.</td>
</tr>
<tr>
<td>Obtains information from custodians of plutonium at smaller sites and assesses ES&amp;H vulnerabilities.</td>
<td>Review and evaluate information from site facilities.</td>
<td>Visit sites. Verify and validate information. Identify and organize vulnerabilities.</td>
</tr>
<tr>
<td>Reviews Site and Working Group Assessment Teams reports for consistency across DOE complex. Characterizes &amp; prioritizes vulnerabilities.</td>
<td>Identify adverse conditions and vulnerabilities.</td>
<td>Prepare Site Team report.</td>
</tr>
</tbody>
</table>
Figure 3-3

Plutonium ES&H Vulnerability Assessment Project Schedule

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<td>Site Reports (See Sec. 3.5 for Site Assessment Team Work and Report Schedule Requirement)</td>
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<tr>
<td>Question Set Responses by Sites not Initially scheduled for visit</td>
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</table>

Key for Site Assessment:
- Preparation
- On-site
- Report writing

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4.0 REFERENCES


To establish a foundation for decision making regarding the safe management of its plutonium, DOE needs a comprehensive understanding of the environment, safety, and health issues surrounding its entire inventory of plutonium outside of intact nuclear weapons. While not all plutonium in storage is surplus, this vulnerability assessment will serve as the information base to support the larger Nuclear Materials Disposition Project, which is mandated to develop options, make recommendations, and implement decisions for the safe management of surplus fissile materials.

**DOE Plutonium**

Table A-1 summarizes project scope in terms of general plutonium categories held by DOE. In this context, the term "plutonium" includes all isotopes of plutonium and the isotopes of other transuranic elements, such as Americium, Curium, Neptunium or Californium, or U-233 as a decay product that are co-mingled (i.e., intermixed or in-grown) or co-located with plutonium materials in the same facility. Pu-238 and Pu-239 have substantially different properties, for example, a different spectrum of hazards. Distinctions will be made, as necessary, when identifying associated ES&H vulnerabilities. The "Remarks" column of Table A-1 either clarifies what is included in the stated "Category" or justifies why a category is out of scope.

By Secretarial directive, intact nuclear weapons (and therefore nuclear explosive assemblies) are excluded from the scope of this Project.

Very low-irradiated reactor fuel containing plutonium was assessed as part of the DOE Spent Fuel Working Group project in late 1993. However, this fuel was not assessed for plutonium ES&H vulnerabilities, so it is included in the scope of this assessment. Other irradiated fuel covered in the spent fuel assessment is excluded here. Unirradiated plutonium-bearing fuel is included in this assessment.

**Exclusion of Plutonium Not in DOE Custody**

DoD-controlled plutonium materials are outside the scope of this project. A very small fraction of plutonium (outside of spent fuel) is in the custody of licensees of the Nuclear Regulatory Commission or "agreement states." Much of this material is in the form of sealed sources. The ES&H responsibility for such plutonium rests with the licensee, with oversight by the NRC or the agreement state. Plutonium is also in the custody of government agencies, such as NIST, EPA, and the military, and is held under an NRC license. These plutonium materials are excluded from the scope of this project.

**Other Scope Considerations**

This project will evaluate Department of Energy sites possessing plutonium. These sites are listed in Attachment 2. Based on the initial estimates of plutonium holdings and the forms and conditions of these materials, a subset of the DOE sites has been selected by the Support Group for Working Group Assessment Team site visits. These sites are listed in the box on the following page.

All sites having plutonium in scope as defined in Table A-1 will undertake the self-assessment process, respond to the Question Set, and prepare a draft Site Assessment Team report. Sites other than those initially selected may warrant a site visit, based on the vulnerability self-assessment in the Site Assessment Team report. The Support Group and DOE...
management will review these sites on a case-by-case basis. Sites initially identified as having only out-of-scope plutonium as defined in Table A-1 will be asked to confirm that information.

Safeguards and security are not considered to be within the project scope except to the extent that they might affect ES&H vulnerabilities.

Waste

There are three categories of waste materials that may contain plutonium:

- High-level Waste,
- Low-level Waste, and
- Transuranic Waste.

The vulnerability assessment of waste materials will differ considerably from the assessment of bulk plutonium due to the waste's chemical and physical forms, dilution, packaging, confinement, etc. Further, these waste forms are the subject of other DOE programs, including analysis and characterization, disposal, and packaging. From the perspective of weapon usable material, waste contains very small amounts of fissile material in very dilute and nonrecoverable forms. For these reasons, the categories of high-level waste, low-level waste, and transuranic waste, as described in Table A-1, are excluded from the scope of this project, unless these materials are co-located in the plutonium facilities that are subject to this assessment.
### Table A-1
**Plutonium Categories**

<table>
<thead>
<tr>
<th>Category</th>
<th>Scope</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process hold-up</td>
<td>In</td>
<td>Category includes Pu in ventilation systems, process vessels, piping, materials removed from the Nuclear Material Management and Safeguards System (NMMSS), etc.</td>
</tr>
<tr>
<td>Metal</td>
<td>In</td>
<td>Category also includes alloys</td>
</tr>
<tr>
<td>Oxide</td>
<td>In</td>
<td>Category includes mixed oxides with other actinides</td>
</tr>
<tr>
<td>Very low irradiated and unirradiated reactor fuel, targets</td>
<td>In</td>
<td>Category includes ZPPR fuel</td>
</tr>
<tr>
<td>Weapons components, pits</td>
<td>In</td>
<td>Category includes weapons components in DOE custody</td>
</tr>
<tr>
<td>Scrap/residues/compounds</td>
<td>In</td>
<td>Category includes Pu nitride, Pu carbides, slag and crucibles, ash, graphite, etc.</td>
</tr>
<tr>
<td>Solutions</td>
<td>In</td>
<td>Category includes product/residue solutions, lab samples, etc.</td>
</tr>
<tr>
<td>Sealed sources in DOE custody</td>
<td>In</td>
<td>Category includes all sealed sources</td>
</tr>
<tr>
<td>High-level waste</td>
<td>Out</td>
<td>Category includes calcined and liquid material meeting DOE Waste Management Definition</td>
</tr>
<tr>
<td>TRU &amp; low-level wastes</td>
<td>Out</td>
<td>Category includes material packaged and declared LLW or TRU waste and material in burial sites. However, LLW or TRU co-located in plutonium facilities subject to this assessment are in-scope</td>
</tr>
<tr>
<td>Materials in facilities accepted for D&amp;D by EM</td>
<td>Out</td>
<td>Category out-of-scope; other DOE programs are addressing this material</td>
</tr>
<tr>
<td>Materials in areas subject to funded environmental restoration programs</td>
<td>Out</td>
<td>Category out-of-scope; other DOE programs are addressing this material</td>
</tr>
<tr>
<td>Materials in NRC or agreement state licensee custody</td>
<td>Out</td>
<td>Category out-of-scope; the licensee has ES&amp;H responsibility</td>
</tr>
<tr>
<td>Irradiated spent fuel and targets</td>
<td>Out</td>
<td>This category was covered in the spent nuclear fuel vulnerability assessment</td>
</tr>
<tr>
<td>Expended in nuclear device tests</td>
<td>Out</td>
<td>Category includes undetermined areas/locations, unrecognizable forms</td>
</tr>
<tr>
<td>Intact nuclear weapons and nuclear explosive assemblies in DOE Custody</td>
<td>Out</td>
<td>Secretarial charter specifies this category out-of-scope</td>
</tr>
</tbody>
</table>
The following table lists DOE sites possessing plutonium and the Operations Offices corresponding to those sites (shown in bold). This list was prepared based on information contained in the Nuclear Material Management and Safeguards System (NMMSS) database, and confirmation by telephone with the respective sites.

Based on the kind, quantity, form or configuration of the plutonium possessed, and the potential for ES&H vulnerabilities, several sites have been identified by the Support Group to require a Site Assessment Team report and a Working Group Assessment Team visit.

Other listed sites are believed to possess either out-of-scope plutonium, or plutonium having a lower potential for ES&H vulnerabilities, for example, sites possessing sealed sources, only. Operations offices will identify any additional sites which hold plutonium. The Support Group will provide copies of the Project Plan and Assessment Plan to such sites and request the sites to provide responses to the Question Set for each facility possessing plutonium.

Facilities that complete Question Set questions Q-1 and Q-2 and determine that all their plutonium is out-of-scope, as defined in Table A-1, may return the partially completed Question Set to the Support Group. Sites with several facilities containing out-of-scope plutonium may prepare a consolidated list of such facilities and provide a brief description of the out-of-scope plutonium materials and the gross quantities of plutonium contained therein. Facilities that complete Question Set questions Q-1 and Q-2 and determine that their plutonium is in-scope, must complete the entire Question Set and return the response to the Support Group.

Question Set responses will be reviewed by the Support Group to confirm in-scope/out-of-scope determinations, the potential for ES&H vulnerabilities, or the need for a Site Assessment Team report and a Working Group Assessment Team visit. Adjustments to the level of assessment will be identified by the Support Group on a site by site basis, as necessary.

Responses are due to the Support Group by May 30, 1994.
<table>
<thead>
<tr>
<th>Location</th>
<th>Q-Set &amp; Visit</th>
<th>Q-Set</th>
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</thead>
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<tr>
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<tr>
<td>Sandia National Laboratories, Albuquerque</td>
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<tr>
<td>Sandia National Laboratories, California</td>
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<td>EG&amp;G Mound Applied Technologies, Inc.</td>
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<td></td>
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<tr>
<td>Inhalation Toxicology Research Institute</td>
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<tr>
<td>Mason &amp; Hanger–Silas Mason, Pantex</td>
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<tr>
<td>Martin Marietta, Pinellas</td>
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<tr>
<td>Allied–Signal Aerospace, Kansas City</td>
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<td><strong>Chicago</strong></td>
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<tr>
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<td>New Brunswick Laboratory</td>
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<tr>
<td>Fermi National Accelerator Laboratory</td>
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<tr>
<td>Ames Laboratory, Iowa</td>
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<td>Princeton Plasma Laboratory</td>
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<td>Brookhaven National Laboratory</td>
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<td>Idaho</td>
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04/25/94

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The criteria presented here will be used for selecting members of the Site Assessment Teams and Working Group Assessment Teams.

**Site Assessment Teams**
(M&O contractor and operations office personnel)

Best knowledge in:
- Operations, maintenance, radiological protection, occupational safety and health, process safety management, configuration management associated with plutonium, and plutonium storage and operations
- Site or lab inventory of plutonium materials
- Operations and storage facilities' authorization, safety, and operational bases
- Accident and risk analyses
- Limiting conditions for operation and administrative controls
- Operational history and occurrences
- Operations and storage facilities' ES&H considerations, including:
  - design basis, including natural phenomena hazard considerations
  - conditions of plutonium materials and associated confinements, safety systems, and structures
  - accident prevention and mitigation
  - aging-related degradation
  - other related technical information

**Working Group Assessment Team**
(Selected Working Group members, DOE staff, and expert consultants)

Specialized knowledge in:
- Plutonium chemistry and processing
- Plutonium storage
- Storage designs and analysis
- Safety systems design and analysis
- Seismic and structural analysis
- Criticality safety
- Natural phenomena hazard analysis
- Corrosion and aging analyses
- Accident analysis
- Vulnerability analysis
- National, international, industry, and government standards on plutonium storage and handling
- Plutonium transportation and hazards analysis
- Field experience with the above technical issues
- Health physics
Attachment 4 is a tentative list of team members as of April 25, 1994.

TEAM #1  Argonne National Laboratory—East (ANL-E)  New Brunswick Laboratory (NBL)

Draft Site Assessment Team Report— May 16, 1994
Working Group Assessment Team Site Visit— May 23, 1994
Site Assessment Team Report— June 3, 1994
Draft Working Group Assessment Team Report— June 3, 1994

Team Members:

- Pete Rodrick, DOE/EH-14, Team Leader 303-966-5973, 303-966-7890 F
- Burt Rothleder, DOE/EH-64, Deputy Team Leader 301-903-3726, 301-903-9523 F
- Billy Lee, Battelle, 614-424-4064, 614-424-3404 F [Criticality]
- Henry Peterson, INEL, 208-526-8657, 208-526-9982 F [Health Physics]
- Clinton Bastin, DOE/NE, 301-903-5259, 301-903-3419 F [Safety Analysis]
- Bruce Moran, ORNL/MM, 615-576-8269, 615-574-5169 F [Safeguards Security]

Site Contact—

<table>
<thead>
<tr>
<th>ANL-E:</th>
<th>NBL:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ray Wilson, 708-252-4471, 708-252-7433 F</td>
<td>Margaret Lachman, 708-252-2492, 708-252-6256 F</td>
</tr>
<tr>
<td>Steve Ludwig, 708-252-2233, 708-252-2361 F</td>
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</tr>
</tbody>
</table>

Working Group Assessment Team Coordinator—

- Julie Sellers, INEL, 208-526-8263, 208-526-2930 F [Administrative Support]
TEAM # 2  Lawrence Livermore National Laboratory (LLNL)
              Lawrence Berkeley Laboratory (LBL)

Draft Site Assessment Team Report-- May 16, 1994
Working Group Assessment Team Site Visit-- May 23, 1994
Site Assessment Team Report-- June 3, 1994
Draft Working Group Assessment Team Report-- June 3, 1994

Team Members:

- Marty Seitz, DOE/EM-64, Team Leader 301-427-1564, 301-427-1839 F
- Lisa Chan, DOE/DP-40, Deputy Team Leader 202-586-9637, 202-586-1217 F
- Rick Stachowiak, ORNL/MM, 615-574-9979, 615-241-2023 F [Criticality]
- Dan Guzy, DOE/EH-12, 301-903-2428, 301-903-2329 F [Seismic]
- Diane Durban, WHC/DP-22, 301-903-2992, 301-903-5821 F [Operations Maintenance]
- Bryce Rich, EG&G, 208-523-8025, 208-523-8247 F [Health Physics]
- Calvin Lai, DOE/EH-12, 301-903-6357, 301-903-2329 F [Safety Analysis]

Site Contact--

LLNL: Brent Ives, 510-423-2636, 510-423-1685 F
      Dawn Wechsler, 510-422-2547, 510-422-2832 F
      Ken Rivera, 510-486-6343, 510-486-4710 F

Working Group Assessment Team Coordinator--

- Colleen Yelle, Scientech, 301-428-9583, 301-428-3104 F [Administrative Support]
TEAM #3  Mound

Draft Site Assessment Team Report-- May 16, 1994
Working Group Assessment Team Site Visit-- May 23, 1994
Site Assessment Team Report-- June 3, 1994
Draft Working Group Assessment Team Report-- June 3, 1994

Oak Ridge National Laboratory (ORNL)

Draft Site Assessment Team Report-- June 13, 1994
Working Group Assessment Team Site Visit-- June 20, 1994
Site Assessment Team Report-- July 1, 1994
Draft Working Group Assessment Team Report-- July 1, 1994

Team Members:

- Allen Gunter, DOE/SR, Team Leader 803-952-4536, 803-952-4002 F
- Richard W. Miller, INEL, Deputy Team Leader 208-526-9956, 208-526-2930 F
- Michael Todosow, BNL, 516-282-2445, 516-282-7650 F [Criticality]
- James Shuler, DOE/D-9, 301-903-5513, 301-903-6623 F [Health Physics]
- Joe Salolo, OGDEN, 505-881-9228, 505-881-9357 F [Safety Analysis]

Site Contact--
Mound: Wayne Amos, 513-865-3058, 513-865-3485 F
ORNL: Calvin Hopper, 615-576-8617, 615-576-3513 F
Garland Proco, 615-576-9293, 615-576-7813 F

Working Group Assessment Team Coordinator--
- Paula Olson, INEL, 208-526-2287, 208-526-2930 F [Administrative Support]
TEAM # 4 Pantex

Draft Site Assessment Team Report- June 6, 1994
Working Group Assessment Team Site Visit- June 13, 1994
Site Assessment Team Report- July 1, 1994
Draft Working Group Assessment Team Report- July 1, 1994

Team Members:
- Dave Templeton, DOE/RL, Team Leader 509-373-2966, 509-373-0695 F
- Herb Berman, Scientech, Deputy Team Leader 303-278-4338, 303-278-0092 F
- Jor-shan Choi, LLNL, 510-423-8032, 510-423-2854 F [Criticality]
- Richard Rahl, INEL, 208-526-0371, 208-526-6974 F [Seismic]
- Laverne Dingman, LATO-RFO, 303-966-4080, 303-966-4993 F [Operations Maintenance]
- Wayne Britz, Battelle, 301-320-3110, 301-320-6379 F [Health Physics]
- Lee Hyder, WSRC, 803-644-5424, 803-644-5051 F [Safety Analysis]
- David Bennett, SNL, 301-428-9583, 301-428-3104 F [Safeguards Security]

Site Contact- Pantex: Robb Wright, 806-477-6299, 806-477-6298 F
Hector Chavez, 806-477-3148, 806-477-3141 F
Steven S. Payne, 505-845-6300, 505-845-6431 F

Working Group Assessment Team Coordinator-
- Jan Ulrich, INEL 208-526-7909, 208-526-7910 F [Administrative Support]
TEAM # 5 Rocky Flats

Draft Site Assessment Team Report— June 6, 1994
Working Group Assessment Team Site Visit— June 13, 1994
Site Assessment Team Report— July 1, 1994
Draft Working Group Assessment Team Report— July 1, 1994

Team Members:

- Charles Gilbert, DOE/DP-9, Team Leader 301-903-5012, 301-903-6623 F
- Rowland Felt, WINCO, Deputy Team Leader 208-526-3409, 208-526-0665 F
- Mark Bronson, LLNL, 510-422-3061, 510-422-3165 F [Pu Technology, Process Safety]
- Hans Ludewig, BNL, 516-282-2624, 516-282-5730 F [Criticality]
- Hans Dahlke, INEL, 208-526-9777, 208-526-6974 F [Seismic]
- Clyde Alley, Mason & Hanger, 806-378-1543, 806-378-1529 F [Operations Maintenance]
- Pat Ward, Scientech, 301-428-9583, 301-428-3104 F [Operations Maintenance]
- Tracy Ikenberry, PNL, 509-375-2338, 509-375-6943 F [Health Physics]
- Peter Cybulskis, PNL, 614-424-7509, 614-424-3404 F [Safety Analysis]
- Larry Forsythe, DOE/NE, 301-903-4610, 301-903-4765 F [Safety Analysis]
- Jack McClure, OGDEN, 303-843-6210, 303-843-6215 F [Safeguards Security]
- Venkataraman Pasupathi, Battelle/OR, 615-220-4019, 615-482-7964 F [Waste]

Site Contact— Rocky Flats: Jeff Kerridge, 303-966-2648, 303-966-5857 F
Steven Browdy, 303-966-7719, 303-966-5706 F

Working Group Assessment Team Coordinator—

- Debby Myler, INEL, 208-526-1441, 208-526-2930 F [Administrative Support]
**TEAM # 6** Los Alamos National Laboratory (LANL)

Draft Site Assessment Team Report- June 6, 1994  
Working Group Assessment Team Site Visit- June 13, 1994  
Site Assessment Team Report- July 1, 1994  
Draft Working Group Assessment Team Report- July 1, 1994

**Team Members:**

- Fred Witmer, DOE/DP-35, Team Leader 301–903–5012, 301–903–6623 F
- Harold Burton, Scientech, Deputy Team Leader 301–428–9583, 301–428–3104 F
- Ronald Knief, OGDEN, 505–881–9228, 505–881–9357 F [Criticality]
- Jeff Kotsch, Scientech, 301–468–6425, 301–468–0883 F [Health Physics]
- Dick Chitwood, DOE/NE, 301–903–5254, 301–903–5434 F [Safety Analysis]

**Site Contact**—LANL: K. Pillay, 505–667–2556, 505–667–7966 F  
Patricia Berglund, 505–665–5049, 505–665–4504 F  
Steven S. Payne, 505–845–6300, 505–845–6431 F

**Working Group Assessment Team Coordinator**—

TEAM # 7  Savannah River Site (SRS)

Draft Site Assessment Team Report-- June 6, 1994
Working Group Assessment Team Site Visit-- June 13, 1994
Site Assessment Team Report-- July 1, 1994
Draft Working Group Assessment Team Report-- July 1, 1994

Team Members:

- Mike Zamorski, DOE/AL, Team Leader 505-845-4094, 505-845-6867 F
- Al Williams, SAIC, Deputy Team Leader 301-353-8228, 301-428-0145 F
- Dave Horrell, LANL, 505-665-7630, 505-665-8002 F [Pu Technology, Process Safety]
- Chet Everline, Scientech, 619-755-4535, 619-755-4336 F [Criticality]
- Roger Brewer, LANL, 505-667-7752, 505-665-4970 F [Criticality]
- Mark Russell, INEL, 208-526-1608, 208-526-6974 F [Seismic]
- Larry Leach, Scientech, 208-523-9552, 208-523-9380 F [Operations Maintenance]
- James Durham, PNL, 509-375-2705, 509-375-6936 F [Health Physics]
- Charles Bell, LANL, 505-667-9402, 505-665-4322 F [Safety Analysis]
- William Hogle, PNL, 301-846-4269, 301-846-4269 F [Safety Analysis]
- Richard Cross, PNL, 509-372-4472, 509-372-4487 F [Safeguards Security]

Site Contact-- Savannah River: Edward Moore, 803-725-2603, 803-725-2978 F
                     Don Bridges, 803-725-5530, 803-725-1372 F

Working Group Assessment Team Coordinator--

- Barbara Kneece, Asta Engineering, 301-428-9583, 301-428-3104 F [Administrative Support]
TEAM # 8 Richland (RL)

Draft Site Assessment Team Report- June 6, 1994
Working Group Assessment Team Site Visit- June 13, 1994
Site Assessment Team Report- July 1, 1994
Draft Working Group Assessment Team Report- July 1, 1994

Team Members:

- William Rask, DOE/RF, Team Leader 303-966-2648, 303-966-5857 F
- Tony Muscatello, LATO/RF, Deputy Team Leader 303-966-5994, 303-966-4933 F
- Dimitrios Cokinos, BNL, 516-282-2146 [Criticality]
- Alam Mozumder, DOE/DP-35, 301-903-4287, 301-903-6623, F [Seismic]
- Barry Cochran, DOE/OR, 615-576-4296, 615-576-7813 F [Operations Maintenance]
- Nazir Khalil, DOE/SR, 803-725-9855, 803-725-1372 F [Operations Maintenance]
- Sam Aoki, INEL, 208-526-0583, 208-526-6249 F, [Health Physics]
- Peter Kohut, BNL, 516-282-4982, 516-282-5730 F [Safety Analysis]
- Dick Sutton, OGDEN, 303-935-6505, 303-935-6575 F [Safeguards Security]
- George Becker, WSRC, 803-725-5516, 803-725-2978 F [Waste]

Site Contact- Richland: Lou Guillen, 509-376-4762, 509-376-0695 F
Rich Szempruch, 509-373-1468, 509-373-4274 F
Deborah Dickman, 509-372-4432, 509-372-4431 F

Working Group Assessment Team Coordinator-
- Freadle Frost, EG&G, 301-816-7789, 301-816-7767 F [Administrative Support]
TEAM #9  ANL-W/INEL

Draft Site Assessment Team Report- May 23, 1994
Working Group Assessment Team Site Visit- May 30, 1994
Site Assessment Team Report- June 6, 1994
Draft Working Group Assessment Team Report- June 6, 1994

SNL

Draft Site Assessment Team Report- June 13, 1994
Working Group Assessment Team Site Visit- June 20, 1994
Site Assessment Team Report- June 27, 1994
Draft Working Group Assessment Team Report- June 27, 1994

Team Members:
- Tom Hull, DOE/EH-11, Team Leader 301-428-9583, 301-428-3104 F
- Milton Haas, WHC/EM-60, Deputy Team Leader 202-484-0903, 202-484-0875 F
- Andrew Pritchard, Battelle/PNL, 509-376-8590, 509-372-4411 F [Criticality]
- Carl Cooper, INEL, 208-526-9183, 208-526-2930 F [Safety Analysis]
- Casper Sun, BNL, 516-282-3469, 516-282-5810 F [Health Physics]

Site Contact—

ANL-W: Doug Crawford, 208-533-7456, 208-533-7863 F
       Ernie Hughes, 208-533-7446, 208-533-7422 F
SNL: Terri Lovato, 505-845-8791, 505-845-8952 F
      Jon Peschong, 508-845-4687, 508-845-4671 F
      Steven S. Payne, 505-845-6300, 505-845-6431 F
INEL: Darrell Hinckley, 208-526-0173, 208-526-1148 F

Working Group Assessment Team Coordinator—
- Cindie Jensen, INEL, 208-526-9144, 208-526-2930 F [Administrative Support]
The vulnerability assessment process shown in Figure A-1 examines materials at risk, the packaging and barriers used to protect the materials, adverse conditions/events that can lead to containment or barrier failure, compensatory measures that can prevent or mitigate the effects of releases or exposures, and finally the impact or consequences on the worker, the public, and the environment. Information will be gathered by several methods, including the following:

(1) Site response to the Question Set for each category of information,
(2) Facility walkdowns, and
(3) Tabletop discussions based on issues stemming from the site response and walkdowns.

Inventory and material information consists of both inventory validations and a review of material characteristics associated with each form of plutonium currently onsite. Information for physical barriers will also be collected. Adverse conditions resulting in internal and external events (natural and humanmade) and compensatory measures and plans will be examined to determine the consequences on the worker, the public, and the environment.

The methodology is a qualitative approach that relies on the experience and expertise of the Site Assessment Teams in making judgments regarding the likelihood and severity of containment or barrier failures, relevant historical experience, and the frequency of adverse events/conditions. The implications or consequences of those events are then determined. The Question Set is geared toward collecting the necessary data on materials, barriers, and adverse conditions. The Site Assessment Teams are also being asked to use the Question Set to identify consequences and vulnerabilities. Both Site and Working Group Assessment Teams will then use historical data, tabletop discussion topics, and the Question Set answers to review and develop a comprehensive understanding of the consequences and potential vulnerabilities resulting from current plutonium storage and handling operations. Vulnerabilities identified as a result of this process will be documented on Vulnerability Assessment Forms.

The Working Group Assessment Plan contains a more detailed explanation of the methodology and implementing procedures for conducting this assessment.
Figure A-1
ES&H VULNERABILITY ASSESSMENT APPROACH

Question 1
Facility

Question 2
Holdings and Packaging

Question 3
Physical Barriers

Question 4
Adverse Conditions

Question 5
Events

Question 6
Compensatory Measures
Preventive/Mitigative

Question 7
Consequences

Identification of ES&H Vulnerabilities
- Environment
- Worker
- Public
Some information about materials and processes needed for the Plutonium ES&H Vulnerability Assessment may be classified. It is anticipated that general summaries will be compiled in an unclassified form. It is the goal of this project to present and report as much information as possible for each site in an unclassified form. This will apply primarily to the Site Assessment Team reports, Working Group Assessment Team reports, and the Final Report. Any classified information will be reviewed for declassification: If it cannot be declassified, it will be segregated in classified appendices.

The Working Group meetings will be unclassified. Personnel from sites with classified descriptions and data will be required to prepare for the second Working Group meeting by properly separating and identifying unclassified and classified information about their site. No presentations or discussions at these meetings can divulge or reveal classified information.

To allow complete access to all technical security areas of classified sites, Support Team and Working Group Assessment Team members must have current Q clearances.

For Working Group Assessment Team visits to classified sites, the site will provide safeguards and security administrative support. This includes secure work environments and equipment for all meetings and team work areas and secure handcarry between security areas. Areas approved for classified work should be identified during the site orientation.

Administrative support provisions must include access to authorized classifiers to ensure that written material leaving the site is unclassified. If information must be preserved for segregated classified appendices, arrangements to transfer the classified material to a DOE–HQ classified area will be made.

The scope of site administrative support includes the following:

1. Secure work areas/work areas outside security zones
2. Access to unclassified and secure equipment (personal computers, laser printers, copiers, etc.)
3. Unclassified and classified document storage (approved repository)
4. Classification/declassification support (authorized classifier)
5. Site classified documents (SARs, etc., only if necessary)
6. Handcarry/transport of classified documents and notes
7. Mail channels to DOE–HQ Germantown
8. Marking and handling of documents and notes
9. Personnel access/badging
10. Telephone availability (including secure telephone)

The goal is to provide classified work support such that classified documents, notes, and discussions can be revised and interpreted as unclassified so as to not impede the work of the Working Group Assessment Team.

Appropriate DOE Security Requirements will apply to all activities of the Plutonium ES&H Vulnerability Assessment Project.
A.2

DOE Plutonium ES&H Vulnerability Assessment

Assessment Plan
ASSESSMENT PLAN

Department of Energy
Plutonium ES&H Vulnerability Assessment Project

April 25, 1994
DEPARTMENT OF ENERGY
PLUTONIUM ES&H VULNERABILITY
ASSESSMENT

ASSESSMENT PLAN

April 25, 1994
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PREFACE

This Assessment Plan is an implementing document for the Secretary's Initiative to evaluate the Department's environment, safety, and health (ES&H) vulnerabilities stemming from plutonium operations and storage. A Project Plan that describes essential features of the initiative and the role of this Working Group Assessment Plan has been prepared. The user of this Assessment Plan should be familiar with details of the Project Plan. The principal users of this plan are the Site Assessment Teams and the Working Group Assessment Teams, which are responsible for identifying and characterizing vulnerabilities. This assessment will serve as the information base for identifying interim corrective actions and options for the safe management of fissile materials.

OBJECTIVE

The first objective of this plan is to provide Site Assessment Teams with a systematic, effective, and efficient methodology to assess vulnerabilities associated with plutonium operations and storage.

The second objective of this plan is to provide Working Group Assessment Teams with an effective methodology to verify and validate information supplied by the "Site Assessment Teams," and to identify if there are any additional vulnerabilities, and then prioritize and document all vulnerabilities. The methodology developed can be applied uniformly at all sites by both the Site Assessment Teams and Working Group Assessment Teams. This methodology serves to minimize disparate interpretations, ensure common terminology among the reports, and facilitate the efforts of the Working Group to summarize and prioritize the vulnerabilities for the final report to the Secretary.

What are vulnerabilities?

The term "ES&H vulnerabilities" in nuclear facilities is defined for the purpose of this project to mean conditions or weaknesses that may lead to unnecessary or increased exposure of the workers, release of radioactive materials to the environment, or radiation exposure of the public. For example, some DOE facilities had plutonium metal fires caused by poor control of pyrophoric materials, degradation of storage and handling systems, or personnel contamination.

Some other examples of vulnerabilities associated with plutonium material, packaging, and facilities include the following:

1. Vulnerabilities identified or documented in previous hazard analyses.

2. Vulnerabilities arising from subsequent changes to conditions or assumptions in prior analyses, including:
   - mission change
   - aging/deterioration
   - plans to change material form, packaging, or facilities
   - knowledge base
   - administrative controls
   - standards and criteria.

3. Unidentified or unanalyzed hazards, which can arise from:
   - uncertainty in the knowledge base about material, packaging, or facilities
   - inadequate monitoring of material, packaging, or facilities
   - unknown changes to the material, packaging, or facilities.

OVERVIEW

The Site Assessment Team consists of management and operations (M&O) contractor and operations office personnel selected for their knowledge about plutonium storage and operations at the site. The Site Assessment Team prepares the draft Site Assessment Team report, which is made available to the Working Group Assessment Team prior to its arrival at the site.
The Working Group Assessment Team consists of members of the Working Group for the Plutonium ES&H Vulnerability Assessment Project and expert consultants. Expert consultants are selected for their experience in areas important to ES&H protection in plutonium storage and operations.

External Stakeholder Organizations are intended to be involved in the Working Group process. Their participation will be coordinated by the Nuclear Materials Disposition Project.

ROLES AND RESPONSIBILITIES

The Site Assessment Team will accomplish the following activities.

- Organize itself under the direction of Site Assessment Team co-leaders (one Federal employee and one M&O contractor representative) who serve as the points of contact with the Working Group Assessment Team leader and deputy leader.

- Prepare response to the Question Set for its site on all plutonium holdings within the scope of this project.

  NOTE: The term "holdings" is used to indicate that the scope encompasses more than plutonium material types inventoried on the accountability books.

- Ensure completion of its draft report, including completed Vulnerability Assessment Forms, before the Working Group Assessment Team arrives on-site.

- Ensure that on-site training and logistics for the Working Group Assessment Team are arranged.

- Assign technical discipline leads for interaction with their counterparts on the Working Group Assessment Team.

- Accompany counterparts from the Working Group Assessment Team during facility walkdowns and participate in tabletop discussions with Working Group Assessment Team members.

Before a Working Group Assessment Team visits a designated site, it will coordinate with the Site Assessment Team on logistics, counterparts, schedules, etc. The Working Group Assessment Team will accomplish the following activities during the site visit.

- Review the results of other relevant assessments (e.g., Tomsk-II, chemical vulnerability assessment, DOE plutonium storage safety assessment, and others) as they relate to the Plutonium ES&H Vulnerability Assessment Project, and include relevant findings in the current assessment where appropriate.

- Review the site's response to the Question Set on facility conditions and missions, plutonium holdings, material and packaging conditions, physical barriers, adverse conditions, events, compensatory measures, and ES&H vulnerabilities.

- Evaluate the responses (data) via independent verification, exploratory discussions, direct observation of facilities (walkdowns), interviews with knowledgeable personnel, and review of documents and programs.

- Evaluate (and validate as necessary) the site's list of issues and exercise the methodology presented in this document to identify and characterize vulnerabilities.

- Write a draft Working Group Assessment Team report and provide it to the Site Assessment Team for factual accuracy review and comment.
• Communicate identified vulnerabilities to other site Working Group Assessment Teams as appropriate.

• Brief external stakeholders during site entrance meetings.

SITE ASSESSMENT TEAM PROCESS

Organization and Training

Management at each site to be visited should select two individuals to act as co-leaders (one Federal employee and one M&O contractor representative) for the Site Assessment Team. The co-leaders will be responsible for the overall conduct of the Site Assessment Team activities, which include performing the self-assessment, coordinating the Question Set responses for all facilities, drafting the Site Assessment Team report, and coordinating all requirements and logistics to support the Working Group Assessment Team visit. Both facility and operations management for facilities to be visited should support this effort.

The Site Assessment Team leaders should arrange and organize their teams to best accommodate their needs. Smaller sites with a limited number of facilities may best be organized with one Site Assessment Team. Larger sites with many facilities may find it helpful to develop facility Assessment Subteams that will take on the responsibilities of performing the self-assessment, writing their sections of the final report, and acting as the technical leads and hosts for the Working Group Assessment Team. For larger sites, the Site Assessment Team leaders should expect the Working Group Assessment Team to break into two or more smaller subteams that will work in parallel during the site visit. Sufficient office and conference space should be made available to support parallel efforts.

Training of the Site Assessment Team is the responsibility of the Site Assessment Team co-leaders, who attended training in Colorado on April 18–22, 1994. This training included details on the vulnerability assessment methodology and process; plutonium technical training, including historical events review; and segments in team building. It is incumbent on the co-leaders to take this training back to their sites and ensure that all Site Assessment Team members have a thorough understanding of the process and procedures to ensure a successful assessment. At the start of the Site Assessment Team work, the Working Group Assessment Team leaders will meet with the respective Site Assessment Team to review the scope and organization of the site assessment process.

Protocol

The Site Assessment Team should conduct a detailed and thorough review of all conditions or events that could lead to vulnerabilities for the worker, environment, or public. It should be emphasized to all participants that this is not a compliance audit or fault-finding effort. Success in identifying vulnerabilities requires a complete and open exchange of information between the Working Group Assessment Team, the DOE operations office staff, and the M&O contractor personnel. Key aspects of a successful self-assessment include those listed below.

• A thorough and complete review of materials and facility conditions, and concerns about those materials and conditions. Unknown or uncharacterized conditions that may exist should be clearly identified.

• Documentation of these concerns in responses to the Question Set (Attachment 1) and on Vulnerability Assessment Forms (Attachment 2).

• Hosting an entrance meeting with the Working Group Assessment Team, Site Assessment Team, and site
management. The Site Assessment Team should also provide summary facility briefings, including mission description, holdings, and Question Set responses.

- Candid verbal communications among all parties, with secure settings provided for classified discussions.
- Arrangement for facility discussions and walkthroughs.
- Identification of technical-administrative contacts to support the Working Group Assessment Team.
- A classifier to review all Working Group Assessment Team documentation and ensure that all Working Group Assessment Team members are aware of site security requirements.
- Factual review of the Working Group Assessment Team report.
- Recognition by all parties that the vulnerability assessment is an integral part of the Department's activities to ensure the safety of workers, the public, and the environment, and that all personnel involved in the activity share that common goal.

Procedure

The Site Assessment Team should have the expertise and information needed to complete responses to the Question Set. This procedure briefly describes how the Question Set is completed and how vulnerabilities that may result from plutonium storage/handling are identified.

Step 1. Preparation

The Site Assessment Team leaders will be trained in the methodology prior to initiating their assessment. They will select team members with appropriate experience, expertise, and clearances. In addition, at the start of the Site Assessment Team work the Working Group Assessment Team leaders will meet with the respective Site Assessment Team to review the scope and organization of the site assessment process.

Step 2. Organization of the Assessment

The Site Assessment Team leaders will develop a detailed plan to ensure that all plutonium holdings within the scope of this assessment are included. This plan should include the identification of facilities and the breakdown of process/storage areas into aggregates that would have similar vulnerabilities. Knowledge of the site, facilities, material holdings, and packaging are required to organize the assessment.

The purpose of aggregating process/storage areas is to assist the Site Assessment Team in completing the Question Set so that the answers and data are organized along the lines of vulnerability identification. When the Question Set is completed in such a manner, the vulnerabilities will be clearly supported by the data in the answers. Additionally, similar vulnerabilities will be grouped, thereby avoiding duplication, and dissimilar vulnerabilities will be separated.

For example, if a building contained a liquid processing line, vaults, and gloveboxes, it might be appropriate to organize that assessment in three aggregates. However, if there were two distinct vaults, one inerted and the other with an air atmosphere, or if the confinement systems were very different, more aggregates might be appropriate. Similarly, if two distinct types of materials and/or packages were located in the gloveboxes, additional aggregates might be appropriate.

Step 3. Data Gathering

The purpose of Question 1 is to organize the assessment and gather appropriate documents. Questions 2 through 7 will then be completed for each aggregate identified. The purpose of Question 2 is to identify the
types of material and appropriate information about its packaging. Tables A1, A2, and A3 provide keys to assist in package and material definitions. Multiple barriers incorporated into a package should be identified. This information will be entered into a database and can be compared with information on material/packaging conditions to identify possible deteriorated conditions.

The purpose of Question 3 is to identify barriers that may prevent material or radiation from affecting workers, the public, or the environment. A sketch may be appropriate to identify and explain all barriers. The identification of barriers by their codes (see Table A4) will be captured in a database for crosscut evaluations.

Step 4. Analysis of Past or Current Adverse Conditions

The purpose of Question 4 is to identify those adverse conditions that might result in vulnerabilities associated with the material aggregates from Questions 1, 2 and 3. Several adverse conditions are usually associated with the material/package and barrier combinations. For example, a glovebox that was originally in use as a processing line may have deteriorated as a storage area. It is reasonable to expect adverse conditions, such as inadequate preventive maintenance (large backlog of work orders) and equipment failures (out of service), when the facility's mission changed.

Site Assessment Team members may be able to identify adverse conditions associated with the material/packages based on their knowledge of deficiencies in similar material/packages (noted in the training materials).

The purpose of Question 5 is to identify events that may result from adverse conditions identified in Question 4. In general, such events can result in consequences to workers. Question 5 also identifies events that have been analyzed for the material/packages, barriers, and adverse conditions identified in Questions 2, 3, and 4, which represent the most bounding condition for an analysis of public health and safety and/or environmental releases.

Several such events may be evaluated to identify vulnerabilities. For example, a facility storing a vessel of plutonium compound in liquid form that has not been maintained is subject to leakage from flanges or valve stem packing. Such spills and their cleanup could expose workers. A number of bounding accident analyses are usually performed in the Safety Analysis Report (SAR) for the facility. Reviewing these analyses for the material/packaging and barriers will assist the team in identifying possible vulnerabilities.

The purpose of Question 6 is to evaluate compensatory measures applied within the facility to prevent and/or mitigate events that could result in vulnerabilities. Generally, there are many preventive measures, usually administrative. All applicable items should be identified. Current and past deficiencies in administrative compensatory measures should be noted. Safety features designed to mitigate accidents should be noted and any deficiencies in these systems identified. If such systems are out of service on a frequent basis, this should also be noted.

Step 5. Results

The purpose of Question 7 is to identify the consequences of events described in Question 5 for which compensatory measures might be inadequate. If a consequence is identified, a vulnerability exists and a Vulnerability Assessment Form must be completed. Consequences with more than three independent events to occur can be considered to be highly unlikely. In these cases, a VAF need not be completed. However, common mode failures need to be recognized.

The purpose of Question 8 is to allow the Site Assessment Team the opportunity to summarize and prioritize the overall
vulnerabilities from plutonium holdings. This question also prompts the Site Assessment Team to identify potential corrective actions.

**Step 6. Site Assessment Team Report**

The Site Assessment Team writes the Site Assessment Team report and provides the draft version to the Working Group Assessment Team one week prior to its arrival. Attachment 3 provides an outline for the Site Assessment Team report. The DOE site management organization should approve the Site Assessment Team report. However, due to the time constraints placed on the project, site managers may wish to delegate this responsibility to the Site Assessment Team co-leaders.

**WORKING GROUP ASSESSMENT TEAM PROCESS**

**Site Visit Agenda**

Each Working Group Assessment Team should develop a site visit agenda specific to the needs of the site and the assessment team. A proposed agenda for the site visit (Attachment 4) is provided for guidance.

Sites with large holdings, such as Rocky Flats, Savannah River, Los Alamos, and Hanford, need larger Working Group Assessment Teams that can subdivide into smaller subteams and work in parallel, taking several days to accomplish all elements. Sites with small holdings may use small teams. Starting with the proposed agenda, each Team Leader will develop a site-specific agenda. This agenda should be developed as early as possible so that both the Site and the Working Group Assessment Teams are familiar with what is planned and expected. The agenda should be developed in coordination with site contacts.

**Protocol**

The Working Group Assessment Team review should include a complete and open exchange of information between the Site Assessment Team, the DOE operations office staff, and M&O contractor personnel. Key aspects of successful communication include those listed below.

- A preliminary Working Group meeting with representatives of the M&O contractor, operations office, and program office to review the scope, Project Plan, and Assessment Plan, and to provide assessment process training.

- Entrance discussions between the Working Group and Site Assessment Teams, the DOE operations office, and the M&O contractor regarding the objectives of the assessment and the DOE and M&O contractor perspectives on facility operations.

- Arrangement for facility discussions and facility walkdown.

- Identification of technical and administrative contacts (operations office and M&O contractor) for the Working Group Assessment Team.

- Candid verbal communication among all parties.

- Daily meetings (lasting approximately 1 hour) between the Working Group Assessment Team and site management (both operations office and M&O contractor). These meetings should result in the arrangement and scheduling of activities, such as interviews, walkdowns, and technical discussions. Published schedules should be used and activities should be planned to the maximum extent practical.

- Agreement at the end of the assessment among the M&O contractor, the DOE operations office, and the Working Group Assessment Team that the vulnerabilities identified are factual and reflect the best available knowledge. The Working Group Assessment Team
The report will not be finalized and issued until factual review by the Site Assessment Team is completed. Any delay will affect schedules. Therefore, schedules should be formalized to the extent possible.

- Recognition by all parties that the vulnerability assessment is an integral part of the Department's activities to ensure the safety of the workers, the public, and the environment, and that all personnel involved in the activity share that common goal.

This study represents a Department-wide ES&H vulnerability assessment. All Department elements should work together, recognizing that their specific roles and responsibilities are assigned solely to facilitate and manage the work. The Site Assessment Team is the primary source of vulnerability identification. The Working Group Assessment Team provides external verification and validation, identifies and characterizes additional vulnerabilities not recognized by the Site Assessment Team, and organizes the information. Technical assessments are conducted by all group members. All M&O managers, DOE operations office managers, and Cognizant Secretarial Officers (CSOs) are expected to interact effectively to produce a comprehensive report.

Procedure

The procedure to be used by each Working Group Assessment Team during its site visit is described here. The procedure covers the essential functions of the visit: review, evaluation, verification and validation of Site Assessment Team responses to the Question Set as well as the identification and compilation of consequences and vulnerabilities that result from plutonium storage/handling. These results will be recorded on Vulnerability Assessment Forms (VAFs), which provide for a formatted and consistent documentation tool to be used by each Assessment Team: Any member of the Working Group Assessment Team can initiate a VAF. The procedure begins with the first meeting between the Working Group Assessment Team and the Site Assessment Team (see proposed Agenda in Attachment 4).

Working Group Assessment Team membership will include experts in criticality safety, seismic analysis, health physics, waste management, maintenance and operations, safety analysis, security, and plutonium chemistry/processing, depending on the site/facility under consideration. Each Working Group Assessment Team will be led by a Federal employee. A deputy team leader and other team members generally will include Federal employees, M&O contractors, laboratory personnel, and independent consultants. Although each member will focus on and be an expert in his/her discipline, overlap, crosscutting, and synergism are expected to occur. Sites with major holdings of plutonium and those with multiple buildings containing plutonium will be visited by larger teams. Team size will vary from 6 to 15 members, depending on the challenge of the site.

All potential credible challenges to the environment and to the safety and health of workers and the public must be addressed. It is the responsibility of the designated Site Assessment and Working Group Assessment Teams to conduct a thorough review, identify vulnerabilities and, at the close of the review period, defend the vulnerabilities to the Working Group. The Working Group will review and approve the final vulnerability report.

Specific steps for the Working Group Assessment Team are outlined below. These will be discussed thoroughly during the team building and team training sessions prior to site visits.

Step 1. Preparation

Each Working Group Assessment Team member has received training on technical
aspects, methodology, and team building. After the Site Assessment Teams have been formed, the respective Working Group Assessment Team leaders will meet with them to review the scope and organization of the site assessment process.

Working Group Assessment Team members will review appropriate background information (e.g., Tomsk-II, chemical vulnerability assessment, Site Assessment Team draft report, SARS, occurrence reports, technical safety appraisals, and ES&H studies) as they relate to the Plutonium ES&H Vulnerability Assessment Project and assemble relevant documentation.

The Working Group Assessment Team leader (or deputy team leader) and Site Assessment Team co-leaders will coordinate site-specific training required for escorted access by Working Group Assessment Team members to areas necessary for the review.

The Site should designate the Site Assessment Team co-leaders as points of contact for the Working Group Assessment Team.

The Working Group Assessment Team leader (or deputy team leader) will ensure that team members obtain site-specific training, where applicable for large sites, prior to the site visit.

The Working Group Assessment Team Leader (or deputy team leader) will define the visit strategy, taking into consideration personnel expertise and the number of facilities to be visited.

The Working Group Assessment Team leader (or deputy team leader) will solicit input from Working Group Assessment Team members on their suggested assessment methods, contacts, and agenda; provide feedback; and coordinate with the Site Assessment Team.

The Working Group Assessment Team Leader (or deputy team leader) will verify necessary clearances (e.g., sigma levels) to gain access to facilities.

Step 2. In-briefing at Site by Working Group Assessment Team

The Working Group Assessment Team will brief site management on the scope and purpose of the visit.

The Working Group Assessment Team will be briefed on site plutonium activities and be provided with a general overview of facility responses to the Question Set.

Participation of local stakeholders in site entrance meetings will be coordinated by the Nuclear Materials Disposition Project.

The Working Group Assessment Team members will be trained and qualified on site procedures to enter facilities under knowledgeable escort if such training has not already been completed.

Step 3. Facility Review with the Site Assessment Team

The Site Assessment Team will present its report describing the site, operations and storage facilities, mission(s) of these facilities, and identified vulnerabilities. The Site Assessment Team will describe activities at plutonium storage and operations facilities to provide the Working Group Assessment Team with an understanding of the complexity, frequency, and volume of plutonium movements and other activities pertaining to plutonium handling and storage.

Validation and verification of packaging configuration and conditions should be conducted when appropriate. If the Working Group Assessment Team requires that packages be opened or reviews the data from past programs for the opening of packages, team members should review all packaging-related operations and procedures and analyze them for vulnerabilities. Since observations at one site may be applicable to packaging
configurations at other sites, a special effort should be made to document all important configurations and conditions observed during inspections of packaging.

In addition to physical inspections, methods that may be used to evaluate packages include the review of logs, videos, and photographs, and the use of nondestructive techniques. If packaging is found to be different than the records indicate, this difference should be noted.

Pertinent inspection and repackaging activities are currently being conducted at Los Alamos National Laboratory, Savannah River Site, and Rocky Flats Plant. An inventory reduction repackaging activity has been completed at Lawrence Livermore National Laboratory. Results of this work will be used as baseline data points for comparison with material and packaging conditions that may exist currently or in the future at other sites with similar material/packaging. A database of the material/packaging configurations and unpackaging observations will be made available for reference.

The Site Assessment Team will provide the results of all recent relevant reviews, assessments, and self-assessments. The Working Group Assessment Team may build upon these results if the facility's mission and current mode of operations remain within the context of those reviews.

Step 4. Review of Draft Responses to Question Set and Summary Checklists

The Working Group Assessment Team will review the Question Set responses and the summary checklists prepared by the Site Assessment Team. Working Group Assessment Team members should discuss each response to the Question Set in sufficient depth to gain a clear understanding of the condition of stored plutonium and storage facilities, facility operations, and institutional controls. Working Group Assessment Team members will pursue information to ensure that the Team has a thorough basis for its conclusions. However, Working Group Assessment Team members should remember that this study is not a fault finding, inspection or a compliance audit, and lines of inquiry should be oriented toward the objective of the assessment. Attachment 1 provides guidance for conducting the Question Set review and tabletop discussions.

Step 5. Facility Walkdowns

An initial facility walkdown will be conducted to familiarize Working Group Assessment Team members with the facility layout and features, the condition of the facility, and any plutonium materials contained therein. Facility walkdowns will always be accompanied by knowledgeable escorts to protect team members from ever changing facility conditions. The Working Group Assessment Team members may conduct additional walkdowns to identify and characterize vulnerabilities. Information gained during the review of the Site Assessment Team report should be used to augment the plan for the facility vulnerability review described in Step 6. Areas identified as potential vulnerabilities should be explored fully to document the causes of any adverse conditions. Attachment 1, Section IV, provides a set of candidate activities to be performed by the Working Group Assessment Team during the walkdown. These activities include interviews with cognizant plant personnel. In addition, current and past plant operations should be reviewed with potential ES&H vulnerabilities in mind. The Working Group Assessment Team should recognize that walkdowns may involve more than one visit to a particular facility.

A facility representative knowledgeable of facility conditions and operations should always be present during the walkdowns. Technicians and operators in the facility should be involved in the assessment at every opportunity to provide benefit of their specialized knowledge of plutonium storage
and handling operations. For instance, technicians may be asked to explain what they know about the stored materials, how plutonium operations are performed, and the hazards involved.

Each Working Group Assessment Team member should tailor walkthrough activities according to his/her individual expertise and the goal of obtaining all relevant information should a Vulnerability Assessment Form (VAF) be needed. As in previous cases, VAFs will be reviewed later by the Working Group Assessment Team for completeness, accuracy, and defensibility.

Step 6. Facility Review and Identification of Vulnerabilities

This activity, which is to be conducted by the Working Group Assessment Team, consists of evaluating and documenting the vulnerabilities identified in Step 5. In addition, vulnerabilities identified by the Working Group Assessment Team will be included to complete the site vulnerability profile. The methodology for this process is presented in Attachment 1. The Vulnerability Assessment Form (Attachment 2) will be used to document the results. The Site Assessment Team may be present during this activity but acts only as a source of information and clarification.

In this activity, the Working Group Assessment Team formally identifies the vulnerabilities associated with plutonium storage and operations using the VAFs, the Question Sets, and information gathered from the tabletop discussions and technical discussions. Each vulnerability initiated on one of these forms should have an acceptable technical basis. An initially identified vulnerability may be deleted only if full consensus is reached that it is not a vulnerability. In all other cases, the vulnerability is included in the Working Group Assessment Team report.

Once all vulnerabilities have been identified by this process, they will be reviewed with the Site Assessment Team for factual accuracy. Consensus is not required. The support of the cognizant subject matter expert on the Working Group Assessment Team and the team leader or deputy team leader will be sufficient to include a vulnerability in the final Working Group Assessment Team report.

NOTE: Any member of the Site Assessment Team or Working Group Assessment Team can initiate a VAF.

Step 7. Summary Meeting

The two teams will reconvene with the objectives of: (1) clearing all questions or unfinished business needed for the Site Assessment Team to finish its report; (2) reviewing and condensing vulnerabilities; (3) systematically addressing each vulnerability for substance and factual accuracy; and (4) completing data entry on each remaining VAF.

Step 8. Exit Briefing

The Working Group Assessment Team will brief site management (DOE operations office and M&O contractor) on the conclusions reached during its assessment.

Step 9. Working Group Assessment Team Report

The Working Group Assessment Team will reconvene (without the Site Assessment Team) to draft the Working Group Assessment Team report.

NOTE: Attachment 3 provides an outline and additional guidance for the Working Group Assessment Team report and an outline for the Site Assessment Team report.
Overview

The objective of this attachment is to provide more specific guidance to the Working Group Assessment Teams for conducting facility walkdown activities and tabletop discussions. The purpose of the facility walkdown activities and tabletop discussions is to assess and validate the Site Assessment Team responses to the Question Set by way of exploratory questioning, independent sampling, direct observations of facilities, and review of applicable programs.

Section I provides the overall methodology to be used in conducting the plutonium ES&H vulnerability assessment. It also includes the detailed Question Set to be filled out by the Site Assessment Teams.

Section II provides criteria for evaluating the responses to the Question Sets. If the Working Group Assessment Team finds that the Site Assessment Team responses to the Questions Set are incomplete or unclear, tabletop discussions should be held to obtain additional information or clarifying responses.

Section III provides a list of tabletop discussion topics designed to address consequences to workers, the public, and the environment resulting from the materials, barriers, adverse conditions and events, and compensatory measures identified by the Site Assessment Team in the Question Sets and summary checklists. The intent of the tabletop discussions is to examine and provoke thought on contributing factors and causal factors associated with identified consequences. The discussion topics were generated from a review of historical events and occurrences associated with plutonium storage and handling operations in the DOE complex.

Section IV provides guidance criteria for facility walkdown activities. At larger sites, the Working Group Assessment Teams should be divided into parallel groups (two to four persons) and walkdown activities should be performed in parallel at all selected facilities. The general criteria provided should be used to guide the walkdown activities since it is impractical for all Working Group Assessment Team subject matter experts to visit all facilities.

If a concern is identified within a facility and the subject matter expert is not on that particular tour, every effort should be made to discuss the concern with the expert. If necessary, the subject matter expert can perform a follow-up review of the concern/issue.

I. Vulnerability Assessment Methodology

The methodology (Figure A-1) examines materials at risk, the barriers used to protect the materials, adverse conditions/events that can lead to barrier failure, compensatory measures used to respond/react to the failures, and the impact or consequences on the environment, the worker, or the public. Figure A-2 illustrates more detailed examples of possible combination of materials, packaging, and physical barriers. Information will be gathered by several methods, including the following:

- Site response to a specific Question Set for each category of information (Question Set is attached);
- Tabletop discussions; and
- Facility walkdowns.

Inventory and material information consists of both inventory validations and a review of material characteristics associated with each chemical form of plutonium currently
processed or stored on site. Information for physical barriers will also be collected. Adverse conditions/events from internal as well as external events (natural and human-made) and compensatory actions and plans will be examined to determine the consequences on the environment, the worker, and the public. Information data elements for this methodology are included in Figure A-3, which is part of Questions 3, 4, and 5 of the Question Set.

The methodology is a qualitative approach that relies on the experience and expertise of the Site Assessment Teams in making determinations regarding the likelihood of barrier failures, relevant historical experience, and the frequency of adverse conditions/events. The implications or consequences of those events are then determined. The Question Set is geared toward collecting the necessary data on materials, barriers, and adverse conditions/events. The Site Assessment Teams are also asked to use the Question Set and checklist to identify consequences and vulnerabilities. The Working Group Assessment Teams will then use historical data, tabletop discussion topics, and the Question Set and checklist to review and develop a more comprehensive understanding of the consequences and potential vulnerabilities resulting from current plutonium storage and handling operations. Vulnerabilities identified as a result of this process will be documented on Vulnerability Assessment Forms (Attachment 3). The Site Assessment Teams will complete Vulnerability Assessment Forms (VAFs) as part of Question 7. The identification of a vulnerability on a VAF is not intended to replace occurrence reporting in accordance with DOE 5000.3B.
Figure A-1
ES&H VULNERABILITY ASSESSMENT APPROACH

- Glovebox (Barrier)
- Material
- Packaging (Barrier)
- Ventilation (Barrier)
- Facility Building (Barrier)

- Site Boundary (Distance Barrier)

Question 1: Facility
Question 2: Holdings and Packaging
Question 3: Physical Barriers
Question 4: Adverse Conditions
Question 5: Events

Question 6: Compensatory Measures
Preventive/Mitigative

Question 7: Consequences

Identification of ES&H Vulnerabilities
- Environment
- Worker
- Public
Figure A-2

1. Material, can, drum, pad, tent

2. Solution, pencil tanks, room

3. Material, inner can, slip-lid can

4. Material, glovebox, HVAC, room, building

5. Solution, Raschig rings, tank, room

6. Plugs, storage container, steel shell, dirt-covered magazine
## Figure A-3
### INFORMATION DATA ELEMENTS

### 1.0 MATERIAL INFORMATION

<table>
<thead>
<tr>
<th>NMMSS’ MATERIAL TYPE</th>
<th>Facilities</th>
<th>Information</th>
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<tbody>
<tr>
<td>Disassembled Weapons</td>
<td>Component</td>
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<td>Oxide</td>
<td>Scrap/Residues</td>
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<tr>
<td>Solutions</td>
<td>Sealed Sources</td>
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<tr>
<td>Other Forms</td>
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<td>Holdup</td>
<td>High Level Liquid Waste</td>
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<tr>
<td>TRU Waste</td>
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</table>

### 2.0 BARRIERS

#### 2.1 PHYSICAL

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<thead>
<tr>
<th>Worker Barrier Types</th>
<th>Public Environment/BARRIER</th>
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<tbody>
<tr>
<td>Duct</td>
<td>Facility Boundary</td>
</tr>
<tr>
<td>Vault</td>
<td>HVAC/Confinement</td>
</tr>
<tr>
<td>Room</td>
<td>Liquid/Containment</td>
</tr>
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<td>Cell</td>
<td>Site Boundary</td>
</tr>
<tr>
<td>Burial Ground</td>
<td>Bunkers</td>
</tr>
<tr>
<td>Tanks</td>
<td>Trenches</td>
</tr>
<tr>
<td>Piping</td>
<td>Storage Vault</td>
</tr>
<tr>
<td>Gloveboxes</td>
<td>Canyons</td>
</tr>
<tr>
<td>Canyon</td>
<td>Pad</td>
</tr>
<tr>
<td>Hot Cells</td>
<td>Caisson</td>
</tr>
<tr>
<td>Transfer System</td>
<td>Pond</td>
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#### 2.2 ADMINISTRATIVE CONTROLS

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<tr>
<th>Procedures</th>
<th>Training</th>
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<tr>
<td>ops., maint., surveil.</td>
<td>Organization</td>
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<tr>
<td>Material Limits</td>
<td>Lessons Learned</td>
</tr>
<tr>
<td>Regulatory Commission</td>
<td>Surveillance</td>
</tr>
<tr>
<td>Configuration Control</td>
<td>Resources</td>
</tr>
<tr>
<td>Quality Assurance</td>
<td>Personnel Reliability</td>
</tr>
<tr>
<td>Emergency Preparedness</td>
<td>Assurance Program</td>
</tr>
<tr>
<td>Conduct of Operations</td>
<td>Records</td>
</tr>
<tr>
<td>Authorization Basis (safety analysis)</td>
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### 3.0 ADVERSE CONDITIONS/EVENTS

#### 3.1 IN-FACILITY

<table>
<thead>
<tr>
<th>Adverse Condition/Event</th>
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<tbody>
<tr>
<td>Aging</td>
<td>Fire</td>
</tr>
<tr>
<td>Explosion</td>
<td>Contamination</td>
</tr>
<tr>
<td>Combustible Loading</td>
<td>Equipment Failure</td>
</tr>
<tr>
<td>Inadequacy of Design Basis</td>
<td>Design Deficiency</td>
</tr>
<tr>
<td>Organic/Nitrile Acid Reaction</td>
<td>Worker Exposure</td>
</tr>
<tr>
<td>Human Error</td>
<td>Flooding</td>
</tr>
<tr>
<td>Inadequate Drains</td>
<td>Inadvertent Transfers</td>
</tr>
<tr>
<td>Failure</td>
<td>Inadequate Configuration</td>
</tr>
<tr>
<td>Emergency Preparedness</td>
<td>Inadequate Seals</td>
</tr>
<tr>
<td>Conduct of Operations</td>
<td>Corrosion</td>
</tr>
<tr>
<td>Authorization Basis</td>
<td>Other Colocated Hazards</td>
</tr>
<tr>
<td>Other - Specify</td>
<td>Leakage and Spills</td>
</tr>
<tr>
<td>Potential Water Source</td>
<td>Inadequate Preventative Maintenance</td>
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<tr>
<td>Other - Specify</td>
<td>Inadequate Configuration</td>
</tr>
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<td>Inadequate Knowledge</td>
<td>Inadequate Preventative Maintenance</td>
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<td>Inadequate Seals</td>
<td>Other - Specify</td>
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<td>Corrosion</td>
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#### 3.2 EXTERNAL

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<tbody>
<tr>
<td>Aircraft Crash</td>
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<tr>
<td>Vehicle Accident</td>
<td>Worker, Public</td>
</tr>
<tr>
<td>Personnel Radiation Exposure</td>
<td>Worker Exposure</td>
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<td>Explosion</td>
<td>Adjacent Facility Accident</td>
</tr>
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<td>Power Failure</td>
<td>Ex-facility Fire</td>
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<tr>
<td>Erosion Damage</td>
<td>Institutional Regulatory Requirements</td>
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<td>Floods Damage</td>
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<td>Flooding</td>
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<td>Extreme Temperature</td>
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### 4.0 CONSEQUENCES

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#### 4.2 EXPOSURE

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### 4.3 ENVIRONMENTAL INSULT

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### 4.4 DIRECT INJURY

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### 4.5 TRENDS

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### 4.6 INCIDENTS/NEAR-MISSES

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### 5.0 COMPENSATORY MEASURES

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</tr>
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<td>Procedures</td>
<td>Safety Systems</td>
</tr>
<tr>
<td>Preventative Maintenance</td>
<td>Alarm Systems</td>
</tr>
<tr>
<td>Organization</td>
<td>Lessons Learned</td>
</tr>
<tr>
<td>Testing/Verification of Integrity</td>
<td>Monitoring</td>
</tr>
<tr>
<td>Trending</td>
<td>Training</td>
</tr>
</tbody>
</table>

*NMMSS Nuclear Materials Management & Safeguards System (Material in DOE Custody Managed by DP-27)*
QUESTION SET

The purpose of this Question Set is to provide a common approach for identifying ES&H vulnerabilities at the various DOE plutonium storage and handling facilities/sites. Site Assessment Teams will prepare responses to this Question Set and will identify and document vulnerabilities in their respective Site Assessment Team reports.

For each facility, the Question Set requires a summary description of the facility, the facility's plutonium holdings, how the holdings are packaged, and the physical barriers around the packages. The Site Assessment Team is asked to make an assessment of potential adverse conditions that are applicable to the material, packaging, barriers, and facilities. Once adverse conditions have been identified, the Site Assessment Team will identify potential events/concerns that may result from those adverse conditions and will describe compensatory measures (both preventive and mitigative) and potential consequences. While tables included in the Question Set have been designed for ease of preparation (checklists), the Site Assessment Team is encouraged to include adequate engineering judgment in its descriptive narrative, particularly identifying likely and realistic scenarios.

General guidance for the preparation of the Question Set is outlined here.

- Responses will be made on a WordPerfect 5.1 text file, using the supplied computer file template.
- Limit narrative to 1–2 pages per narrative question and include references.
- Do not be restricted by the size of the tables. They are expandable and allow for more than one line per item.
- Aggregate materials and facilities where appropriate.

Guidance on specific questions is provided below.

- For Q2, if packaging beyond what is visible is not known, state that fact.
- Q2A is provided for classified information. Such information will be made available to the Working Group Assessment Team in the proper secure setting and will remain at the site.
- Q1 through Q7 will be completed for each facility at the site. Facilities are defined as buildings or functional areas covered within a Safety Analysis Report (SAR). A Question Set should be completed for each function within a facility.
- Q8 will be completed by site management (operations office and M&O contractor).
<table>
<thead>
<tr>
<th>SITE:</th>
<th>FACILITY (Building or Location):</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOE HEADQUARTERS FACILITY LANDLORD</td>
<td></td>
</tr>
<tr>
<td>DOE HEADQUARTERS PROGRAM SPONSOR</td>
<td></td>
</tr>
<tr>
<td>FACILITY AGE</td>
<td>DESIGN LIFE</td>
</tr>
</tbody>
</table>

**Question 1: Facility**

Provide a summary description of the facility, including description of processes, simplified process/material flow diagrams, operations, and storage where applicable. Also address the following in the descriptions.

- Design mission, interim mission, current use.
- Include historical information on Unusual Occurrence Reports, Unreviewed Safety Questions, Occurrence Reports, Defense Nuclear Facility Safety Board concerns, and other regulatory concerns. Attach documentation on this historical information.
- List pertinent ES&H documentation, such as SAR, EA, EIS, and Basis for Interim Operations, and the date of publication for this facility.
- Identify important facility design features (i.e., seismic, fire protection, ventilation, atmosphere control, shielding, etc.).
- Identify uncertainties in the design basis and current configuration for facility features (e.g., seismic design basis, foreign material in ventilation systems or drains, safety systems whose operability has uncertainty).
- Describe the location of the facility on the site and the distance to the site boundary.
- Identify general aggregation areas of plutonium within the facility (e.g., glovebox, vault, cell, room, tank, pad, burial ground, and holdup locations) and include a simplified sketch of the containment barriers present.
Question 2: Holdings

Characterize facility plutonium\(^1\) holdings by completing the appropriate blocks in the table below. Use a separate line entry for each packaging type with a common grade of plutonium. Identify the range of age for each packaging type.

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Grade of Plutonium(^2)</th>
<th>Packaging Types(^3)</th>
<th>Range of Age (Yrs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disassembled Weapons Components (Pits)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxide</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scrap/Residues(^4)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solution(^4)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sealed Sources</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRU Waste(^4)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Holdup (in ducts, pipes, etc.(^5))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unirradiated Reactor Fuel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High-level Liquid Waste</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other (specify)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site</td>
<td>Facility (Building or Location):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------</td>
<td></td>
<td></td>
</tr>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Function:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

**Question 2 Continued:**

**Applicable References:**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. Include isotopes of transuranic elements that are co-mingled (i.e., intermixed or grown in) or co-located in the facility, such as Neptunium, Americium, Curium, Californium, or U-233 as a decay product.

2. Using the information on grades of plutonium in Table A1, enter the code letter in the block to identify the plutonium grade of each material type.

3. Using the list of packaging types in Table A2, enter the code number or numbers in the adjacent block that identify the packaging type(s) for each material type.

4. For Scrap/Residues, Solution, TRU Waste, and Holdup, add the code letters as defined in Table A3.

5. Holdup has no packaging. Identify location of holdup.
Characterize facility plutonium holdings by filling in the appropriate blocks in the table below. Use the same groupings as in Question 2.

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Grade of Plutonium</th>
<th>Total Mass Pu (kg)</th>
<th>Number of Packages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disassembled Weapons Components (Pits)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxide</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scrap/Residues</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sealed Sources</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRU Waste</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Holdup</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unirradiated Reactor Fuel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High-level Liquid Waste</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cumulative Inventory Difference</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Other (specify)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SITE:</td>
<td>FACILITY (Building or Location):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>---------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FUNCTION:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Question 2A Continued:**

**Applicable References:**

---

1 Identify probable location.
TABLE A1 – Grades of Plutonium
Typical Isotopic Composition, wt.%

<table>
<thead>
<tr>
<th>Grade</th>
<th>Code</th>
<th>$^{238}$Pu</th>
<th>$^{239}$Pu</th>
<th>$^{240}$Pu</th>
<th>$^{241}$Pu</th>
<th>$^{242}$Pu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Source</td>
<td>H</td>
<td>83.5</td>
<td>14</td>
<td>2.0</td>
<td>&lt;0.5</td>
<td>--</td>
</tr>
<tr>
<td>Weapons</td>
<td>W</td>
<td>--</td>
<td>93.6</td>
<td>6</td>
<td>&lt;0.4</td>
<td>--</td>
</tr>
<tr>
<td>Fuel</td>
<td>F</td>
<td>--</td>
<td>86</td>
<td>12</td>
<td>1.6</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Reactor</td>
<td>R</td>
<td>1.5</td>
<td>58</td>
<td>24</td>
<td>1.6</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Neptunium</td>
<td>Np</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Americium</td>
<td>Am</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curium</td>
<td>Cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Californium</td>
<td>Cf</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If significant amounts of transplutonium elements (TPE) are present with the plutonium, use codes for both plutonium and the TPE (e.g., RAm means Reactor Grade plutonium with significant amounts of americium). A dash (--) means the isotope may be present, but only in very small amounts.
<table>
<thead>
<tr>
<th>Example</th>
<th>Packaging</th>
<th>Material</th>
<th>Subcode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cans</td>
<td>C</td>
<td>0</td>
<td>unknown</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>food-pack/rim seal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>slip lid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>screw lid</td>
</tr>
<tr>
<td>Plastic bagging</td>
<td>B</td>
<td>0</td>
<td>unknown</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>polyethylene</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>PVC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>PVDC (saran wrap)</td>
</tr>
<tr>
<td>Metal foil</td>
<td>F</td>
<td>0</td>
<td>unknown</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>aluminum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>lead</td>
</tr>
<tr>
<td>Vessels</td>
<td>V</td>
<td>0</td>
<td>unknown</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>welded</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>knife-edge seal (i.e., conflat)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>elastomeric seal (o-ring)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>compression seal (swag/clock, etc.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>screw lid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>unspecified/sealed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>unspecified/unsealed</td>
</tr>
<tr>
<td>Glass</td>
<td>G</td>
<td>0</td>
<td>unknown</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>screw-lid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>sealed vials/capsules</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>glass-metal seal</td>
</tr>
<tr>
<td>Plastic containers</td>
<td>P (for bottle)</td>
<td>0</td>
<td>unknown</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>polyethylene-sealed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>polyethylene-unsealed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>polyethylene-unknown</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>other plastic – sealed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>other plastic – unsealed</td>
</tr>
<tr>
<td>Ceramic containers/misc.</td>
<td>R (for reactor</td>
<td>0</td>
<td>unknown</td>
</tr>
<tr>
<td>bottle material containers</td>
<td>materials)</td>
<td></td>
<td>graphite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>magnesium oxide</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>unknown crucible</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>reactor metal (Ta, W, V, etc.)</td>
</tr>
<tr>
<td>Unknown</td>
<td>U</td>
<td>0</td>
<td>unknown</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>suspected to be metal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>suspected to be plastic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>suspected to be ceramic</td>
</tr>
<tr>
<td>Drums</td>
<td>D</td>
<td>0</td>
<td>unknown</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>55–gallon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>30–gallon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>&lt; 30-gallon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>&lt; 5–gallon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>unspecified</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>add V if wanted</td>
</tr>
<tr>
<td>Tanks</td>
<td>T</td>
<td>0</td>
<td>unknown</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>Raschig ring filled</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>geometrically favorable</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>other</td>
</tr>
<tr>
<td>Wooden/crates/boxes</td>
<td>W</td>
<td>0</td>
<td>unknown</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>metal burial box</td>
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<tr>
<td></td>
<td></td>
<td>2</td>
<td>cardboard</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>wooden</td>
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<tr>
<td></td>
<td></td>
<td>4</td>
<td>fiberglass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>misc/unspecified</td>
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<td>unknown</td>
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<tr>
<td></td>
<td></td>
<td>1</td>
<td>standard</td>
</tr>
<tr>
<td>Material Type</td>
<td>Form</td>
<td>Code</td>
<td></td>
</tr>
<tr>
<td>--------------------</td>
<td>------------------------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>Scrap/Residue</td>
<td>Pyrochemical Salts</td>
<td>PS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Filters</td>
<td>F</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Combustibles</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Incinerator Ash</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduction Residues</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dissolver Heel</td>
<td>DH</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ceramics</td>
<td>CR</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Non-Pu Metal Scrap</td>
<td>MS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alloyed Pu Metal</td>
<td>AL</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sludge</td>
<td>SL</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Graphite</td>
<td>G</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>GL</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Impure Oxide</td>
<td>IO</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chlorides</td>
<td>Cl</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>OT</td>
<td></td>
</tr>
<tr>
<td>Solution</td>
<td>Nitric Acid</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydrochloric Acid</td>
<td>Cl</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mixed Nitric/Hydrochloric</td>
<td>MI</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Organic</td>
<td>OR</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>OT</td>
<td></td>
</tr>
<tr>
<td>TRU Waste</td>
<td>Same as Scrap/Residue or Unknown</td>
<td>U</td>
<td></td>
</tr>
<tr>
<td>Holdup</td>
<td>Same as Scrap/Residue or Unknown</td>
<td>U</td>
<td></td>
</tr>
</tbody>
</table>
Question 3: Physical Barriers

Characterize facility physical barriers by completing the appropriate blocks in the table below. Complete a separate table for each material aggregation.

Material Aggregation (list material types included from Question 2)

<table>
<thead>
<tr>
<th>Barrier #</th>
<th>Worker Protection</th>
<th>Environment and Public Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SITE:</td>
<td>FACILITY (Building or Location):</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FUNCTION:</td>
<td></td>
</tr>
</tbody>
</table>

**Question 3 Continued:**

**Applicable References:**
<table>
<thead>
<tr>
<th>Worker Barrier</th>
<th>Public/Environmental Barrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>WB-1 Glovebox</td>
<td>EB-1 Facility Boundary/Building</td>
</tr>
<tr>
<td>WB-2 Transfer System</td>
<td>EB-2 HVAC/Confinement</td>
</tr>
<tr>
<td>WB-3 Duct</td>
<td>EB-3 Liquid/Containment</td>
</tr>
<tr>
<td>WB-4 Filter</td>
<td>EB-4 Site Boundary</td>
</tr>
<tr>
<td>WB-5 Vault</td>
<td>EB-5 Bunkers</td>
</tr>
<tr>
<td>WB-6 Room</td>
<td>EB-6 Trench</td>
</tr>
<tr>
<td>WB-7 Canyon</td>
<td>EB-6.1 Backfilled</td>
</tr>
<tr>
<td>WB-8 Hot Cell</td>
<td>EB-6.2 Enclosed</td>
</tr>
<tr>
<td>WB-9 Cell</td>
<td>EB-6.3 Open</td>
</tr>
<tr>
<td>WB-10 Burial Ground</td>
<td>EB-6.4 Other – Specify</td>
</tr>
<tr>
<td>WB-11 Piping</td>
<td>EB-7 Storage Vault</td>
</tr>
<tr>
<td>WB-12 None</td>
<td>EB-8 Canyons</td>
</tr>
<tr>
<td>WB-13 Confinement</td>
<td>EB-9 Pad</td>
</tr>
<tr>
<td>WB-14 Shielding</td>
<td>EB-10 Caisson</td>
</tr>
<tr>
<td>WB-15 Distance</td>
<td>EB-11 Pond</td>
</tr>
<tr>
<td>WB-16 Respiratory Protection</td>
<td>EB-12 Other – Specify</td>
</tr>
<tr>
<td>WB-17 Remote Handling</td>
<td></td>
</tr>
<tr>
<td>WB-18 Other – Specify</td>
<td></td>
</tr>
</tbody>
</table>

1 Barrier between plutonium and worker.
2 Last barrier between plutonium and public and environment.
Question 4: Adverse Conditions

Indicate actual or potential adverse conditions that are applicable to those materials, packages and barrier aggregates developed in Questions 1, 2, and 3 by checking the appropriate items and describing below.

<table>
<thead>
<tr>
<th>Adverse Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>In-Facility</strong></td>
</tr>
<tr>
<td>□ Inadvertent Transfers</td>
</tr>
<tr>
<td>□ Aging</td>
</tr>
<tr>
<td>□ Organic Nitric Acid Reaction</td>
</tr>
<tr>
<td>□ Equipment Failure</td>
</tr>
<tr>
<td>□ Change in Mission</td>
</tr>
<tr>
<td>□ Other Co-Located Hazards</td>
</tr>
<tr>
<td>□ Corrosion</td>
</tr>
<tr>
<td>□ Inadequate Configuration Knowledge</td>
</tr>
<tr>
<td>□ Combustible Loading</td>
</tr>
<tr>
<td>□ Inadequate Seals</td>
</tr>
<tr>
<td>□ Potential Water Sources</td>
</tr>
<tr>
<td>□ Inadequate Drains</td>
</tr>
<tr>
<td>□ Inadequacy of Design Basis (e.g., seismic, fire, wind, etc.)</td>
</tr>
<tr>
<td>□ Inadequate Preventive Maintenance</td>
</tr>
<tr>
<td>□ Administrative Controls</td>
</tr>
<tr>
<td>□ Other – Specify</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Material</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>□ Pressurization</td>
</tr>
<tr>
<td>□ Pyrophoricity</td>
</tr>
<tr>
<td>□ Radioactivity</td>
</tr>
<tr>
<td>□ Chemical Reactivity</td>
</tr>
<tr>
<td>□ Am Buildup</td>
</tr>
<tr>
<td>□ Hydrogen Buildup</td>
</tr>
<tr>
<td>□ Radiolysis</td>
</tr>
<tr>
<td>□ Volumetric Expansion</td>
</tr>
<tr>
<td>□ Oxidation</td>
</tr>
<tr>
<td>□ Other – Specify</td>
</tr>
</tbody>
</table>
An existing situation that gives rise to a potential event or concern.

---

<table>
<thead>
<tr>
<th>SITE:</th>
<th>FACILITY (Building or Location):</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FUNCTION:</td>
</tr>
</tbody>
</table>

**Question 4 Continued:**

Describe Each Adverse Condition:

**Applicable References:**
Question 5: Events

Identify those historical, current, or potential events that have or may result from the adverse conditions identified in Question 4. Similar events for different material, package and barrier aggregates may be grouped together on a single form: Check the appropriate blocks and describe below.

POTENTIAL EVENTS

<table>
<thead>
<tr>
<th>In-Facility</th>
<th>External</th>
<th>Natural Phenomena</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ Fire</td>
<td>□ Aircraft Crash</td>
<td>□ Earthquake Damage</td>
</tr>
<tr>
<td>□ Explosion</td>
<td>□ Vehicle Accident</td>
<td>□ Wind Damage</td>
</tr>
<tr>
<td>□ Worker Exposure</td>
<td>□ Explosion</td>
<td>□ Flood Damage</td>
</tr>
<tr>
<td>□ External</td>
<td>□ Adjacent Facility Accident</td>
<td>□ Erosion Damage</td>
</tr>
<tr>
<td>□ Internal</td>
<td>□ Power Failure</td>
<td>□ Snow/Ash Loading Damage</td>
</tr>
<tr>
<td>□ Contamination</td>
<td>□ Institutional/Regulatory Requirements</td>
<td>□ Extreme Temperature Damage</td>
</tr>
<tr>
<td>□ Flooding</td>
<td>□ Personnel Radiation Exposure</td>
<td>□ Other – Specify</td>
</tr>
<tr>
<td>□ Leakage/Spills</td>
<td></td>
<td></td>
</tr>
<tr>
<td>□ Other Accidents – Specify</td>
<td></td>
<td></td>
</tr>
<tr>
<td>□ Human Error</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td></td>
<td></td>
</tr>
<tr>
<td>□ Criticality</td>
<td></td>
<td></td>
</tr>
<tr>
<td>□ Fissile Material Release</td>
<td></td>
<td></td>
</tr>
<tr>
<td>□ Breach of Container</td>
<td></td>
<td></td>
</tr>
<tr>
<td>□ Fire</td>
<td></td>
<td></td>
</tr>
<tr>
<td>□ Other – Specify</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Describe Each Event:
<table>
<thead>
<tr>
<th>Question 5 Continued:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Describe Each Event:</td>
</tr>
</tbody>
</table>

| Applicable References: |
Compensatory measures at the facility prevent and/or mitigate the adverse conditions and events identified in Questions 4 and 5. Check the applicable items in the table below and reference documents describing the compensatory measures. Identify any uncertainties or concerns in the checked compensatory measures.

<table>
<thead>
<tr>
<th>Compensatory Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Preventive</strong></td>
</tr>
<tr>
<td>□ Procedures: ops., maint., surveillance</td>
</tr>
<tr>
<td>□ Material Limits</td>
</tr>
<tr>
<td>□ Training</td>
</tr>
<tr>
<td>□ Quality Assurance</td>
</tr>
<tr>
<td>□ Conduct of Operations</td>
</tr>
<tr>
<td>□ Authorization Basis (safety analysis, BIOs)</td>
</tr>
<tr>
<td>□ Surveillance</td>
</tr>
<tr>
<td>□ Organization</td>
</tr>
<tr>
<td>□ Structure</td>
</tr>
<tr>
<td>□ Management Involvement</td>
</tr>
<tr>
<td>□ Staffing</td>
</tr>
<tr>
<td>□ Lessons Learned</td>
</tr>
<tr>
<td>□ Configuration Control of Design</td>
</tr>
<tr>
<td>□ Preventive Maintenance</td>
</tr>
<tr>
<td>□ Monitoring</td>
</tr>
<tr>
<td>□ Trending (Performance Indicator)</td>
</tr>
<tr>
<td>□ Testing/Verification of Integrity</td>
</tr>
<tr>
<td>□ Regulatory Requirements</td>
</tr>
<tr>
<td>□ Records</td>
</tr>
<tr>
<td>□ Personnel Exposure</td>
</tr>
<tr>
<td>□ Equipment</td>
</tr>
<tr>
<td>□ Waste Inventory</td>
</tr>
<tr>
<td>□ QA</td>
</tr>
<tr>
<td>□ Personnel Reliability Assurance Program</td>
</tr>
<tr>
<td>□ Other – Specify</td>
</tr>
<tr>
<td><strong>Mitigative</strong></td>
</tr>
<tr>
<td>□ Emergency Preparedness</td>
</tr>
<tr>
<td>□ Emergency Management</td>
</tr>
<tr>
<td>□ Emergency Planning</td>
</tr>
<tr>
<td>□ Emergency Procedures</td>
</tr>
<tr>
<td>□ Emergency Response</td>
</tr>
<tr>
<td>□ Safety Systems</td>
</tr>
<tr>
<td>□ Alarm Systems</td>
</tr>
<tr>
<td>□ Other – Specify</td>
</tr>
<tr>
<td>Compensatory Measure</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>Uncertainty or Concern</td>
</tr>
</tbody>
</table>
Question 7: Consequences

For each event identified in Question 5, and taking into account compensatory measures described in Question 6, identify potential consequences to the worker, environment, or public. If a vulnerability exists, record a Y and complete the VAF. If a vulnerability does not exist, record an N and explain below.

<table>
<thead>
<tr>
<th>EVENT</th>
<th>WORKER</th>
<th>ENVIRONMENT</th>
<th>PUBLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CONTAMINATION</td>
<td>EXPOSURE</td>
<td>INJURY</td>
</tr>
<tr>
<td></td>
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</tbody>
</table>

Explanation:
Question 8: Overall Site Summary

Based on the Site Assessment Team report, provide an overall assessment of the site ES&H vulnerabilities.

The response to this question should address each of the elements listed below, and should not exceed 2 pages in length.

- A description of the site's most important ES&H concerns related to plutonium storage, handling, processing, and/or shipping.
- A description of which plutonium activities pose the highest risk to the environment, worker, and public at your site.
- A discussion of current planned actions to minimize worker exposure, reduce environmental risks, and protect the public at and near your site.
- Provide any noteworthy programs or practices related to plutonium storage, handling, processes, and/or shipping.
Question 8 continued:
II. Question Set Review Items for Site and Working Group Assessment Teams

The criteria presented here can be used jointly by both the Site and Working Group Assessment Teams.

1. Are the responses to the Question Set complete? What information, if any, is still needed from the Site Assessment Team? Have all the elements identified in each question been considered/discussed? Have the holding quantities been clearly identified? Have known plutonium holdings in excess of the Nuclear Materials Management Safeguards System (NMMSS) inventory been quantified?

2. Are any of the responses unclear or confusing? What information, if any, is needed from the Site Assessment Team or facility personnel to clarify the responses?

3. Review the Site Assessment Team's ranking of adverse conditions/events or concerns provided in response to the Question Set. By way of discussion with the Site Assessment Team, determine the logic or method used as a basis for determining qualitative relative rankings. Is the logic or method consistent? For example, did the Site Assessment Team identify numerous recent handling accidents but rank handling events as having a low likelihood of occurrence?

4. Are there any other disparities within the Site Assessment Team's responses to the Question Set? What information is needed to resolve any disparity? Is the answer to each question supported by answers to other questions?

5. Are the responses to the Question Set supported by observations made by the Working Group Assessment Team during the facility walkdown? An example where this is not the case is as follows: Fire detection systems are identified as mitigating systems and the likelihood of large fires is ranked as low. However, during the facility tour, the Working Group Assessment Team learns that significant portions of the heat detection system have been out of service for the last several months due to equipment problems.

6. Are all of the other ES&H vulnerabilities identified by the Site Assessment Team clearly understood? Is it clear why the Site Assessment Team considers the vulnerabilities to be important?

7. Is there enough information provided for the identified ES&H vulnerabilities to assess their importance.

III. Tabletop Discussions

The following questions should be used by the Working Group Assessment Teams to help them characterize and gain a better understanding of potential ES&H vulnerabilities that may result from the conditions listed. These constitute just a sample of the questions that should be addressed during tabletop discussions between the Working Group Assessment Team, M&O facility manager, and operations managers. In many cases, cognizant personnel from the DOE operations office should also be present for discussions on global issues. The question numbers used here correspond to those used in Figure A-3 to assist the Working Group Assessment Teams in using the assessment logic established by the Working Group.
1.0 Uncertainties About Material That Could Result in Vulnerabilities

1.1 NMMSS Material
- Could unknowns about the quantity of material in residues or waste cause limits to be exceeded?
- What is the condition of materials in tanks in terms of homogeneity, concentration limits, etc.? What could cause changes that might result in vulnerabilities?
- Are there questions about material-related vulnerabilities, such as fires, explosions, etc., that might warrant urgent action or characterization?
- What is known about materials still in process, e.g., ion exchange columns, dissolvers, etc.?
- Is there a material inspection program and what has it shown?
- What measures have been taken to account for holdup?

2.0 Uncertainties About Barriers to Release

2.1 Physical Barriers
- What packaging materials are used, e.g., polyethylene, polyvinyl chloride, or other organic material?
- What are the conditions of packaging?
- What vulnerability could be associated with packaging and repackaging?
- Is plutonium in places where it may not belong and may not be accounted for and monitored, such as in ducts, pipes, or traps?

2.2 Administrative Barriers
- Could material in the facility exceed limits analyzed in the Safety Analysis Report (SAR)?
- What forms of plutonium were analyzed in the SAR and what is the impact on the source term?
- Are there clear lines of responsibility and authority in the organization?
- Are training programs effective in maintaining competency in ongoing and new missions?
- What are the attitudes toward operational limits, e.g., criticality limits, Operational Safety Requirements (OSRs), Limiting Conditions of Operation (LCOs), etc.?
- Have the number of Unusual Occurrence Reports (UORs) increased over the past 5 years? If so, why?
- What is the history of inadvertent and misrouted transfers?
- What are the trends in human errors?

3.0 Adverse Conditions and Events Leading to Vulnerabilities

3.1 In-facility
- Are there neutron absorbers (Raschig rings or dissolved chemicals) that might change configuration or concentration and result in vulnerabilities?
What co-located materials could increase vulnerabilities associated with plutonium?
Are there constraints that prevent the relocation of materials to areas with lower ES&H vulnerability?
Have mission changes resulted in ES&H vulnerabilities, or could they do so?
What is the status of the facility? Is it operating or shut down?
Is there a clear chain of responsibility for the stored material within DOE?
Are there requirements for the inspection of materials that result in ES&H vulnerabilities (e.g., unnecessary exposure)?
Are institutional safety margins so conservative that other important ES&H vulnerabilities are not addressed properly?
Are there requirements for "two-man rule" that result in greater exposure?
Are there uncertainties connected with mission changes that result in ES&H vulnerabilities?
What is the maintenance backlog on safety system equipment? Is it improving?
Do you have LCOs for equipment out for maintenance?
How often are you in LCO conditions?
How do you know that your operability tests are adequate?
Do the drawings reflect the true configuration of the facility and its systems?
Are the modifications included in drawings?

Have there been any equipment-related fires or explosions?

3.2 External
Are there regulatory issues about the classification of materials that increase ES&H vulnerabilities?
Are actions being taken to meet hazardous waste regulations that increase ES&H vulnerabilities?
Have actions been taken in response to oversight organization recommendations that have increased ES&H vulnerabilities?
Have any corrective actions been identified or taken as a result of additional assessments (e.g., Tomsk-II or chemical vulnerability assessment)? Are there any other recommended references?

3.3 Material
Are there possible contaminants in process materials that might affect spontaneous reactions (e.g., Ca, Mg)?

4.0 Existing Consequences and Trends

4.1 Contamination
Have you reduced the square footage of surface contaminated areas?
Are contaminated areas spreading?

4.2 Exposure
Have you increased/decreased the number of high-radiation areas?
• What is your reportable exposure and contamination history?
• What are the exposure trends?

4.3 Environmental Insult
• What environmental releases have been reported?

4.4 Direct Injury
• What is the history of work-related injuries?

4.5 Trends
• What are the trends for all of the above topics during the past 5 years?

4.6 Incidents/Near-Misses
• What is the incident and near-miss history.

5.0 Compensatory Measures Status
• Is there an emergency planning and response program? Is it exercised to ensure its effectiveness?
• Have you identified likely accidents that reflect the current status of the facility and developed recovery plans?
• Have you identified hazards to workers in light of new missions and facility status? Are workers trained to deal with possible off-normal conditions/incidents?
• Are there backups to essential safety systems? Is their function verified?
• Are operations/activities overly dependent on an individual’s personal knowledge (i.e., is there important information that is not documented)?
• Are numerous compensatory measures in place to adjust for failed or absent safety systems?
• How long will they be in place?

6.0 Vulnerabilities Due to Safeguards and Security
• Do lock-down procedures ever prevent access to resolve an adverse condition or prevent timely evacuation of a facility?
• What measures have been taken to minimize exposures during inspections, inventory, and material transfers?
• Are weapons allowed in areas with plutonium?
• What are the procedures for security response within an area?

IV. Walkdown
The Working Group Assessment Team will determine which of the site's facilities require a walkdown based on review of the vulnerabilities identified in the Site Assessment Team report. Further walkdown of additional facilities may occur based on information from the tabletop sessions and feedback from Working Group Assessment Teams at other sites.

The Working Group Assessment Teams should use the following topics as guidelines during their walkdown activities. The topics should be used as broad guidance, not as a checklist or data-gathering effort.

1.0 Material Information
• What types of materials are processed or stored in the facility?
• Can you show us some stored or in-process material?
• Are the materials compatible with the storage environment?
• Do you have any method or technology for nonintrusive examination of materials and
2.0 Barrier Information
(In reviewing the following items in each facility, look for degradation of equipment or inoperative equipment. Safety response under both normal and abnormal conditions and environments is important. Review surveillance documentation and logbooks.)

2.1 Physical Barriers
- Air Monitors (fixed head and portable)
  - What are the locations of the monitors?
  - What is the reliability of control room alarms?
  - Are processes monitored and controlled with instrumentation?
  - Are those instruments calibrated and tested?
  - What is the confidence level that instrumentation on inactive process systems is functional or will be functional when called on?
  - Is the operations response to upset conditions adequate?
- Criticality Alarms
  - Is the criticality alarm system tested according to requirements?
  - Is the system's sensitivity adequate?
  - Is the system audible throughout the facility?
  - Is there a supervisory alarm to detect criticality alarm failure?
- Radiation Sensors
  - Are area radiation sensors functional and tested?
  - Are survey instruments and air monitors functional, calibrated, and strategically placed?
  - Are the correct (radiation type) instruments available for the task or environment? Are they tested and calibrated adequately?
  - Is extremity and whole body dosimetry utilized appropriately for the task?
- Other Sensors
  - Are heat sensors and indicators available in high-heat zones?
  - Are oxygen sensors and indicators utilized in confined spaces?
  - Are humidity sensors and indicators utilized in high-humidity spaces?
  - What are the alarm frequencies?
- Drains
  - Have all potential leak paths to the environment been identified and mitigated?
  - Are criticality drains functional and configured to analysis specifications?
  - Does the ventilation system have draining capability?
- Material Holdup
  - Has material holdup in ducts, drains, and filters been identified, measured, and mitigated?
  - Is there a continuing inspection or measurement program for holdup?
  - Is there a criticality potential/concern relative to holdup?
- Do stagnant ventilation branches exist?

- Safety Systems (SS)
  - Are safety systems adequate to define the safety envelope?
  - Is there redundancy to safety system equipment?
  - What is the reliability of safety systems and their backups?
  - What is the maintenance backlog for safety systems? What is the downtime history?
  - Are the reliability goals for safety systems adequate for the current facility mission?

- HVAC Systems
  - Do surveillance records for pressure zones and differentials show that they are maintained to design specifications?
  - Are high-efficiency particulate air (HEPA) filters tested and replaced at the required frequency?
  - Does movement of Special Nuclear Material (SNM) cease during ventilation upset conditions?
  - How are the HVAC systems inspected? How often are they inspected?
  - Are there pathways from the HVAC systems to the environment?
  - Are there interlocks on the HVAC systems to maintain negative pressure?

- Confinement
  - Are gloveboxes, gloves, and seals adequately maintained and inspected as part of a surveillance program?

- Power
  - What is the reliability of the facility power source?
  - Is it backed up?
  - Is it tested and on what frequency?
  - If a battery uninterruptable power supply (UPS) is utilized, what is its design availability?

2.2 Administrative Barriers
- Procedures
  - What are the personnel protection features (clothing, etc.)?
  - Do personnel understand the importance of health protection?

- What is the maintenance backlog on control room equipment?
- Is lockout/tagout utilized appropriately and according to procedure?
- Criticality
  - Are criticality safety limits (CSLs) posted?
  - Are inventories within the CSLs? (Spot check)
gloveboxes containing plutonium.)
- Are waste storage areas covered by CSLs? If not, should they be?
- Personnel
  - Are there areas of restricted access? Why are they restricted? Are there provisions for emergency access?
  - Are personnel adequately trained for their assigned jobs?
- Configuration Control
  - Is there a configuration control program?
  - Are drawings current and available for the facility and its systems?

3.0 Adverse Conditions/Events
(Discussion in this area is aimed at determining the presence of ES&H vulnerabilities in plutonium process equipment, whether the equipment is in use or inactive. Also verify material and packaging information, especially for chemical forms of plutonium stored in plastic bags, cans, and drums.)

3.1 In-facility Adverse Conditions/Events
- Inside Gloveboxes
  - Are there excess combustibles?
  - Is there evidence of degradation of confinement barriers (e.g., corrosion)?
  - Are materials neatly arranged and well labeled?
- Process Area
  - Are safety equipment and systems blocked?
  - Are there areas of restricted access? Why are the areas restricted?
- Storage Area
  - Are the storage racks corroded?
  - Is the storage area clean and neat?
  - Can material be moved in or out with relative ease?
  - What are the requirements for personnel access?
  - Are there excess combustibles?
- Hallways
  - Are there areas of restricted access or egress? Why are the areas restricted?
  - Are safety equipment and systems blocked?
  - Are there engineered or surreptitious alarm cutouts or bypasses?
  - Are status boards functional, monitored, and responded to?
  - What is the frequency of alarm conditions? How long does the alarm last and what is the human response?
  - Are the control room layout and functionality adequate?
- Storage Rack Conditions
  - Are plutonium storage racks securely fabricated and mounted?
  - Is corrosion evident?
- O₂ Analyzers
  - Are readings consistent with LCOs?
  - Are the units operable?
  - Have there been recurring problems with the atmosphere?
- Gloveboxes
  - Are the gloveboxes serviceable?
- Have there been recurring leaks/releases to the room?
- What is the condition of the gloves? What are the frequency and basis of the change out?
- Is proper shielding being used?

- Ion Exchange Columns
  - What is the ion exchange resin chemical form (anion or cation, chloride or nitrate, organic or inorganic)?
  - Is it kept wet at all times?
  - Is it protected from strong oxidizing agents (e.g., concentration HNO₃ or dichromate)?
  - What is the plutonium holdup on the column?
  - Do columns have pressure relief valves?
  - Are the columns protected from elevated temperatures (>70°C)?

- Solvent Extraction Systems
  - Is process equipment that contains organic solvents protected from elevated temperatures?
  - How is criticality controlled?
  - Are combustible or toxic solvents used?
  - Are leaks and spills of concern?
  - Is the operating history good?

- Tanks
  - Is there any way to detect internal corrosion in tanks and pipes?
  - Is there a possibility for inadvertent addition of incompatible chemicals?
  - What is the primary criticality control method?

- What are the design life and age of the tank?
- If Raschig rings are used, what is their condition?
- Are sight glasses made of durable material?
- Are tanks subject to frequent leaks/spills?
- Are tank vents operational?
- Are stored plutonium solutions characterized?
- What is the planned response to leaks and spills?

- Transfer Systems
  - Are conveyor systems operable and in good shape?
  - Are there safety problems with transfer systems?
  - Are pipelines under configuration control?
  - Are pipelines subject to frequent leaks?
  - Is there plutonium holdup in pipelines?
  - Are vacuum or pressure systems working?

- Handling Equipment/Cranes
  - Are they in good condition and operable?
  - Are workers and material protected from accidents?

- Corrosion/Degradation
  - Is the process equipment free from obvious corrosion and degradation?

- Flanges (on piping)
  - Are flanges maintained/torqued regularly?
  - Are they subject to frequent leaks?
  - Are flanges shrink-wrapped to catch leaks?
- Material Holdup
  - How much fissile material is held up in process equipment?
  - What is the radiation field from the holdup?
  - Are there criticality safety considerations?
  - What is the chemical form of the holdup?
- Configuration Control
  - Are as-built drawings current for piping, process systems, equipment, and electrical systems?
- Co-located Hazards
  - Are materials stored or used in potentially severe environments?
  - Is there a history of upset/accident conditions with co-located hazards?
  - Are co-located hazards adequately isolated?
- External Equipment
  - Are there other energy sources that put the material in jeopardy?
  - Are there any potential interconnections between external equipment?
  - What is the maintenance backlog? How reliable is external equipment?
  - What potential hazards exist with external equipment?
  - What is the safety relationship between external equipment and the material at risk?

3.2 External Adverse Conditions/Events

- Other Seismic Systems
  - What is the consequence of a seismic event on water, steam, gases, vacuum, and compressed air systems?
  - Are these systems protected or their consequences mitigated?
  - What are the leak paths for contamination following a seismic event?
  - How is glovebox overpressurization avoided?
  - Are there chemical reactivity concerns following a seismic event?

3.3 Material-related Adverse Conditions/Events

- Radiation Levels
  - Are there area surveys showing neutron and gamma levels? If there are areas of high radiation, why?
  - Are there ducts showing high radiation levels? Do they affect operations?
  - What are the radiation levels in the walk-in storage vault?
  - What are the radiation levels in the process areas?
  - What are the primary sources of the radiation?
- Is shielding used for high-radiation sources?

- Contamination Levels
  - Are there areas showing removable alpha contamination? Should they be cleaned?
  - Are there areas showing direct (nonremovable) contamination? Should they be cleaned?
  - Is paint or tape used to mask contamination?

- Conditions
  - Are there contamination areas (on mask)?
  - Can operators perform functions safely?
  - Are there industrial safety concerns with operations and maintenance activities

- Material Transfers
  - Are there analyzed and specified limits on material transfers?
  - Are engineered barriers in place to prevent human error in material transfers?
  - What is the adequacy of the confinement/packaging for material transfers?
  - What is the assurance of source and destination for solution transfers?
  - Are there any issues with chemical compatibility?
  - What are the engineered and administrative barriers for criticality in liquid systems?

- Package Integrity
  - Is the package material doing its job?
  - Is frequent repackaging required?

- Degradation

- Is the material degrading/changing form?

- Are the packaging materials degrading?

- Is there an interaction between materials and packaging?

- Are there time limits for storage in plastic bags?

- Tape Seals
  - Are tape seals still in place?
  - Do they need frequent replacement?

- Drums
  - Are drum lid clamps in place?
  - Are drum vents needed?
  - Are drum vents corroded?
  - What are the drum radiation levels?

- Thermal Stabilization
  - Are materials analyzed before processing?
  - Are materials analyzed after processing?

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Page A1 – 38
| Block #1: Title of Vulnerability. (<20 words) |
| Block #2: Executive Summary. (<50 words) Concise description of the sequence of events leading to the vulnerability. |
| Block #3: Describe the material, packaging, barrier and facility combinations that contribute to the vulnerability. |
| Block #4: Describe adverse conditions, events, and related concerns that contribute to the vulnerability. |
| Block #5: Describe the compensatory measures that reduce the severity of the vulnerability. |
| Block #6: Describe the likelihood of the event which causes this vulnerability and consequences which could result. |
## Vulnerability #

**Block #7:** Describe the timing of corrective actions (if any). Use the terms immediate (imminent ES&H issue), near-term (ES&H issue that may become an imminent hazard with further degradation), or longer term (ES&H issues which are being mitigated by barriers/compensatory measures).

**Block #8:** Additional comments, views, or plans by the site operations office and M&O Contractor to mitigate or minimize any potential vulnerability.

**Block #9:** Database Criteria. (Use identifiers from question set tables.)

**List adverse conditions:**

- 
- 

**List potential events/concerns:**

- 
- 

**Potential Consequences.**

<table>
<thead>
<tr>
<th>Environment</th>
<th>Worker Safety and Health</th>
<th>Public Safety and Health</th>
</tr>
</thead>
<tbody>
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<td>Contamination</td>
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<tr>
<td>Water</td>
<td>Exposure</td>
<td>Exposure</td>
</tr>
<tr>
<td>Air</td>
<td>Physical Injury</td>
<td>Physical Injury</td>
</tr>
</tbody>
</table>

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Signature, Team Member  
Signature, Team Leader
ATTACHMENT 3: Working Group Assessment Team and Site Assessment Team Report Outlines

WORKING GROUP ASSESSMENT TEAM REPORT OUTLINE

- Executive Summary
- List of Facilities Included
- Evaluation of Site Team Report and Site Team Vulnerabilities
  - Facility A
  - Facility B
  - ....
- Summary of Additional Vulnerabilities Identified by Working Group Assessment Team
  - Facility A
  - Facility B
  - ....

APPENDICES

- Working Group Assessment Team Vulnerability Assessment Forms
- Site Assessment Team Report
- Working Group Assessment Team Members
- References

Guidance for Working Group Assessment Team Report:

- To the extent practical, all supporting material should be typed in Word Perfect 5.1. Handwritten information, such as relevant field notes from interviews or walkdowns, should be retained by the Working Group Assessment Team member and the Working Group Assessment Team leader. All material for the report, including appendices, should be typed.
- Facility and material descriptive information should be brief and concise, limited to the detail required to support assessment conclusions. References should be relied on for more detailed descriptions (e.g., either the Site Assessment Team report or facility documentation, such as SARs and system or component design descriptions).
- The report will provide clearly defined technical bases for conclusions and identified vulnerabilities.
- Materials prepared by the Working Group Assessment Team (i.e., reports, notes, working papers) must be reviewed by a site classifier before the Team materials leave the site.

SITE ASSESSMENT TEAM REPORT OUTLINE

- Executive Summary
  - Summary by Facility
  - Site-wide Conclusions
- Identification of Facility
  - Brief Description
  - Holdings
- Discussion by Facility
  - Summary of Response to Question Set
  - Identification of ES&H Vulnerabilities

APPENDICES

- Site Team Membership
- Responses to Question Set (each facility)
- Vulnerability Assessment Forms
- References
ATTACHMENT 4

Proposed Agenda for Working Group Assessment Teams

Before Day "0"
- Review ORPS report.
- Review prior assessments (including recent field office assessments).
- Review authorization basis documentation.
- Review environmental evaluations.
- Assign responsibilities and facility coverage to team members.
- Identify required security clearances.
- Conduct site-specific training as applicable for each site.
- Coordinate with Site Assessment Team.

Day "0" (Assembly on day prior to visit, usually Sunday afternoon or evening)
- Team arrives at designated hotel.
- Meeting in hotel. (Team Leader is responsible for time and place of meeting.)
  Purpose: to organize site visit and responsibilities.
  1- Leader (or deputy leader) makes introductions with background (if needed).
  2- Leader (or deputy leader) reviews activities of site visit, names, locations.
  3- Leader (or deputy leader) reviews agenda for first on-site day and schedule
     for entire visit.
  4- Leader (or deputy leader) reviews protocol, reviews Assessment Plan, and
     modifies responsibilities as necessary.
  5- Team completes the review of documentation if not available prior to Day 0.
  6- Discussion is held.

Day 1 (First on-site day)

In-briefing
- Team meets with the host and external stakeholders; host and team make brief
  introduction covering background, purpose, activities, and external stakeholders
  provide their comments.
- Team proceeds through access gates, takes required site-specific training if
  needed, goes to first meeting with the Site Assessment Team.
- Depending on size of site (number of plutonium facilities), host will provide
  overview briefing describing site, mission, history, locations of plutonium facilities,
  logistics (i.e., tours, meeting facilities, etc.), overview of facility Question Set
  responses, make-up of Site Assessment Teams, physical security requirements,
  and other information.
- At this point the Working Group Assessment Team may divide into smaller teams
  (i.e., subteams). Subsequent items below may therefore be done in parallel.

First Meeting(s) with Site Assessment Team

Begin procedure. The following items correspond approximately with the procedure.
- Site Assessment Team presents specific facility briefing.
- Site Assessment Team presents summary response to each question in Question
  Set.
- Working Group Assessment Team tours facilities and records additional
  information and potential vulnerabilities.
- Each subteam debriefs Working Group Assessment Team at the end of each day.
Day 2 and Subsequent Days

- Working Group Assessment Team completes facility tour (if not done on Day 1).
- Site Assessment Team presents ES&H concerns.
- Working Group Assessment Team evaluates concerns and records vulnerabilities using Vulnerability Assessment Forms (Attachment 3).
- Summary meeting of the two teams is held to review previous results (especially the vulnerabilities) for additional information and factual accuracy.
- Working Group Assessment Team meeting is held at end of day (attended by site coordinator).

Note: The above activities should result in concurrences and/or advisories to the Site Assessment Team so the Site Assessment Team report can be finalized.

- Working Group Assessment Team then concentrates on assessment of vulnerabilities using the methodology described in the procedure.
- Working Group Assessment Team organizes vulnerabilities and begins assembly of report.
- Working Group Assessment Team conducts factual accuracy review with Site Assessment Team as required.
- Working Group Assessment Team finishes draft of report (or section for that facility).

Note: The above process will be repeated as needed to complete reports for each facility and then to assemble the final Working Group Assessment Team report. At the end of each day's activities, the Working Group Assessment Team leader will assemble the Team for a status meeting to organize the next day's activities.

Final Day

- Working Group Assessment Team conducts final (i.e., exit) briefing with Site Assessment Team and site management, including review of draft Working Group Assessment Team report.
- Working Group Assessment Team departs.
A.3

MEMORANDUM FOR OPERATIONS OFFICE MANAGERS

FROM: SARBES ACHARYA, PROJECT LEADER
PLUTONIUM ES&H VULNERABILITY ASSESSMENT

SUBJECT: PLUTONIUM ES&H VULNERABILITY ASSESSMENT: GUIDANCE FOR EXTERNAL STAKEHOLDER INVOLVEMENT AND PHYSICAL INSPECTIONS OF PLUTONIUM MATERIALS IN STORAGE

This memorandum transmits the final versions of guidance for the Plutonium ES&H Vulnerability Assessment Project regarding 1) External Stakeholder Involvement, and 2) Physical Inspections of plutonium materials in storage. The draft versions of these guidances were transmitted to you on May 5, 1994 for your review and comment.

There were no comments received on the guidance for stakeholder involvement (Attachment 1). Therefore, the final version of this guidance is the same as before. This guidance states that the Operations Offices will coordinate all external stakeholder involvement and be responsible for notification, communications and logistical arrangements, and sets a minimum level of involvement. While each site already has policies and practices for local stakeholder involvement, implementation of the attached framework will provide consistency across sites for the minimum level of involvement of stakeholders, while allowing flexibility for additional involvement if desired.

The comments received on guidance for physical inspections (Attachment 2) were related to ES&H, safeguards and security, and material/container integrity considerations for conducting actual inspections. An informal comment correctly recognized that the inspection of materials in containers with impaired integrity may lead to container failure, resulting in release of plutonium and leading to facility and worker contamination. These comments have been incorporated in the revised text of Attachment 2.

Your site public affairs officer may contact me at (301) 428-9583 or Mary Freeman of DOE Public Affairs Office at (202) 586-6868 and Craig Lobdell of DOE Congressional, Intergovernmental and International Affairs Office at (202) 586-2779 if they need any further clarification.

Dr. Sarbes Acharya
c/o Scientech, Inc.
20030 Century Boulevard, Suite 210
Germantown, Maryland 20874
Telephone: (301) 428-9583
Fax: (301) 428-3104
cc: Area Office Managers
    Field Office Managers
    M&O Contractors
    Tara O'Toole, EH-1
    Charles Curtis, S-3
    WGAT Team Leaders
    SAT Team Leaders
    Mary Freeman, CA-1
    Craig Lobdell, CI-1
    Tom Rollow, EH-10
    Andy Marchese, EH-12
    Advisory Group Members
Attachment 1

PLUTONIUM VULNERABILITY ASSESSMENT PROJECT
GUIDANCE FOR EXTERNAL STAKEHOLDER INVOLVEMENT

The following points are offered to Operations Offices as guidance for the involvement of external stakeholders in the Plutonium Vulnerability Assessment Project. This guidance should represent a minimum level of the opportunity for external stakeholder involvement.

1. The Operations Offices will coordinate all external stakeholder involvement, and be responsible for notification, communications and logistical arrangements. All communications with stakeholders will be through a point of contact designated by the Operations Office to assure consistent and accurate information and to provide for classification review (if necessary). The Operations Office should also coordinate their efforts with the DOE Headquarters Offices of Public Affairs (contact: Mary Freeman at 202–586–6868) and Congressional, Intergovernmental and International Affairs (contact Craig Lobdell at 202–586–2779).

2. Stakeholders will be notified of and provided the opportunity to attend the formal and unclassified in-briefing and out-briefing meetings between Operations Office management, M&O site management, the Site Assessment Team and the Working Group Assessment Team. The agenda for each meeting will allocate time for stakeholder participation. The Operations Office may provide a facilitator for stakeholder participation in the meetings.

3. Depending on the site, there may be several levels of external stakeholder involvement. The following categories of stakeholders may wish to participate:

   (a) State or federal regulatory agencies.

   Some personnel may have a Q clearance, and the Operations Office may provide for additional site opportunities for these individuals.

   (b) Citizen or public interest organizations or groups, and interested individuals.

   (c) The press.

The Operations Office will be responsible for defining any further involvement or participation of citizen/public interest groups or the press beyond the formal in-briefing and out-briefing meetings.

4. To provide for clear communication and to prevent misunderstanding, it is requested that the stakeholder issues be characterized in writing at or after the entrance meeting for the Assessment Teams and site management. Efforts should be made to limit issues to the scope and process of the Plutonium ES&H Vulnerability Assessment Project as outlined in the Project and Assessment Plans.
5. The Site Assessment Team and the Working Group Assessment Team will consider stakeholder comments and concerns. It is not intended that separate responses will be prepared for stakeholder issues by the assessment teams, but this can be decided on a case by case basis, and site protocol should dictate the course of action.

6. Technical information about the Project needed for any communication with stakeholders should be provided by the designated site point of contact, working in coordination with the local public affairs staff.
Operations Office managers, the M&O contractor and the Site Assessment Team should consider the following additional guidelines in preparing their answers to the Question Set. The objective of this study is to perform a comprehensive assessment of the ES&H vulnerabilities. To ensure the credibility of the study, this assessment should rely, to the maximum extent practical, on physical inspection of the material in its existing packaging or containers (e.g., cans, bottles, tanks, etc.) combined with appropriate records and data to formulate sound conclusions. The assessment should consider a 5 to 10 year extension of current configurations, or make appropriate conservative assumptions about the minimum time that material will remain in its current configuration. Further:

1. Information about physical and chemical conditions of the materials and packaging should be current, preferably within the last year, since rapid degradation has been observed in some material packages.

2. The scope and rigor of MC&A inspections should be evaluated to determine if they can be relied upon to provide detection of degraded materials, containers or systems. It is not clear that such inspections currently provide adequate assurance of detection of ES&H vulnerabilities.

3. If inspections have not occurred, or are judged to be not reliable for the requisite information, sampling inspections of potentially vulnerable containers could be considered. If inspections are done prior to the Working Group Assessment Team visit, samples should be available for evaluation during the visit.

4. ES&H, safeguards and security, and material/container integrity considerations must prevail in considering whether to conduct physical inspections. If physical inspections are to be performed, all requirements must be followed, including establishment of appropriate safety envelopes, procedures, training, worker exposure limits (consistent with ALARA principles), and planning for emergency response.

5. The Site Assessment Team Report should document the basis for any results or conclusions about material and package conditions.

   If actual inspections can be performed, the results should be documented.

   If inspections cannot be performed, then a technical basis for continued storage under current conditions, and/or a conclusion that currently there are no actual or potential vulnerabilities, should be documented.

6. The assessment schedule should be a consideration in deciding whether to conduct physical inspections, or to describe uncertainties about material and container conditions as an ES&H vulnerability with appropriate conservative assumptions.
A.4

Guidance for Vulnerability Screening Criteria; Vulnerability Evaluation and Prioritization Process; and Vulnerability Quantification for Prioritization (Letter June 3, 1994)
June 3, 1994

MEMORANDUM FOR WORKING GROUP ASSESSMENT TEAM LEADERS AND SITE ASSESSMENT TEAM LEADERS

FROM: SARBES ACHARYA, PROJECT LEADER
PLUTONIUM ES&H VULNERABILITY ASSESSMENT

SUBJECT: PLUTONIUM ES&H VULNERABILITY ASSESSMENT: GUIDANCE FOR: VULNERABILITY SCREENING CRITERIA; VULNERABILITY EVALUATION AND PRIORITIZATION PROCESS; AND VULNERABILITY QUANTIFICATION FOR PRIORITIZATION

Please find enclosed the following documents for your use during Plutonium ES&H Vulnerability Assessment. These are:

1. Screening Criteria for Plutonium ES&H Vulnerability Assessment
2. Evaluation/Prioritization of ES&H Vulnerabilities
3. Guidelines for Estimating Radiological Dose and Environmental Contamination as Measures of Vulnerability Severity

Please note that Document 1 is identical to the one separately transmitted to you on May 18, 1994. It is enclosed here for consolidation only. Drafts of Documents 2 and 3 were transmitted to you and others on May 19, 1994 for comment. The Project Support Group reviewed all comments received and is preparing response to them for record. Comments which necessitated changes to the drafts have been incorporated in the enclosed final versions.

Document 3 is an analytical back-up for Document 2. It has been implemented as a computer software which is also enclosed for your use.

You may contact me at (301) 428-9583 or write to me at the following address if you have any questions.

Dr. Sarbes Acharya
c/o Scientech, Inc.
20030 Century Boulevard, Suite 210
Germantown, Maryland 20874
Telephone: (301) 428-9583
Fax: (301) 428-3104

Enclosures: Documents 1, 2, 3, and computer software on diskette as stated above

cc w/o diskette:
Advisory Group Members
Area Office Managers
Field Office Managers
M&O Contractors
T. O'Toole, EH-1
P. Brush, EH-2
T. Rollow, EH-10
A. Marchese, EH-12
J. Fitzgerald, EH-30
H. Pettengill, EH-40
Screening Criteria for Plutonium ES&H Vulnerability Assessment

Directions: Use the following Screening Criteria to identify adverse conditions which could result in potential vulnerabilities for plutonium storage or operations. Preserving plutonium material in its intended state and emplacement of various barriers to its release form a part of a "defense in depth" system for preventing and mitigating consequences to workers, the public, and the environment. Any defect in the material state or barriers should be considered to be a potential vulnerability and the remainder of the "system," the potential events and compensatory measures, should be conservatively evaluated to determine if a vulnerability exists.

Criteria are developed based on a zero defect or zero tolerance standard in order to rigorously evaluate the potential for vulnerability. If a criterion is not met, the assessment will conservatively evaluate the capability of redundant and multiple barriers to prevent or mitigate consequences. The severity of the vulnerability will depend on the inventory of the material at risk and the postulated scenario for the event which results in the vulnerability.

In all cases, a facility should apply its own criteria if there is a defensible technical basis for the criteria. This set of criteria should not be considered to be all-inclusive and the expert members of the assessment teams should review the list for applicability and completeness.

1.0 Materials - There must be no change, indication of an impending change or inference of a change from observations with similar materials (when direct observation of the assessed material may not be practical) in the chemical or physical form of the material.

Criticality safety must have been analyzed and allowance made for any possible changes in the physical or chemical form of the material or in the storage array.

Disassembled Weapons Components (Pits) - Unacceptable conditions include: failed tube seals, failed joints or welds, and unanalyzed alterations in storage arrays.

Plutonium Metal - Unacceptable conditions include: oxidation of metal as evidenced by the presence of removable quantities of plutonium oxide, presence of plastic or organics in the proximity of metal, water vapor or hydrogen in contact with the metal, and measurable weight gain (>0.5%) or volume change or increase in neutron generation rate.

Plutonium Oxide - Unacceptable conditions include: any presence of moisture or water in contact with the oxide, plastic or organics exposed to oxide powder, unstabilized oxide, and unknown condition/characterization of the oxide.

Scrap/Residues - Unacceptable conditions include: high radiation fields from Molten Salt Extraction salts, corrosive gas generation and high neutron radiation fields by plutonium fluorides and sand, slag and crucibles (including unreacted Ca metal and CaI), acid fumes and/or hydrogen generation in ion exchange resins and wet combustibles (particularly if gases can collect), high radiation fields from americium buildup in higher plutonium concentration residues, water absorption, hydrogen generation, and corrosion by pyrochemical salts, reactive metals or materials in pyrochemical salts, strong nitric acid in contact with leaded rubber gloves, potential for the presence of RCRA regulated material mixed with scrap/residues, exposure of ion exchange resins to heat (>70°C) or >9N nitric acid, drying out of ion exchange resins in columns (< half full of water or very dilute (~0.35N) nitric acid), plastic in contact with contaminated scrap/residues, combustibles with residual nitric acid present and presence of pyrophoric plutonium hydride.
Solutions - Unacceptable conditions include: leakage of liquids, corrosive gas release from acid solutions, corrosion and embrittlement of containers, hydrogen generation from radiolysis in unvented or uninerted containers, combinations of combustible organics and oxidizers which could be expected to explode and disperse radioactive materials, and potential for sludge formation in low acidity high plutonium concentration solutions because of radiolytic destruction of acid (e.g. ...ge in criticality margin).

Sealed Sources - Unacceptable conditions include: loss of integrity of the container, missing quality control documentation, and missing inventory.

Unirradiated Reactor Fuel - Unacceptable conditions include: breached cladding, cladding weakened by corrosion, and unanalyzed alterations in storage arrays.

Holdup - Unacceptable conditions include: unaddressed radiation fields or criticality safety concerns (uncharacterized material), blockage of ventilation or drainage paths, and radiolysis or corrosion of filters.

High Level Liquid Waste - Not in scope.

TRU Waste - Not in scope unless co-located, then similar to scrap/residues.

Other - Specify - Facilities which identify materials in this category should develop criteria for unacceptable conditions.

2.0 Barriers

Packaging Barriers - Unacceptable conditions include: evidence of deterioration or degradation as indicated by corrosion, discoloration caused by thermal or radiolytic attack, cracking or other phenomena; evidence that the physical integrity of the package is challenged by deformation due to pressurization (bulging, seam splitting, rupture); direct contact between the material and organic packaging for time in excess of one year (unless a longer time can be justified by specific packaging inspection data); innermost packaging is unknown, (unless justification of acceptability documented, i.e., frequent surveillance); barriers intended for temporary storage which have exceeded design life; atmosphere not controlled within the package (including packages without verifiable sealing); and atmosphere outside the container different than that required within the container.

Barriers for Worker Protection - Unacceptable conditions include: a workplace where respiratory protection is routinely required for worker activities, areas or rooms which are contaminated and entry is either not allowed or severely restricted (i.e., entries have routinely required respiratory protection); a confinement system (e.g., glovebox and ventilation system) exhibiting failures as evidenced by documented contamination incidents; seals which leak contaminated material or allow contaminants into controlled atmosphere storage areas; equipment (i.e., seals, gloves, valves, fire suppression system) which is a barrier to release not maintained; vital monitoring system (heat detection, criticality monitoring, continuous air monitors) which is not properly maintained give false alarms; rotation of personnel to meet radiation exposure limits: areas of high radiation (e.g. Am-241) or neutron level increase due to oxidation to levels above a shielding design basis; transfer or remote handling systems which require significant exposure to maintain; gloveboxes, ducts, or other equipment with significant plutonium buildup (>400 grams).
Barriers for Public and Environmental Protection - Unacceptable conditions include: actual or postulated (under acceptable analytical methods) releases to the environment; exposure to the public under design basis accident conditions; unverified design or construction to satisfy seismic criteria; inoperable or untested fire detection/suppression systems; liquid containment or HVAC confinement systems which are not maintained functional or verified for operability.

Administrative Controls - Many administrative controls serve as "barriers" rather than as compensatory measures. The following administrative controls should be considered in the assessment, in so far as they impact the ES&H vulnerabilities.

1. Configuration control program which provides certified documentation and controls the operability status of all safety systems.

2. An emergency preparedness program for the facility.

3. A training program which provides training and qualification on facility hazards, safety equipment and alarm response procedures.

4. A conduct of operations program which assures controlled operations.

5. The facility will have an authorization basis developed from a Design Basis Accident Analysis. This authorization should establish operational and safety requirements and limits.

6. A quality assurance program should be in place to assure operations are conducted to specifications.

7. A preventative maintenance program to assure operability of systems.

8. A staffing policy to ensure organization staffing, resources, and communications to deal with process hazards and mitigation of staff turnover.

9. A facility hazards analyses which provides established safety and procedural requirements for worker, public, and environmental protection.

10. A Material Control and Accountability and Security program to assure that material remains in its intended location.

During the training program, presentation information was provided for evaluating most of the important administrative controls which constitute a majority of the Compensatory Measures (Question 6). Also during the training program, additional information was handed out on examples of preventive administrative controls.
Evaluation/Prioritization of ES&H Vulnerabilities

**Background:** Screening Criteria are used to identify adverse conditions resulting in potential vulnerabilities for plutonium storage or operations. Screening criteria are based on a zero defect or zero tolerance standard in order to evaluate the maximum potential for vulnerability.

Preserving plutonium material in its intended state and emplacement of various barriers to its release form a part of a "defense in depth" system for preventing and mitigating consequences to workers, the public, and the environment. Any defect in the material state or barriers should be considered to be a potential vulnerability, and the remainder of the "system," the potential events and compensatory measures, should be conservatively evaluated to determine if a vulnerability exists. The severity of the vulnerability will depend on the inventory of the material at risk and the postulated scenario for the event.

Quantitative estimates will generally have large uncertainties for radiological dose or environmental contamination from radioactive material release that may be associated with an identified vulnerability. Time constraints on this project do not allow performing quantitative estimates of these uncertainties. Therefore, a simplified, consistent and conservative method to allow evaluation/prioritization of vulnerabilities is required.

**Directions:** Since this vulnerability assessment is intended to be used only for baseline information for developing options for safe management of the plutonium holdings, scoping estimates of dose and environmental contamination using conservative assumptions and bounding experimental data will be appropriate. These estimates will also require site-specific data to be obtained by the Working Group Assessment Teams. The required site-specific data are identified in Attachment A. The WGATs will record the data in a specific database format associated with the Vulnerability Assessment Form (VAF). The WGATs will also perform the analysis as a part of the verification/validation effort using the guidance provided in Attachment A. This will be done following review of the response to VAF questions. WGAT's may request assistance of the Support Group in performing the analysis if there is uncertainty about the assumptions.

It should be recognized that this effort will likely result in estimates from the upper end of the uncertainty range. With this perspective, input values from Safety Analysis Reports (SARs) for various parameters in the dose or environmental contamination calculation chain will be checked to assure that consistency is assured in the way the values are obtained for this assessment process. If any non-conservative values are identified, they will be adjusted by more uniform conservative values for this analysis, the reasons documented, and added to the database. The resulting "adjusted" release, dose, or exposure will be used as a **comparative measure** of "severity" of the vulnerability. See the Attachment A guidelines for estimating radiological dose and environmental contamination for this vulnerability comparison. Following the conservative quantitative evaluation, the measure of severity will be compared to the reference levels stated below to group the vulnerabilities into high, medium, and low categories.

The categories are defined as follows:

- **Worker Safety and Health** (including co-located worker)
  - **High** - Death, disability, exposure, or contamination leading to potential short-term radiological health effects; dose greater than 50 rem CEDE.

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-Medium- Lost-time injury, exposure above highest annual regulatory limits for routine operations; dose greater than 5 rem CEDE.

-Low- Reportable injury, bodily contamination, or exposure above expected annual value for routine operations.

- Public Safety and Health
  -High- Exposure above offsite emergency response levels; dose greater than 1 rem CEDE.
  -Medium- Exposure above highest annual regulatory limits for routine operations; dose greater than 100 mrem CEDE.
  -Low- Exposure does not exceed limits but may require notification of public.

- Environmental Damage
  -High- Event results in offsite measurable contamination above background.
  -Medium- Event results in only onsite measurable contamination outside of Radiological Control Area.
  -Low- Event results in onsite measurable contamination which may not require cleanup.

The likelihood will be determined based upon the following criteria:

-High- Condition currently exists or event is likely to occur within two years.

-Medium- Event is not likely to occur immediately but is likely to occur within a two- to five-year time frame.

-Low- Event is not likely to occur within the next five years but is likely to occur within the expected life of the facility.

Those vulnerabilities that fall within the HH, HM, MH, MM, HL, and LH combinations of severity and likelihood will be subject to further simple verification. Other combinations (LL, LM, and ML), representing lower hazard and lower likelihood, will be identified for completeness. The vulnerabilities can be logically grouped by type of vulnerability as well as categorized for corrective action. Examples of such groupings are:

- Material which is degrading due to package degradation and requires expedited management action, such as temporary repackaging, in less than a year.

- Packages which are suspected to be degrading due to design life considerations which require repackaging within five years.
- Barriers which are ineffective for protecting the environment and should be modified within five years.

A DOE sitewide matrix will be prepared for the Working Group by the support group. This matrix will be subject of discussion and verification in the second Working Group meeting. The Working Group will approve the final evaluation/prioritization and categorizations for summary report preparation.
Guidelines for Estimating Radiological Dose and Environmental Contamination as Measures of Vulnerability Severity

Quantitative estimates of radiological dose and environmental contamination that may be associated with an identified vulnerability generally will have large uncertainties. Time constraints on this project do not allow us to perform quantitative estimates of the central values of dose and environmental contamination or address uncertainties in their estimates. However, since this vulnerability assessment is intended to provide baseline information for developing options for safe management of the Department's plutonium inventory, scoping estimates of dose and environmental contamination using conservative assumptions and bounding experimental data in the calculation chain will be appropriate. This would likely capture the contribution from the upper end of the uncertainty range. With this perspective, the following steps should be used to estimate the scoping values of the dose and environmental contamination for a given vulnerability.

The Working Group Assessment Teams (WGAT) will be responsible for analysis, comparing to the severity categories, and prioritizing the vulnerabilities. This analysis will be coordinated with the Site Assessment Team (SAT) Leaders and appropriate personnel to review and concur with the analysis.

**Standard Methods for Estimating Dose and Environmental Contamination**

The following sections describe simple, standard methods for estimating dose to an individual and environmental contamination from a release of radioactive material from a facility.

**A. Material released to the outside of the facility**

1. Dose from inhalation of radioactive material by an individual outside the facility (co-located worker or public) is calculated as follows:

\[
\text{Dose} = \sum_i \text{MAR}_i \cdot f_i \cdot \text{SA}_i \cdot \chi/Q \cdot BR \cdot CEDE_i
\]

(1)

In the above:

- \(\text{MAR}_i\) is the isotopic material (of kind \(i\)) at risk associated with the vulnerability under evaluation (g).

- \(f_i\) is the conservatively assumed respirable fraction of material at risk released to outside of the facility due to adverse conditions (zero tolerance) at hazard critical control points (see note at the end). This may range from a fraction of a percent to a few percent based on scenarios.

The factor, \(f_i\), is the product of the damage ratio (\(DR_i\)) (i.e., fraction of \(\text{MAR}_i\) damaged from the event), airborne release fraction (\(ARF_i\)), respirable fraction (\(RF_i\)) and leak path fraction (\(LPF_i\)) appropriate for the location of the event (See Tables 1 and 2).

- \(\text{SA}_i\) is the specific activity of the radioisotope \(i\)(ci/g).
\( \chi/Q \) is the conservatively assumed value of atmospheric dilution factor at the location of target individual (i.e., co-located worker or public) (s/m³). Use values from US NRC Regulatory Guide 1.3 plot (attached) for atmospheric stability class F, wind speed 1 m/s for short term (0-8 hr) and ground level release.

- BR is the breathing rate of an active individual \((3.5 \times 10^{-4} \text{ m}^3/\text{s})\)

- CEDE\(_i\) is the committed effective dose equivalent due to inhalation of unit quantity of radioisotope \(i\) (rem(ci inhaled) based on values from DOE/EH-0071, Internal Dose Conversion Factors for Calculation of Dose to the Public (See Table 3)

- Summation is over all types of radioisotopes, \(i\), present in the release.

2. Gamma shine dose to an individual from immersion in a radioactive cloud outside the facility (co-located worker or public) is calculated as follows:

\[
\text{Dose} = \sum_i \text{MAR}_i \cdot f_i \cdot \text{SA}_i (\text{ci/g}) \cdot \chi/Q \cdot \text{EED}_i \text{ (rem/sec per ci/m}^3\text{)}
\]

In the above:

- \(\text{MAR}_i\), \(\text{SA}_i\), and \(\chi/Q\) have the same meanings as before.

- \(f_i\) is the conservatively assumed fraction (respirable plus non-respirable fractions) of material at risk released to outside.

The factor, \(f_i\), is the product of the damage ratio (DR\(_i\)), airborne release fraction (ARF\(_i\)) and leak path fraction (LPF\(_i\)) appropriate for the location of the event.

- EED\(_i\) is the external effective dose rate for radioisotope \(i\), due to immersion in contaminated air (rem/sec per ci/m\(^3\)) based on values from DOE/EH-0070, External Dose Rate Conversion Factors for Calculation of Dose to the Public (See Table 3).

B. Material released to the interior of the facility

1. Dose from inhalation of radioactive material by an individual worker inside the facility is calculated as follows:

\[
\text{Dose} = \sum_i \text{MAR}_i (\text{g}) \cdot F_i \cdot \text{SA}_i (\text{ci/g}) \cdot \text{BR} (\text{m}^3/\text{sec}) \cdot \Delta T (\text{sec}) \cdot \text{CEDE}_i (\text{rem}/\text{ci})/\text{V(m}^3\text{)}
\]

In the above:

- \(\text{MAR}_i\) and \(\text{SA}_i\) have the same meanings as before.

- \(F_i\) is the conservatively assumed respirable fraction of material at risk released to the atmosphere inside the facility surrounding the worker due to adverse conditions (zero tolerance) at hazard critical control
points (see note at the end). This may range from fraction of a percent to tens of percents based on scenarios.

The factor, $F_i$, is the product of the damage ratio ($DR_i$), airborne release fraction ($ARF_i$), respirable fraction ($RF_i$).

- $V$ is the volume of air surrounding the worker (such as $3\text{m} \times 3\text{m} \times 3\text{m}$) in which the release material would be airborne immediately following the release ($\text{m}^3$)

- $BR$ is the worker's breathing rate ($3.5 \times 10^{-4}\text{m}^3/\text{s}$)

- $\Delta T$ is the time during which the worker breathes the contaminated air without respiratory protection and before being evacuated (s). A reasonable minimum value should be assumed.

- $CEDE_i$ (rem/ci inhaled) is as discussed before

No credit will be given for exposure interdictions such as diethylene triamine penta-acetic acid (DTPA) administration, lung lavage, nasal irrigation, etc.

2. Dose to an in-facility worker from gamma shine or neutrons due to release of material inside the facility is not simple to calculates. Attempts should be made for inferring such dose from measurement and professional judgment.

C. Criticality Events

All criticality events that are likely to occur within the life of the facility are "high" vulnerabilities for interior of facility. A bounding release of $10^{19}$ fissions should be assumed for fission product released to the outside of facility.

D. Environmental Contamination

The following equation should be used to calculate the environmental contamination. Specific Activity values for different isotopes and the bounding values for $ARF$ and $RF$ for this calculation.

$$\text{Contamination (dps/m}^2) = \sum \text{MAR}_i (g) \cdot f_i \cdot \text{SA}_i (\text{ci/g}) \cdot \chi/Q (\text{s/m}^3) \cdot V_d (\text{m/s}) \cdot (3.7 \times 10^{10 \text{dps/Ci}})$$

In the above:

- $\text{MAR}_i, f_i, \text{SA}_i$, and $\chi/Q$ have the same meaning as in equate (2) above.

- $V_d$ is the ground deposition velocity. The value of 0.01 m/s should be used. (Reference provided on 8/19/94: USRNC's WASH-1400 and NUREG-1150)

Information that are required for performing the above calculations will be from three sources:

1) existing Safety Analysis Reports and studies,
For each vulnerability identified, the first step is to ascertain the Material at Risk (MAR), the Damage Ratio, and building Leak Path Fraction. For worker exposure in each event, the duration of time, $\Delta t$, that worker breathes the contaminated air, the volume of air surrounding the worker at the location of the event will be required.

The values for Airborne Release Fraction, and Respirable Fraction, were in the presentation package prepared by Jofu Mishima. These values have been published in chapter 4 of the "U.S. DOE Safety Survey Report, Nov. 1993", and incorporated in the U.S. DOE "Recommended Values and Technical Bases for Airborne Release Fractions (ARFs), Airborne Release Rates (ARRs), and Respirable Fractions (RFs) at DOE Non-Reactor Nuclear Facilities (draft), DOE-HDBK-0013-93." Bounding data from Mishima's presentation on ARF and RF applicable to plutonium are shown in Table 1.

Leak path fractions to be used in these scoping calculations are shown in Table 2.

The Specific Activities, Committed Effective Dose Equivalent, and External Effective Dose Rates came from the following references:

DOE/EH-70, "External Dose Rate Conversion Factors for Calculation of Dose to the Public"
DOE/EH-71, "Internal Dose Conversion Factors for Calculation of Dose to the Public"

The values required for selected radionuclides are contained in the materials provided during the Plutonium ES&H Vulnerability Assessment team training in Colorado Springs. These values are included in Table 3.

**NOTE:** In the context of the Plutonium ES&H Vulnerability Assessment, the term "hazard critical control points" means the following:

1) **Hazard Control at Source:** Maintaining the plutonium material at risk in its intended condition (i.e., metal remains as metal, oxide remains in a stable form, etc.) is the first hazard critical control point.

2) **Hazard Control by Packaging Material:** Maintaining the packaging and containers in their intended condition (i.e., metal containers remain sealed; intact plastic bags retain contamination; plastic bottles do not leak; solution tanks and pipes do not leak; drums maintain their integrity; etc.) is the second hazard critical control point.

3) **Hazard Control by Barriers:** Maintaining the barriers in their intended condition (i.e., gloveboxes and their associated seals continue to contain or confine contamination and provide adequate radiation shielding; Raschig Rings and other neutron poisons retain their functions; concentration control is not compromised; HEPA filters perform their filtering function; ventilation system maintains sufficient airflow; low oxygen atmospheres stay below intended $O_2$ concentration limits; vaults provide shielding and protection against seismic events; building walls are sufficient to withstand seismic, wind and impact events; sites are far enough from public access, etc.) is the third hazard critical control point.

4) **Hazard Control by Compensatory Measures:** Implementing and maintaining compensatory measures (i.e., maintaining a high quality safety culture and safety basis for facility operations; providing and ensuring use of appropriate procedures for configuration control,
operations and activities; proper training of personnel on procedures and required job knowledge; analyzing for and using criticality safety limits; ensuring comprehensive understanding of plutonium-associated operations and activities; adhering to Conduct of Operations principles; exercising emergency management plans and procedures; monitoring radiation fields and personnel exposures, etc.) form the fourth and last hazard critical control point.
Table 1

Bounding Vaules for Airborne Release Fraction (ARF) and Respirable Fraction (RF)

<table>
<thead>
<tr>
<th>Conditions for Airborne Release</th>
<th>ARF</th>
<th>RF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plutonium Metal - Solid</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Airborne release from free-fall of solid metal pieces and chips</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Burning Pu metal</td>
<td>5x10^-4</td>
<td>0.5</td>
</tr>
<tr>
<td>Falling molten drops/ disturbed surface</td>
<td>10^-2</td>
<td>1</td>
</tr>
<tr>
<td><strong>Plutonium Oxides - Powder</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Free fall and debris impact on Pu and Pu oxide powders - as a</td>
<td>10^-2</td>
<td>0.3</td>
</tr>
<tr>
<td>result of seismic activity.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Release of Pu oxide powder from a can after can integrity is</td>
<td>10^-3</td>
<td>0.1</td>
</tr>
<tr>
<td>breached by impact</td>
<td>(a)</td>
<td>(c)</td>
</tr>
<tr>
<td>Free fall spill of Pu oxide powder from</td>
<td>3x10^-3</td>
<td>0.6</td>
</tr>
<tr>
<td>&lt; 3 meters height (10 ft.)</td>
<td>(b)</td>
<td>(d)</td>
</tr>
<tr>
<td>Mechanical shock-vibration of clump Pu oxide powder</td>
<td>10^-3</td>
<td>0.1</td>
</tr>
<tr>
<td>Explosive release of Pu oxide blast effect, accelerated air flow,</td>
<td>10^-1</td>
<td>0.7</td>
</tr>
<tr>
<td>parallel to surface, &lt; 0.14 MPa (20 psi)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Explosive release of Pu oxide powder, blast effect</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0.14&gt;E&gt; 0.34 MPa (20 psi-50 psi)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Venting Pressurized Powders, &lt; 3.4 MPa(500 psi)</td>
<td>10^-1</td>
<td>0.5</td>
</tr>
<tr>
<td>Others</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural convection of non-reactive Pu compounds, heating to &lt;</td>
<td>6x10^-3</td>
<td>0.01</td>
</tr>
<tr>
<td>1000 C°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural convection of reactive Pu compounds (except PuF4),</td>
<td>1x10^-2</td>
<td>0.001</td>
</tr>
<tr>
<td>heating to &lt; 1000 C°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural convection of PuF4, heating to &lt; 1000 C°</td>
<td>10^-3</td>
<td>10^-3</td>
</tr>
<tr>
<td>Free fall of aqueous solutions</td>
<td>2x10^-4</td>
<td>0.7</td>
</tr>
<tr>
<td>Free fall of Pu oxide in slurry form</td>
<td>5x10^-5</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Note: The above table is adapted from the ARF and RF table published by Jofu Mishima in Chapter 4 of "U.S.DOE Safety Survey Report, Nov. 1993", and also incorporated in U.S. DOE "Recommended Values and Technical Bases for Airborne Release Fractions (ARFs), Airborne Release Rates (ARRs), and Respirable Fractions (RFs) at DOE Non-Reactor Nuclear Facilities" (draft), DOE-HDBK-0013-93. For a more complete list of release conditions, the original table should be used.

(a) changed to 5x10^-3; (b) changed to 2x10^-3; (c) changed to 0.4; (d) changed to 0.3; (e) changed to 0.7; and (f) changed to 0.5

Above changes were recommended by Dr. Jofu Mishima.

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Table 2

Recommended Values for Leak Path Fraction (LPF)

<table>
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<th>CONDITION</th>
<th>LPF</th>
</tr>
</thead>
<tbody>
<tr>
<td>No HEPA filter, exhaust blower operating</td>
<td>0.5</td>
</tr>
<tr>
<td>No HEPA filter, exhaust blower not operating</td>
<td>0.1</td>
</tr>
<tr>
<td>HEPA filter single stage</td>
<td>0.01 (filter bypass fraction) + 0.99x10^-3 (through filter) =0.011*</td>
</tr>
<tr>
<td>HEPA filter multiple stages</td>
<td>No filter bypass 10^-3 through the entire train of filters **</td>
</tr>
</tbody>
</table>

*LPF changed to 10^-3
**LPF changed to 10^-6

Both these changes resulted from discussion in the team leaders meeting, August 8-12, 1994.
Table 3

Inhalation Dose Factors and Air Immersion Dose Rate Factors for Plutonium and Other Isotopes

<table>
<thead>
<tr>
<th>Radio-Nuclide</th>
<th>Half Life (day)</th>
<th>Specific Activity (Ci/g)</th>
<th>CEDE (rem/ci inhaled)</th>
<th>CEDE (rem/g inhaled)</th>
<th>EED (rem/sec per ci/m3)</th>
<th>EED (rem/sec per g/m3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-233</td>
<td>5.81E+07</td>
<td>9.64E-03</td>
<td>1.30E+08</td>
<td>1.25E+06</td>
<td>3.80E-05</td>
<td>3.67E-07</td>
</tr>
<tr>
<td>Np-237</td>
<td>7.82E+08</td>
<td>7.04E-04</td>
<td>4.90E+08</td>
<td>3.45E+05</td>
<td>3.65E-03</td>
<td>2.57E-06</td>
</tr>
<tr>
<td>Pu-236</td>
<td>1.04E+03</td>
<td>5.32E+02</td>
<td>1.60E+08</td>
<td>8.51E+10</td>
<td>1.89E-05</td>
<td>1.00E-02</td>
</tr>
<tr>
<td>Pu-237</td>
<td>4.53E+01</td>
<td>1.22E+04</td>
<td>1.60E+03</td>
<td>1.94E+07</td>
<td>7.64E-03</td>
<td>9.29E+01</td>
</tr>
<tr>
<td>Pu-238</td>
<td>3.20E+04</td>
<td>1.71E+01</td>
<td>4.60E+08</td>
<td>7.88E+09</td>
<td>1.40E-05</td>
<td>2.40E-04</td>
</tr>
<tr>
<td>Pu-239</td>
<td>8.81E+06</td>
<td>6.20E-02</td>
<td>5.10E+08</td>
<td>3.16E+07</td>
<td>1.30E-05</td>
<td>8.07E-07</td>
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<tr>
<td>Pu-240</td>
<td>2.39E+06</td>
<td>2.28E-01</td>
<td>5.10E+08</td>
<td>1.16E+08</td>
<td>1.37E-05</td>
<td>3.12E-06</td>
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<tr>
<td>Pu-241</td>
<td>5.26E+03</td>
<td>1.03E+02</td>
<td>1.00E+07</td>
<td>1.03E+09</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
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<tr>
<td>Pu-242</td>
<td>1.37E+08</td>
<td>3.94E-03</td>
<td>4.80E+08</td>
<td>1.89E+06</td>
<td>1.16E-05</td>
<td>4.58E-08</td>
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<tr>
<td>Am-241</td>
<td>1.58E+08</td>
<td>3.43E+00</td>
<td>5.20E+08</td>
<td>1.78E+09</td>
<td>3.02E-03</td>
<td>1.03E-02</td>
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<tr>
<td>Am-242m</td>
<td>5.55E+04</td>
<td>9.72E+00</td>
<td>5.10E+08</td>
<td>4.96E+09</td>
<td>7.54E-05</td>
<td>7.33E-04</td>
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<tr>
<td>Cm-242</td>
<td>1.63E+02</td>
<td>3.31E+03</td>
<td>1.70E+07</td>
<td>5.62E+10</td>
<td>1.55E-05</td>
<td>5.14E-02</td>
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<tr>
<td>Cm-243</td>
<td>1.04E+04</td>
<td>5.16E+01</td>
<td>3.50E+08</td>
<td>1.81E+10</td>
<td>2.02E-02</td>
<td>1.04E+00</td>
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<tr>
<td>Cm-244</td>
<td>6.61E+03</td>
<td>8.09E+01</td>
<td>2.70E+08</td>
<td>2.18E+10</td>
<td>1.33E-05</td>
<td>1.07E-03</td>
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<tr>
<td>Cm-245</td>
<td>3.10E+06</td>
<td>1.72E-01</td>
<td>5.40E+08</td>
<td>9.28E+07</td>
<td>1.13E-02</td>
<td>1.94E-03</td>
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<tr>
<td>Cm-246</td>
<td>1.73E+06</td>
<td>3.07E-01</td>
<td>5.40E+08</td>
<td>1.66E+08</td>
<td>1.11E-05</td>
<td>3.41E-06</td>
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<tr>
<td>Cm-247</td>
<td>5.70E+09</td>
<td>9.27E-05</td>
<td>4.90E+08</td>
<td>4.54E+04</td>
<td>5.01E-02</td>
<td>4.64E-06</td>
</tr>
<tr>
<td>Cm-248</td>
<td>1.24E+08</td>
<td>4.24E-03</td>
<td>1.90E+09</td>
<td>8.06E+06</td>
<td>9.76E-06</td>
<td>4.14E-08</td>
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<tr>
<td>Cf-248</td>
<td>3.33E+02</td>
<td>1.58E+03</td>
<td>4.30E+07</td>
<td>6.79E+10</td>
<td>1.07E-05</td>
<td>1.68E-02</td>
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<tr>
<td>Cf-249</td>
<td>1.28E+05</td>
<td>4.09E+00</td>
<td>5.50E+08</td>
<td>2.25E+09</td>
<td>5.20E-02</td>
<td>2.13E-01</td>
</tr>
<tr>
<td>Cf-250</td>
<td>4.78E+03</td>
<td>1.09E+02</td>
<td>2.20E+08</td>
<td>2.40E+10</td>
<td>1.36E-05</td>
<td>1.49E-03</td>
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<tr>
<td>Cf-251</td>
<td>3.29E+05</td>
<td>1.58E+00</td>
<td>5.60E+08</td>
<td>8.85E+08</td>
<td>1.87E-02</td>
<td>2.95E-02</td>
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<td>Cf-252</td>
<td>9.64E+02</td>
<td>5.37E+02</td>
<td>1.30E+08</td>
<td>6.98E+10</td>
<td>1.19E-05</td>
<td>6.39E-03</td>
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<td>Cf-253</td>
<td>1.78E+01</td>
<td>2.90E+04</td>
<td>3.00E+06</td>
<td>8.69E+10</td>
<td>1.80E-07</td>
<td>5.22E-03</td>
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<tr>
<td>Cf-254</td>
<td>6.05E+01</td>
<td>8.49E+03</td>
<td>2.80E+08</td>
<td>2.38E+12</td>
<td>2.05E-09</td>
<td>1.74E-05</td>
</tr>
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</table>

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06/03/94
GROUND LEVEL RELEASE
ATMOSPHERIC DIFFUSION FACTORS FOR VARIOUS TIMES FOLLOWING ACCIDENT

Distance from Structure (meters)

Diffusion Factor X/Q (sec/m³)

0–8 hours

1–4 days

4–30 days
A.5

Plutonium ES&H Vulnerability Assessment
Team Training Manual

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U.S. DEPARTMENT OF ENERGY

PLUTONIUM ES&H VULNERABILITY ASSESSMENT

TEAM TRAINING

APRIL 19-21, 1994
COLORADO SPRINGS, CO
A.5.1

Attendees List

Plutonium Vulnerability Assessment Team Training
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<th>NAME</th>
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| Acharya, Sarbes             | White               | US Department of Energy
  Headquarters, EH-12
  19001 Germantown Rd
  Germantown, MD 20874 | 301 428-9583 | 301 428-3104 F |
| Alley, Clyde                | Orange              | Mason & Hanger
  1st National Bank
  Suite 420
  Amarillo, TX 79101 | 806 378-1543 | 806 378-1529 F |
| Amacker, Obie               | Red                 | PNL                                                                                       | 509 372-4133 | 509 372-4431 F |
| Amos, Wayne                 | Green               | Idaho National Engineering Laboratory
  US DOE
  785 DOE Place
  Idaho Falls, ID | 208 526-0583 | 208 526-6249 F |
| Baldwin, Eula               | White               | EG&G Idaho, Inc.
  P.O. Box 1625, MS 3878
  Idaho Falls, ID 83415 | 208 526-0692 | 208 526-9650 F |
| Bastin, Clinton             | Lt. Blue            | US Department of Energy
  Headquarters, | 301 903-5259 | 301 903-3419 F |
| Bell, Charles               | Black               | Los Alamos National Laboratory
  PO Box 1663
  Los Alamos, NM 87545 | 505 667-9402 | 505 665-4322 F |
| Bennett, David              | Lt. Green           | Sandia National Laboratory
  Dept. 6411, MS 0405
  Albuquerque, NM 87185 | 505 844-3119 |       |
| Berglund, Patricia          | Gray                | US Department of Energy
  Los Alamos Area Office
  528 35th Street
  Los Alamos, NM 87544 | 505 665-5049 | 505 665-4504 F |
| Berman, Herb               | Lt. Green           | SCIENTECH, Inc.
  1746 Cole Blvd, Suite 225
  Golden, CO 80401 | 303 278-4338 | 303 278-0092 F |
| Boccio, John L.             | Staff               | Brookhaven National Laboratory
  Upton, NY 11973 | 516 282-7690 | 516 282-5730 F |
| Borisch, Ron                | Blue                | Westinghouse Hanford Co.
  P.O. Box 1970, R-356
  Richland, WA 99352 | 509 372-3382 | 509 372-3402 F |
| Brewer, R                   | Black               | Los Alamos National Laboratory
  PO Box 1663
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Held at the Radisson, Colorado Springs
A.5.2

Introduction

by

Mark Williams
INTRODUCTION

Mark Williams
PLUTONIUM EVENTS

- Rocky Flats
  - Deferred inspections (April 1993)
  - Oxidized metal (January 1994)
  - Leaks (1990 – Present)

- Los Alamos
  - Failed can (December 1992)
  - Contamination (November 1993)

- Savannah River
  - FB Line bulged cans (December 1993)
  - Oxidized metal (February 1994)

- Consequences
  - Impacts on operations
  - Affects safety envelope
HOW WE GOT HERE

- **Recognition**
  - DOE-wide plutonium storage uncertainties
  - Stored, entrained in process, solution, metal, oxide w/moisture

- **Nuclear Materials Disposition Project Initiated**
  - Started 1/94
  - Long-term disposition

- **Decision making**
  - Need for baseline ES&H assessment
DOE TODAY

- Large quantity of plutonium
  - 43 Sites
  - Very large number of containers

- Many Uncertainties
  - Material form and packaging (oxidation, deterioration of package)
  - Vessel/container integrity (leaks, breached cans, pressurized cans)
  - Recent DP plutonium storage assessment

- Operations are in transition
  - Short term storage – longer term
DOE SITES INITIALLY SELECTED FOR VISIT

- Argonne National Laboratory – East
- Argonne National Laboratory – West
- Hanford
- Idaho National Engineering Laboratory
- Lawrence Berkeley Laboratory
- Lawrence Livermore Laboratory – West
- Los Alamos National Laboratory
- Mound
- New Brunswick
- Oak Ridge
- Pantex
- Rocky Flats Plant
- Sandia National Laboratories
- Savannah River Site
WHERE ARE WE GOING

- Safe interim storage
  - Under Secretary's Materials Disposition Project

- Start with ES&H view today
  - All DOE plutonium
ASSESSMENT TEAM OBJECTIVES

- Characterize ES&H vulnerabilities across DOE
  - Approach

- Identify and prioritize issues
  - Vulnerability prioritization

- Report to DOE management
  - Team reports
  - Final report (9/94)
  - Present results
SITES SELECTED FOR TEAM VISITS

- Pantex
- Rocky Flats
- Los Alamos
- Savannah River
- Hanford
- INEL/ANL-W/SNL
- ANL-E/New Brunswick Lab
- LLNL/LBL
- Mound/ORNL

- May visit other sites after review of their self-assessment report
ASSESSMENT TEAM PROFILE

- Team Leader (DOE)
- Deputy Team Leader
- Plutonium process safety
- Criticality safety
- Structural and seismic safety
- Operations and maintenance
- Health physics
- Safety analysis
- Safeguards and security
- Waste management
- Administrative support
ASSESSMENT TEAM TRAINING

- Team building
- Project/assessment plans
- Plutonium specific training
TRAINING PARTICIPANTS

- Six teams having 11 members
- Three teams having 10 members
- Two Site Assessment Co–Team Leaders per site
- Participants
  - DOE personnel
  - M&O contractors
  - Laboratories
  - Consultants
- Team make–up
  - Color coded badges for identification
SUMMARY

- Secretarial Directives
  - Full participation by DOE complex
  - Involve external stakeholders
  - Funding

- Scope
  - All isotopes and forms of plutonium
    Under DOE custody or control
    Except plutonium in intact nuclear weapons

- Nature of study
  - Factual, not fault-finding, not compliance or oversight audit
  - Accent on material/facility conditions & inspections
  - Objectivity
  - Communication
  - Openness
A.5.3

Team Training Objective and Agenda

by

Sarbes Acharya
DEPARTMENT OF ENERGY
PLUTONIUM ES&H VULNERABILITY ASSESSMENT

ASSESSMENT TEAM TRAINING

April 19–21, 1994
Colorado Springs, Colorado

TEAM TRAINING OBJECTIVE AND AGENDA

Sarbes Acharya
ASSESSMENT TEAM TRAINING OBJECTIVE

- Team members will be able to work as teams to conduct facility assessments in an effective manner

- They will have a clear understanding of
  - the purpose of the study
  - the methodology and evaluation guidelines
  - their roles and responsibilities

- They will have the necessary technical knowledge

- Assessment teams will be capable of identifying plutonium ES&H vulnerabilities
QUALITY

- Quality in the vulnerability assessment is essential
- Results will cause program offices and sites to undertake action:
  - Could cost hundreds of millions
  - Could divert resources from other ES&H problems
- Team must be sure:
  - Facts are irrefutable
  - There is consensus on guidelines
  - Then conclusions will be self-evident
PLUTONIUM VULNERABILITY ASSESSMENT
AGENDA FOR TEAM BUILDING/TEAM TRAINING
RADISSON HOTEL, COLORADO SPRINGS, COLORADO

MONDAY, APRIL 18
7:00PM-9:00PM
REGISTRATION IN THE FIRESIDE AREA OF LOBBY

TUESDAY, APRIL 19
7:00-8:00 REGISTRATION
LOCATED OUTSIDE THE ACADEMY ROOM

8:00-8:30 INTRODUCTION
M. WILLIAMS
ACADEMY ROOM

8:30-9:00 AGENDA
S. ACHARYA
ACADEMY ROOM

9:00-10:45 WG PROCESS/PROJECT PLAN
P. WARD
ACADEMY ROOM

10:00-12:00 TEAM BREAKOUTS
STAFF
BREAKOUT RMS

12:00-1:00 LUNCH

1:00-3:00 TEAM BREAKOUTS
STAFF
BREAKOUT RMS

3:00-5:00 ASSESSMENT METHODOLOGY
A. MUSCATELLO
ACADEMY ROOM

WEDNESDAY, APRIL 20

8:00-9:00 HISTORY-1 (ALL)
T. MCLAUGHLIN
ACADEMY ROOM

9:00-12:00 TEAM BREAKOUTS
STAFF
BREAKOUT RMS

12:00-1:00 LUNCH

1:00-4:00 TEAM BREAKOUTS
STAFF
BREAKOUT RMS

4:00-5:00 PACKAGING CASE STUDIES
J. MARTZ
ACADEMY ROOM

5:00-5:30 RADIOLOGICAL HAZARDS
M. GOLDMAN
ACADEMY ROOM

THURSDAY, APRIL 21

8:00-9:00 SAFEGUARDS AND SECURITY
B. SMITH
ACADEMY ROOM

9:00-12:00 TEAM BREAKOUTS
STAFF
BREAKOUT RMS

12:00-1:00 LUNCH

1:00-5:00 TEAM BREAKOUTS
STAFF
BREAKOUT RMS

5:00-5:30 CLOSEOUT
WILLIAMS/ACHARYA
ACADEMY ROOM
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<td>Working Group Process and Project Plan - P. Ward</td>
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TS-1 Team Skills - Team Dynamics  
TS-2 Team Skills - Interviewing  
TS-3 Team Skills - Conflict Resolution  
HIST-1 Criticality Safety  
HIST-2 Fires and Major Events  
HIST-3 Ion Exchange Resins and Minor Events  
SA Plutonium Standards and Safety Analysis  
DA Database  
PU-1 Plutonium Properties  
PU-2 Plutonium Barriers  
PU-3 Plutonium Hazards/Consequences  
PU-4 Plutonium Storage  
PU-5 Airborne Release Fractions  
PU-6 Radiological Hazards  
S&S Safeguards and Security  
METH Assessment Methodology, Question Set and Guidelines
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*Academy* | HIST-3 Ion Exch Resins/Minor Events - A. Muscatello  
*Tower III* | TS-1 Team Dynamics - B. Parker  
*Academy* | | |
| 8:30 - 9:00 | | | | | |
| 9:00 - 9:30 | HIST-2 Fires and Major Events - Felt/Jackson  
*Tower II* | | | | |
| 9:30 - 10:00 | PU-1 Plutonium Properties - A. Muscatello  
*Tower III* | PU-2 Plutonium Barriers - Felt/Jackson  
*Tower II* | | | |
| 10:00 - 10:30 | | | | | |
| 10:30 - 11:00 | | | | | |
| 11:00 - 11:30 | PU-2 Plutonium Barriers - A. Muscatello  
*Tower II* | PU-1 Plutonium Properties - A. Muscatello  
*Tower III* | | | |
| 11:30 - 12:00 | | | | | |
| 12:00 - 12:30 | Lunch | | | | |
| 12:30 - 1:00 | | | | | |
| 1:00 - 1:30 | HIST-3 Ion Exch Resins/Minor Events - A. Muscatello  
*Tower III* | HIST-2 Fires and Major Events - Felt/Jackson  
*Tower II* | TS-1 (continued) Team Dynamics - B. Parker  
*Academy* | | |
| 1:30 - 2:00 | | | | | |
| 2:00 - 2:30 | TS-3 Conflict Resolution - J. Loewen  
*Tower I* | TS-2 Interviewing - D. Denier  
*Academy* | PU-3 Plutonium Hazards/Consequences - J. Mishima  
*Tower II* | PU-1 Plutonium Properties - A. Muscatello  
*Tower III* | TA-2 Interviewing - D. Denier  
*Academy* |
| 2:30 - 3:00 | | | | | |
| 3:00 - 3:30 | | | | | |
| 3:30 - 4:00 | | | | | |
| 4:00 - 4:30 | PU-4 Plutonium Packaging and Storage Case Studies - J. Hashko/J. Martz  
*Academy* | | | | |
| 4:40 - 5:00 | | | | | |
| 5:00 - 5:30 | PU-6 Radiological Hazards of Plutonium and Other Fissile Materials - M. Goldman  
*Academy* | | | | |

**Key:**
- *Academy* refers to training conducted at the Pacific Northwest National Laboratory (PNNL) Academy.
- **TS-1** Team Skills - Team Dynamics
- **TS-2** Team Skills - Interviewing
- **TS-3** Team Skills - Conflict Resolution
- **HIST-1** Criticality Safety
- **HIST-2** Fires and Major Events
- **HIST-3** Ion Exchange Resins and Minor Events
- **SA** Plutonium Standards and Safety Analysis
- **DA** Database
- **PU-1** Plutonium Properties
- **PU-2** Plutonium Barriers
- **PU-3** Plutonium Hazards/Consequences
- **PU-4** Plutonium Storage
- **PU-5** Airborne Release Fractions
- **PU-6** Radiological Hazards
- **S&S** Safeguards and Security
- **METH** Assessment Methodology, Question Set and Guidelines
<table>
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<th>Teams 1 &amp; 7</th>
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<th>Teams 3 &amp; 4</th>
<th>Teams 8 &amp; 9</th>
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**TS-1** Team Skills - Team Dynamics
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**PU-5** Airborne Release Fractions
**PU-6** Radiological Hazards
**S&S** Safeguards and Security
**METH** Assessment Methodology, Question Set and Guidelines
A.5.4

Project Plan

by

Pat Ward
DEPARTMENT OF ENERGY
PLUTONIUM ES&H VULNERABILITY ASSESSMENT

ASSESSMENT TEAM TRAINING

April 19–21, 1994
Colorado Springs, Colorado

PROJECT PLAN

Pat Ward
PLUTONIUM ES&H VULNERABILITY PROJECT

- **Objective**
  - Identify and prioritize ES&H vulnerabilities
  - Create information base for interim corrective actions and safe management options

- **Special Instructions**
  - All forms and isotopes of plutonium under DOE's custody and control
  - Use of existing studies as applicable
  - CSO, Operations office, M&O contractor participation
  - External stakeholder involvement
  - September 30, 1994

- **Customer**
  - Secretary
  - Under Secretary's Nuclear Materials Disposition Project

- **Responsibility**
  - EH has lead
"... conditions or weaknesses that may lead to unnecessary or increased radiation exposure of the workers, release of radioactive materials to the environment, or radiation exposure of the public."
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<th>Scope</th>
<th>Remarks</th>
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<td>Process hold-up</td>
<td>In</td>
<td>Category includes Pu in ventilation systems, process vessels, piping, materials removed from the Nuclear Material Management and Safeguards System (NMMSS), etc.</td>
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<tr>
<td>Metal</td>
<td>In</td>
<td>Category also includes alloys</td>
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<tr>
<td>Oxide</td>
<td>In</td>
<td>Category includes mixed oxides with other actinides</td>
</tr>
<tr>
<td>Very low irradiated and unirradiated reactor fuel, targets</td>
<td>In</td>
<td>Category includes ZPPR fuel</td>
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<tr>
<td>Weapons components, pits</td>
<td>In</td>
<td>Category includes weapons components in DOE custody</td>
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<tr>
<td>Scrap/residues/compounds</td>
<td>In</td>
<td>Category includes Pu nitride, Pu carbides, slag and crucibles, ash, graphite, etc.</td>
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<tr>
<td>Solutions</td>
<td>In</td>
<td>Category includes product/residue solutions, lab samples, etc.</td>
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<tr>
<td>Sealed sources in DOE custody</td>
<td>In</td>
<td>Category includes sealed sources as per DOE/ANSI standard</td>
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<tr>
<td>High-level waste</td>
<td>Out</td>
<td>Category includes calcined and liquid material meeting DOE Waste Management Definition</td>
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<tr>
<td>TRU &amp; low-level wastes</td>
<td>Out</td>
<td>Category includes material packaged and declared LLW or TRU waste and material in burial sites. However, LLW or TRU co-located in plutonium facilities subject to this assessment are in-scope</td>
</tr>
<tr>
<td>Materials in facilities accepted for D&amp;D by EM</td>
<td>Out</td>
<td>Category out-of-scope; other DOE programs are addressing this material</td>
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<tr>
<td>Materials in areas subject to funded environmental restoration programs</td>
<td>Out</td>
<td>Category out-of-scope; other DOE programs are addressing this material</td>
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<tr>
<td>Materials in NRC or agreement state licensee custody</td>
<td>Out</td>
<td>Category out-of-scope; the licensee has ES&amp;H responsibility</td>
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<tr>
<td>Irradiated spent fuel and targets</td>
<td>Out</td>
<td>This category was covered in the spent nuclear fuel vulnerability assessment</td>
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<tr>
<td>Expended in nuclear device tests</td>
<td>Out</td>
<td>Category includes undetermined areas/locations, unrecognizable forms</td>
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<td>Intact nuclear weapons and nuclear explosive assemblies in DOE Custody</td>
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<td>Secretarial charter specifies this category out-of-scope</td>
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Figure 3-1
PLUTONIUM ES&H VULNERABILITY ASSESSMENT PROJECT
WORK BREAKDOWN STRUCTURE

Task 1 Planning
- 1.a Project organization
- 1.b Plutonium characteristics
- 1.c Planning meetings
- 1.d Working Group organization
- 1.e Facility dry runs
- 1.f Team qualifications
- 1.g Past experiences
- 1.h First Working Group meeting
- 1.i Project and Assessment Plans

Task 2 Training
- 2.a Team membership
- 2.b Team training

Task 3 Assessment
- 3.a Site Assessment Teams assessment
- 3.b Working Group assessment team verification and validation
- 3.c Assessments of smaller sites

Task 4 Analysis
- 4.a Data assembly
- 4.b Vulnerability characterization and summary
- 4.c Prioritization
- 4.d Second Working Group meeting

Task 5 Reporting
- 5.a Data collection and organization
- 5.b Report writing
- 5.c Draft report distribution
- 5.d Final report
- 5.e Management briefings
RESPONSIBILITIES

- Working Group
- Support Group
- Site Assessment Teams
- Working Group Assessment Teams
Figure 3-2
Responsibility/Flow Chart
for
Plutonium Working Group Vulnerability Assessment

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<tr>
<th>Working Group</th>
<th>Site Assessment Teams</th>
<th>W.G. Assessment Teams</th>
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<tr>
<td>Develops vulnerability assessment methodology and process, including Question Set.</td>
<td>Collect facility data. Complete responses to Question Set.</td>
<td>Receive training.</td>
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<tr>
<td>Obtains information from custodians of plutonium at smaller sites and assesses E&amp;H vulnerabilities.</td>
<td>Review and evaluate information from site facilities.</td>
<td>Visit sites. Verify and validate information. Identify and organize vulnerabilities.</td>
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<td>Prepare PLUTONIUM ES&amp;H Vulnerability report.</td>
<td>Prepare Site Team report.</td>
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## Plutonium ES&H Vulnerability Assessment Project Schedule

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<td>Site Reports (See Sec. 3.5 for Site Assessment Team Work and Report Schedule Requirement)</td>
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<td>Question Set Responses by Sites not initially scheduled for visit</td>
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<td>Team 1: NBL/WNL/E (5/16 - 6/3)</td>
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<td>Team 3: MD (5/9 - 5/27)</td>
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<td>CRNL (8/13 - 7/1)</td>
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<td>Team 4: PX (5/31 - 7/1)</td>
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<td>Team 6: LANL (6/8 - 7/1)</td>
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<td>Team 7: SR (5/31 - 7/1)</td>
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<td>Team 9: ARL/WINEL (5/9 - 5/27)</td>
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<td>Vulnerabilities Result and Prioritization Meeting - Support Group/Team Leaders (7/11 - 8/19)</td>
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<td>8/23 - 9/23</td>
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<td>Final Report</td>
<td>9/19 - 9/30</td>
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**Key for Site Assessment:**
- Preparation
- On-site
- Report writing
SITE ASSESSMENT TEAM REPORT OUTLINE

- Executive summary
  - Summary by facility
  - Site-wide conclusions

- Identification of facility
  - Brief description
  - Holdings

- Discussion by facility
  - Summary of responses to question set
  - Identification of ES&H vulnerabilities

- Appendices
  - SAT membership
  - Responses to Question Set (each facility)
  - Vulnerability Assessment Forms
  - References
WORKING GROUP ASSESSMENT TEAM REPORT OUTLINE

- Executive summary

- List of facilities included

- Evaluation of Site Assessment Team report and site-identified vulnerabilities
  - Facility A
  - Facility B

- Summary of additional vulnerabilities identified by Working Group Assessment Team
  - Facility A
  - Facility B

- Appendices
  - WGAT Vulnerability Assessment Forms
  - SAT report
  - WGAT membership
  - References
FINAL REPORT OUTLINE

- Executive summary
- Vulnerability characterization
- Vulnerability prioritization
- Appendices
  - SAT reports
  - WGAT reports
  - Assessment planning documents
- Separate classified appendix (if necessary)
  - Classified appendices from various site reports
  - Classified appendices developed for final report
CLASSIFIED INFORMATION

- Working Group report will contain unclassified information only
- Data collected by assessment teams may be classified
A.5.5

Plutonium Properties

by

Tony Muscatello
DEPARTMENT OF ENERGY
PLUTONIUM ES&H VULNERABILITY ASSESSMENT

ASSESSMENT TEAM TRAINING

April 19–21, 1994
Colorado Springs, Colorado

PLUTONIUM PROPERTIES

Tony Muscatello
AGENDA

- Nuclear properties
- Radiation dose rates
- Physical and chemical properties
  - Pu metal
  - Pu compounds
  - Pu-residues
- Plutonium processing
## TYPICAL ISOTOPIC COMPOSITION OF GRADES OF PLUTONIUM (WT. %)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-Life (Yrs)</th>
<th>Decay Mode</th>
<th>Heat Source</th>
<th>Weapons (LMR)</th>
<th>Fuel (LWR)</th>
<th>Reactor (Power)</th>
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<tbody>
<tr>
<td>$^{238}\text{Pu}$</td>
<td>88</td>
<td>$\alpha$</td>
<td>83.5</td>
<td>&lt;0.05</td>
<td>0.1</td>
<td>1.5</td>
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<tr>
<td>$^{239}\text{Pu}$</td>
<td>24,100</td>
<td>$\alpha$</td>
<td>14.0</td>
<td>93.6</td>
<td>86</td>
<td>58.1</td>
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<tr>
<td>$^{240}\text{Pu}$</td>
<td>6,600</td>
<td>$\alpha$</td>
<td>2.0</td>
<td>6.0</td>
<td>12</td>
<td>24.1</td>
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<tr>
<td>$^{241}\text{Pu}$</td>
<td>14</td>
<td>$\beta^-$</td>
<td>0.4</td>
<td>0.4</td>
<td>1.6</td>
<td>11.4</td>
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<tr>
<td>$^{242}\text{Pu}$</td>
<td>376,000</td>
<td>$\alpha$</td>
<td>0.1</td>
<td>&lt;0.05</td>
<td>0.2</td>
<td>4.9</td>
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<tr>
<td>$^{241}\text{Am}$</td>
<td>433</td>
<td>$\alpha,\gamma$</td>
<td>--</td>
<td>0.02–0.3</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>$^{243}\text{Am}$</td>
<td>7370</td>
<td>$\alpha,\gamma$</td>
<td>--</td>
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</tr>
<tr>
<td>$^{244}\text{Cm}$</td>
<td>18</td>
<td>$\alpha,\gamma$</td>
<td>--</td>
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<td>--</td>
</tr>
<tr>
<td>$^{252}\text{Cf}$</td>
<td>2/6</td>
<td>SF</td>
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</table>
### MINIMUM CRITICAL MASSES

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Critical Mass</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{Pu}$</td>
<td>7.8 kg</td>
<td>Metal sphere reflected by 10 cm iron</td>
</tr>
<tr>
<td>$^{239}\text{Pu}$</td>
<td>509 g</td>
<td>33 g/L Pu, Pu(NO$_3$)$_4$ solution, 30.5 cm sphere, water-reflected</td>
</tr>
<tr>
<td>$^{239}\text{Pu}$</td>
<td>905 g</td>
<td>Unreflected Pu(NO$_3$)$_4$ solution in spherical stainless-steel container</td>
</tr>
<tr>
<td>$^{239}\text{Pu}$</td>
<td>5.4 kg</td>
<td>Pu metal sphere, water-reflected</td>
</tr>
<tr>
<td>$^{241}\text{Pu}$</td>
<td>260 g</td>
<td>32 g/L Pu, fully reflected sphere</td>
</tr>
</tbody>
</table>

Ref.: Seaborg, Katz, and Morss
# GAMMA RADIATION DOSE RATES

<table>
<thead>
<tr>
<th>Form</th>
<th>Pu, kg</th>
<th>Surface</th>
<th>1 Meter</th>
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<tbody>
<tr>
<td>Pit (W Pu)</td>
<td>4</td>
<td>0.8</td>
<td>0.002</td>
</tr>
<tr>
<td>R Pu metal sphere</td>
<td>6</td>
<td>17</td>
<td>0.03</td>
</tr>
<tr>
<td>PuO₂ powder (W Pu)</td>
<td>4</td>
<td>1</td>
<td>0.009</td>
</tr>
<tr>
<td>PuO₂ powder (R Pu)</td>
<td>6</td>
<td>20</td>
<td>0.2</td>
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</tbody>
</table>

W Pu = Weapons grade Pu (0.2% $^{241}$Am)
R Pu = Reactor grade Pu (4% $^{241}$Am)
Ref.: National Academy of Science Report
# CONTACT RADIATION DOSE RATES

(1 kg spheres)

<table>
<thead>
<tr>
<th>Pu Grade</th>
<th>Gamma Dose, rem/hr</th>
<th>Neutron Dose, rem/hr</th>
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</thead>
<tbody>
<tr>
<td>Weapons</td>
<td>1.6–2.3</td>
<td>16</td>
</tr>
<tr>
<td>Reactor</td>
<td>19–41</td>
<td>100</td>
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<tr>
<td>Heat Source</td>
<td>864</td>
<td>4800</td>
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</table>
# Neutron Radiation from Isotopes and Selected Compounds

<table>
<thead>
<tr>
<th>Isotope/Compound</th>
<th>Spontaneous Fission n/s–g (isotope)</th>
<th>Estimated (α,n) n/s–g (isotope)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{Pu}$</td>
<td>$3.4 \times 10^3$</td>
<td>$1.4 \times 10^4$</td>
</tr>
<tr>
<td>$^{238}\text{Pu O}_2$</td>
<td>--</td>
<td>$2.1 \times 10^6$</td>
</tr>
<tr>
<td>$^{238}\text{Pu F}_4$</td>
<td>--</td>
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<tr>
<td>$^{239}\text{Pu}$</td>
<td>$3.0 \times 10^{-2}$</td>
<td>--</td>
</tr>
<tr>
<td>$^{239}\text{Pu O}_2$</td>
<td>--</td>
<td>$4.5 \times 10^1$</td>
</tr>
<tr>
<td>$^{239}\text{Pu F}_4$</td>
<td>--</td>
<td>$4.3 \times 10^3$</td>
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<tr>
<td>$^{240}\text{Pu}$</td>
<td>$1.02 \times 10^3$</td>
<td>--</td>
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<tr>
<td>$^{240}\text{Pu O}_2$</td>
<td>--</td>
<td>$1.7 \times 10^2$</td>
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<tr>
<td>$^{240}\text{Pu F}_4$</td>
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<td>$1.6 \times 10^4$</td>
</tr>
<tr>
<td>$^{242}\text{Pu}$</td>
<td>$1.7 \times 10^3$</td>
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</tr>
<tr>
<td>$^{242}\text{Pu O}_2$</td>
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<td>2.7</td>
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<tr>
<td>$^{242}\text{Pu F}_4$</td>
<td>--</td>
<td>$1.7 \times 10^2$</td>
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</tbody>
</table>

**HEAT GENERATION BY PLUTONIUM**

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half–Life (Yrs)</th>
<th>Milliwatts/g or Watts/kg</th>
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<tbody>
<tr>
<td>$^{238}\text{Pu}$</td>
<td>88</td>
<td>568</td>
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<tr>
<td>$^{239}\text{Pu}$</td>
<td>24,100</td>
<td>1.93</td>
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<td>$^{240}\text{Pu}$</td>
<td>6,600</td>
<td>7.08</td>
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<td>$^{241}\text{Pu}$</td>
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<td>3.41</td>
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<tr>
<td>$^{242}\text{Pu}$</td>
<td>376,000</td>
<td>0.116</td>
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<tr>
<td>$^{241}\text{Am}$</td>
<td>433</td>
<td>114</td>
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Ref: ANSI N15.22 (1987)
PROPERTIES OF PLUTONIUM METAL

- Silvery-white metal resembling iron or nickel in the absence of surface oxidation

- Ignitable at 150°C if < 0.05-mm particles

- Two major allotropic forms (different crystal structures and densities) – α and δ.
  - δ stabilized by 1% Gallium

- Oxidation rate in air depends on humidity, surface area, and surface morphology
  - More rapid in moist argon than in moist air
  - α oxidizes faster than δ
  - Oxidation follows crystal grain boundaries

- Oxidation in moist air or argon produces unstable Pu suboxides and hydrides, which include Pu metal particulates

Refs: Cleveland, p. 7; Allen and Longmire (1993)
STORAGE CONCERNS – Pu METAL

- Surface oxidation generates Pu$_2$O$_3$, PuO$_{1.8-1.9}$, Pu oxide/hydride, and Pu metal fines
  - Potentially pyrophoric (spontaneous ignition in air)
  - Potential fire hazards
  - Not expected to cause ignition of massive Pu metal

- Alpha radiation damages plastic containment materials
  - Potential loss of containment
  - Hydrogen gas generation
  - Potential contamination and fire/explosion concerns

- Oxide expands and can damage (breach) metal containers
  - Potential airborne contamination

Recommended Storage: Inert atmosphere in welded or metal seal containers
# IMPORTANT PLUTONIUM COMPOUNDS

<table>
<thead>
<tr>
<th>Compound</th>
<th>Formula</th>
<th>Notes</th>
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</thead>
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<tr>
<td>Plutonium Oxide</td>
<td>PuO$_2$</td>
<td>Oxidation at $&gt;500^\circ\text{C}$ in air</td>
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<tr>
<td>Plutonium Fluoride</td>
<td>PuF$_4$</td>
<td>Neutron hazard</td>
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<tr>
<td>Plutonium Hydride</td>
<td>PuH$_{2-3}$</td>
<td>Pyrophoric</td>
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<tr>
<td>Plutonium (IV) Nitrate</td>
<td>Pu(NO$_3$)$_4$</td>
<td>Solutions in nitric acid</td>
</tr>
<tr>
<td>Plutonium (III) Chloride</td>
<td>PuCl$_3$</td>
<td>Solutions in hydrochloric acid or solids in salts</td>
</tr>
</tbody>
</table>
PROPERTIES OF PLUTONIUM OXIDE (PuO₂)

- Black to khaki to yellow green solid
- Dispersible, fine powder (depending on source and calcination temperature)
- Absorbs water (up to 2% by wt.)
  - Generates gas
  - Potential pressurization
  - Potential fire hazard from hydrogen gas
- Water removed by heating @ 1000° C (Figure 1)
- Other contaminants possibly present
  - e.g., Nitrates from aqueous processing
- Radiation damages plastic packaging
  - Potential loss of containment
  - Hydrogen gas generation
Figure 1. The temperature dependence of water desorption from plutonium dioxide in vacuum. Data are from a sequence of isothermal measurements with a PuO₂ sample having a specific surface area of 17 m²/g.
PROPERTIES OF PLUTONIUM OXIDE (PuO$_2$) (cont.)

- Normal storage ($\leq$ 1 yr):
  - Stabilized oxide (500° C)
  - Tape sealed metal container
  - Ambient atmosphere
  - Taped plastic bag
  - Taped outer container

- Long term storage ($>$ 1 yr):
  - Stabilized oxide (1000° C)
  - Metal sealed container
  - Inert atmosphere
  - Welded outer container
  - No organic material
STORAGE CONCERNS – PLUTONIUM OXIDE

- Fine powders are a dispersible contamination hazard

- Plastic packaging can be damaged by radiation
  - Potential loss of containment
  - Hydrogen gas generation

- Moisture and other contaminants, if present, also add to gas generation
  - Potential pressurization
  - Fire hazard from hydrogen gas
PROPERTIES OF PLUTONIUM FLUORIDE

- Pink solid
- Dispersible, fine powder
- Neutron hazard \((\alpha, n)\)
  - 4,300 neutrons/sec/gram \(^{239}\text{Pu}\)
  - 2,100,000 neutrons/sec/gram \(^{238}\text{Pu}\)
- Storage concerns similar to those for plutonium oxide
PROPERTIES OF PLUTONIUM HYDRIDE

- Black solid
- Fine powder
- Pyrophoric
  - Ignites in air
- Can be readily formed from metal and H₂ or H₂O
- Not normally stored
PROPERTIES OF PLUTONIUM (IV) NITRATE

- Green solutions in nitric acid

- Radiolysis generates hydrogen gas
  - Potential pressurization of bottle or tank
  - Potential fire hazard if allowed to accumulate

- Radiolysis destroys acidity
  - Plutonium +4 polymerizes at $<0.4\text{M}$ acidity
  - Precipitates out as sludge
  - Potential handling problems (clogged pipes)
  - Possible criticality hazard if in unfavorable geometry

- Not a recommended storage form
PROPERTIES OF PLUTONIUM CHLORIDE

- Blue (Pu$^{3+}$) or brown (Pu$^{4+}$) solutions in hydrochloric acid

- Radiolysis – similar to plutonium nitrate

- Hydrochloric acid requires special containers
  - Plastic or plastic lined.

- Blue or black in pyrochemical (high temperature chemistry) salts

- Storage concerns similar to plutonium oxide for solids

- Solutions are not a recommended storage form
OTHER FORMS OF PLUTONIUM – RESIDUES

- Residues: Plutonium dispersed in other materials

\[ [\text{Pu}] > \text{economic discard limit (EDL)} \]

\( \text{(EDL} = \text{cost to recover} = \text{cost to make new Pu}) \)

- Pyrochemical salts (chlorides and fluorides)
- Scrub alloy (aluminum)
- Ceramics (crucibles, firebrick)
- Sludges
- Graphite
- Combustibles (wet & dry)
- Incinerator ash & dissolver heels
- Ion exchange resins
- Other metals
STORAGE CONCERNS – COMBUSTIBLES

- Alpha and gamma radiation decompose combustibles into hydrogen gas; Oxygen also sometimes released
  - Pressurization and fire hazard
  - Water and CCl₄, if present, are also decomposed (HCl corrosion)
  - PVC produces HCl in the presence of moisture

- Nitric acid can react with cellulosic materials; possible spontaneous combustion
  - Fire hazard
  - Usually occurs soon after contact
  - Acid fumes corrode drums

- Ion exchange resins also generate hydrogen gas
  - Contain both oxidizer (nitrate) and fuel (resin)
  - Acid fumes corrode drums

- Leaded gloves may form unstable lead nitrates
  - Deactivated by water washing
STORAGE CONCERNS – PYROCHEMICAL SALTS

- These residues contain chloride salts and free metals
  - Pu, Mg, Na, K, Ca: reactive metals
  - Bulk salt mitigates hazard by being a heat sink
  - Na₂O₂ (sodium peroxide) can form with electorefining salts, but is unlikely to survive exposure to air

- Radiation damages plastic containment
  - Hydrogen gas generation
  - Contamination potential
STORAGE CONCERNS - FUL-FLO FILTERS

- Filters formed from polypropylene fibers
  - Some exposed to nitric acid; no nitration hazard
  - Radiation generates hydrogen gas
  - Pressurization and fire safety issues
TWO BASIC CHEMICAL PROCESSES

Aqueous
- Dissolution
  - HNO₃
  - HCl
- Separation
  - Solvent extraction
  - Ion exchange
- Conversion to oxide
  - Precipitation and calcination
  - Direct denitration

Pyrochemical
- Purification
  - Electrorefining
  - Molten salt extraction
- Metal conversion
  - Direct oxide reduction
  - Fluorination/reduction
  - Chlorination
OTHER PROCESSING

- Other high temperature processing
  - Calcination
  - Thermal stabilization
  - Metal oxidation
  - Incineration
  - Casting
  - Alloying
  - Heat treatment

- Powder handling
  - Screening
  - Blending

- Manufacturing
  - Foundry
  - Rolling & forming
  - Machining
  - Inspection & assembly
STORAGE

- In process storage
  - Glovebox, canyon, cabinet
  - Tanks
  - In-line shelving, conveyor systems

- Vault storage
  - Cans
    - In-line
    - Off-line
  - Drums

- Other storage
  - Mixed waste drums & boxes
  - Transuranic waste drums
WASTE TREATMENT

- Solid wastes
  - Size reduction
  - Packaging/repackaging

- Liquid wastes
  - Precipitations
  - Immobilization
  - Evaporation
ANALYTICAL AND OTHER LABORATORIES

- Samples
  - Solids
  - Liquids
  - Gases

- Standards
  - Plutonium
  - Other

- Radiography

- NDA
  - Calorimetry
  - n/γ Spectroscopy
  - Standards

- Development
SUMMARY

- Plutonium is a complex and hazardous element
- Plutonium's nuclear properties serve a useful purpose in national defense which have lead to a large number of potential problems from surplus materials:
  - Radiation safety hazards
  - Fire and chemical safety hazards
  - Waste management
A.5.6

Barriers

by

R.E. Felt and M.D. Jackson
DEPARTMENT OF ENERGY
PLUTONIUM ES&H VULNERABILITY ASSESSMENT

ASSESSMENT TEAM TRAINING

April 19–21, 1994
Colorado Springs, Colorado

BARRIERS

Rowland E. Felt
Merle D. Jackson
BARRIERS

- Packaging – Felt
- Storage vaults – Jackson
- Process and ventilation systems – Felt
- Administrative controls – Jackson
- Shielding – Jackson
- Safety systems – Felt
ES&H VULNERABILITY ASSESSMENT APPROACH

Question 1
Facility

Question 2
Holdings and Packaging

Question 3
Physical Barriers

Question 4
Adverse Conditions

Question 5
Events

Question 6
Compensatory Measures
Preventive/Mitigative

Question 7
Consequences

Identification of ES&H Vulnerabilities
- Environment
- Worker
- Public
SAFETY ENVELOPE

- Barriers
- Safety systems
- Maintenance of safety system
- Compensatory measures
PACKAGING

- Initial barrier
- Physical barrier
- Contamination barrier
- Contamination seal
- Degradable plastic and rubber
- Containment seal
<table>
<thead>
<tr>
<th>Packaging Types</th>
<th>Physical Barrier Types</th>
<th>Worker Barrier¹</th>
<th>Public/Environmental Barrier²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal Cans</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC-1 Single Can – Slip</td>
<td>WB-1 Glovebox</td>
<td></td>
<td>EB-1 Facility Boundary</td>
</tr>
<tr>
<td>MC-2 Single Can – Mechanical</td>
<td>WB-2 Transfer System</td>
<td></td>
<td>EB-2 HVAC/Confinement</td>
</tr>
<tr>
<td>MC-3 Single Can – Hermetic</td>
<td>WB-3 Duct</td>
<td></td>
<td>EB-3 Liquid/Containment</td>
</tr>
<tr>
<td>MC-4 Plastic Wrap In Contact With Metal</td>
<td>WB-4 Filter</td>
<td></td>
<td>EB-4 Site Boundary</td>
</tr>
<tr>
<td>MC-5 Double Barrier Cans With Plastic Wrap</td>
<td>WB-5 Vault</td>
<td></td>
<td>EB-5 Bunkers</td>
</tr>
<tr>
<td>MC-6 Double Barrier Cans Without Plastic Wrap</td>
<td>WB-6 Room</td>
<td></td>
<td>EB-6 Trench</td>
</tr>
<tr>
<td>MC-7 Other–Specify</td>
<td>WB-7 Canyon</td>
<td></td>
<td>EB-6.1 Backfilled</td>
</tr>
<tr>
<td>Plastic</td>
<td>WB-8 Hot Cell</td>
<td></td>
<td>EB-6.2 Enclosed</td>
</tr>
<tr>
<td>PL-1 Bags</td>
<td>WB-9 Cell</td>
<td></td>
<td>EB-6.3 Open</td>
</tr>
<tr>
<td>PL-2 Jars/Bottles</td>
<td>WB-10 Burial Ground</td>
<td></td>
<td>EB-6.4 Other–Specify</td>
</tr>
<tr>
<td>PL-3 Other–Specify</td>
<td>WB-11 Piplng</td>
<td></td>
<td>EB-7 Storage</td>
</tr>
<tr>
<td>Drums</td>
<td>WB-12 None</td>
<td></td>
<td>Vault</td>
</tr>
<tr>
<td>DR-1 55 Gal.</td>
<td>WB-13 Other–Specify</td>
<td></td>
<td>EB-8 Canyons</td>
</tr>
<tr>
<td>DR-2 30 Gal.</td>
<td></td>
<td></td>
<td>EB-9 Pad</td>
</tr>
<tr>
<td>DR-3 &lt; 30 Gal.</td>
<td></td>
<td></td>
<td>EB-10 Caisson</td>
</tr>
<tr>
<td>DR-4 &lt; 5 Gal.</td>
<td></td>
<td></td>
<td>EB-11 Pond</td>
</tr>
<tr>
<td>DR-5 Other–Specify</td>
<td></td>
<td></td>
<td>EB-12 Other–Specify</td>
</tr>
<tr>
<td>Tanks</td>
<td></td>
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<tr>
<td>TA-1 Raschig Ring Filled</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>TA-2 Geometrically Favorable</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TA-3 Other–Specify</td>
<td></td>
<td></td>
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<tr>
<td>Crates (box)</td>
<td></td>
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<tr>
<td>CR-1 Metal Burial Box</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CR-2 Cardboard Box</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CR-3 Wooden Crates</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CR-4 Other–Specify</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shipping Containers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC-1 Shipping Containers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC-2 Other–Specify</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Packaging</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NP-1 Basket</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NP-2 Other</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹ Barrier between plutonium and worker.
² Last barrier between plutonium and public and environment.
MATERIALS, PACKAGES, BARRIER EXAMPLES

1. Material, can, drum, pad, tent

2. Solution, pencil tanks, room

3. Material, inner can, slip-lid can

4. Material, glovebox, HVAC, room, building

5. Solution, Raschig rings, tank, room

6. Material, barrel, clay liner, soil, burial ground
Pu metal storage container
short-term duration

6" Maximum

12" Max

INERT ATMOSPHERE

Copper Ring

CON-FLAT flange

Pu metal

Taped Slip-lid Can

HOT

COLD

Bag-Out Bag
Pu oxide storage container

stabilized, unqualified oxide

short term duration

6" Maximum

Up to 12"

Welded Can

Metallic frit filter

Inert atmosphere (He)

Copper ring

CON-FLAT flange

Oxide in slip-lid can

Bag-out bag

Oxide
Pu oxide storage container
qualified oxide
short, intermediate and long term duration

Pu oxide inslip-fit can.
Pu metal storage container
intermediate to long-term duration

6" Maximum

12" Max

INERT ATMOSPHERE

Welded container

Metal gasket

Stainless steel inner container

Pu metal
1. Insert can into sphincter seal

2. Fill can, insert plug and weld can to plug

3. Cut can along center of weld

4. Remove sealed can from glovebox

Bagless transfer concept utilizing automatic rotary TIG welder to seal can
OPENING FOR AUTOMATED HANDLING

ACCESS SLOT FOR LASER SAMPLING DEVICE

LIFTING EARS FOR AUTOMATED HANDLING

RESISTANCE WELDED HONEYCOMB OR ALUMINUM FOAM PACKING

TUBE FOR PURGE, BACKFILL AND GAS SAMPLING OPERATIONS

SLOT IN COVER FOR LASER SAMPLING TUBE

PROTECTIVE COVER

BAGLESS TRANSFER CAN

5" SCHEDULE 40 PIPE

5" SCHEDULE 40 PIPE CAPS, TYPICAL
STORAGE VAULTS

Merle D. Jackson
FUNCTIONAL REQUIREMENTS FOR PLUTONIUM STORAGE VAULT

- Meet plutonium storage requirements
- Maintain facility and equipment
- Safeguard and secure plutonium
- Limit environmental impact
- Limit radiation and contamination exposure
- Remove heat
- Enable inspection
- Present critical array
FUNCTIONAL REQUIREMENTS FOR PLUTONIUM STORAGE VAULT (Continued)

- Provide confinement
- Impact facility interfaces
- Provide capability to decontaminate and decommission
- Meet all applicable regulations, codes, laws, etc.
- Material segregation capability
- Maximize inherent safety
- Place package in/or remove package from storage
Function Flow Diagram Pu Storage Vault
PITS

- Existing Pit Storage
  - ALR8
  - FL
  - 2030-1

- Repackage Pit into Hermetically Sealed Container

- New Storage/Shipping Primary Containment Vessel
  - New Design
  - Modified AT 400A Primary Container

- Shipping Package
  - New Design
  - Modified AT 400A

- Store in Primary Containment Vessel in a "4 Pack" pallet for Criticality Spacing

- Store Bare in Primary Containment Vessel and rely on storage racks and other engineered controls for criticality safety

- Store in Primary Containment Vessel only with "Bird Cage" for Criticality Spacing

- Store in Same Shipping Package

- Store in New Design Storage Overpack (No combustible/degradable Packing Materials)

Alternatives Diagram for PITS Packaging and Storage
OXIDE/ METAL

EXISTING CAN STORAGE
- Food Pack Cans
- Vollrath Cans
- Produce Cans
- Tuna Cans
- Chip Cans

NEW DESIGN CAN
- Repackage Pu Into Bagless Can

NEW PRIMARY CONTAINMENT VESSEL
- New Design

PACKAGE CAN INTO HERMETICALLY SEALED CONTAINER

DOUBLE CONTAINMENT REQUIRED FOR OXIDE SHIPMENT

NEW DESIGN SHIPPING PACKAGE
- Modified 9968
- SAFKEG
- New Design

ALTERNATIVES DIAGRAM FOR OXIDE/METAL PACKAGING AND STORAGE

- Store in Primary Containment Vessel in a "4 Pack" pallet for Criticality Spacing
- Store in Primary Containment Vessel and rely on storage racks and other engineered controls for criticality safety
- Store in Primary Containment Vessel only with "Bird Cage" for Criticality Spacing
- Store in Same Shipping Package
- Store in New Design Overpack (stable/degradable Packing Materials)
PROCESS AND VENTILATION SYSTEMS

Rowland E. Felt
VENTILATION ZONES

Air Flow

Air Lock

Glovebox
Zone 1
1" H₂O Negative

Zone 2
1/4" H₂O Negative
Rooms & Corridors

1/10" H₂O Negative
Offices
Zone 3
Contamination & Physical Barriers

Air Lock

Filters

Physical Barriers

Room

Physical & Contamination Barrier

Barrel
ADMINISTRATIVE CONTROLS

Merle D. Jackson
ADMINISTRATIVE CONTROLS
COMPENSATORY MEASURES

- Procedures: operational, maintenance, surveillance
- Material limits
- Training
- Quality assurance
- Conduct of operations
- Conduct of maintenance
- Housekeeping
- Authorization bases
  - Safety analysis report
  - Technical specification/standards
  - Criticality safety analysis/specifications
- Surveillance
- Organization
  - Structure
  - Management development
  - Staffing
  - Facility related experience
ADMINISTRATIVE CONTROLS
COMPENSATORY MEASURES
(Continued)

- Lessons learned
- Configuration control
- Preventative maintenance
- Monitoring
- Trending
- Testing/verification of integrity
- Emergency management
  - Planning
  - Procedures
  - Response
Shielding

- **Alpha ($\alpha$)**
- **Beta ($\beta$)**
- **Gamma ($\gamma$)**
- **X-ray ($X$)**
- **Neutron ($\eta$)**
SAFETY SYSTEMS
(Continued)

Air activity alarms

Criticality alarms

Criticality engineered features (spacing, equipment, etc.)

Gloveboxes

Process control systems (safety related)

Emergency power

Instrument air system

Breathing air system

Fire protection system
Shielding

Alpha ($\alpha$)

Beta ($\beta$)

Gamma ($\gamma$)

X-ray ($X$)

Neutron ($n$)
SAFETY SYSTEM

Rowland Felt
SAFETY SYSTEMS

- Ventilation (HVAC)
  - Filters (Select – Outlet)
  - Ducts
  - Fans
  - Controls
  - Stack
  - Special atmosphere (nitrogen, dry air)

- Building walls
  - Air locks
  - Security constraints
SAFETY SYSTEMS
(Continued)

- Air activity alarms
- Criticality alarms
- Criticality engineered features (spacing, equipment, etc.)
- Gloveboxes
- Process control systems (safety related)
- Emergency power
- Instrument air system
- Breathing air system
- Fire protection system
VENTILATION AIR REVERSAL AT ROCKY FLATS PLANT

On February 3, 1994, at Rocky Flats Plant Building 371, Radiation Operations personnel discovered air pressure greater than that of the adjacent hallway in room 3305, a surface contamination area. Negative differential pressure was used as an engineered control to preclude the spread of contamination from radiologically controlled areas. Workers discovered the out-of-tolerance differential air pressure in room 3305 during performance of a routine surveillance smoke test. Radiation Operations personnel immediately posted the adjacent hallway requiring respirator protection prior to entry. (ORPS Report RFO-EGGR-371OPS-1994-0016)

Workers adjusted the exhaust and supply air valves to room 3305 and the hallway until the room was at a pressure less than the hallway. Radiological Controls personnel removed the respirator requirement for the hallway after swipe surveys revealed no contamination.

On February 9, 1994, personnel at Rocky Flats Plant Building 371 discovered air pressure in a supplied air house in room 2310, a surface contamination area, that was greater than the pressure in the adjacent hallway. The pressure imbalance between the two areas was created when operating engineers failed to properly adjust the air damper in the supplied air house after replacing the exhaust high-efficiency particulate air filter. (ORPS Report RFO-EGGR-371OPS-1994-0018)

Investigators determined the pressure imbalance occurred because workers did not know the automatic air damper was malfunctioning. After the high-efficiency particulate air filters were replaced, workers set the damper on automatic, but did not verify that the pressure in the supplied air house was negative.

To prevent similar occurrences, management personnel at Rocky Flats will modify the work packages to ensure that workers do not set the air damper on automatic and that they test all air dampers to verify that air is flowing in the proper direction after replacing high-efficiency particulate air filters.

There have been numerous other events at DOE facilities concerning air reversals that resulted in the potential for the spread of contamination. Examples of these events include the following:

- On October 6, 1993, personnel at the Savannah River Old HB-Line facility discovered an air reversal from room 306 into the corridor because a piece of heavy craft paper became lodged in the exhaust duct partially restricting air flow. (ORPS Event SR-WSRC-HCAN-1993-0095)

- On April 12, 1993, personnel at the Rocky Flats Plutonium Processing plant discovered an air reversal from room 3567A into the hallway. Operating engineers manually adjusted the supply damper to create negative air pressure in room 3567A. (ORPS Event RFO-EGGR-371OPS-1993-0028)

- On April 30, 1992, personnel at the Hanford 324 facility discovered air flowing from a radiation area into an uncontrolled area. Investigators concluded that someone working in the area violated operating procedures when they opened the dampers to provide more air flow in an effort to reduce room temperature. (ORPS Report RIL-PNL-324-1992-0011)
On February 12, 1992, personnel at the Savannah River Old HB-Line facility identified an air reversal that resulted in an increase in airborne activity in a corridor. Prior to the event, a worker adjusted a ventilation system damper to reduce a higher-than-usual airborne radioactivity level in an airlock located in another corridor. Although the worker did not notice an immediate change in the air flow after the adjustment, the open damper decreased exhaust capability in the room, which caused room pressure to rise. (SR-WSRC-HCAN-1992-0009)

To preclude similar events, management at other DOE facilities may consider implementing a test program to verify correct air flow after maintenance of air dampers or filters. DOE 5480.19, *Conduct of Operations Requirements for DOE Facilities*, Chapter VIII, C.7, states: "Equipment should be tested following maintenance to demonstrate that it is capable of performing its intended function. The testing should include performance of all functions that may have been affected by the maintenance. The testing should also verify that the maintenance performed served to correct the original problem and that no new problems were introduced. Any testing following maintenance should be specified on the maintenance work order or accompanying documentation (e.g., maintenance procedure). The operations supervisor should ensure that testing appropriately proves equipment operability."
A.5.7

Plutonium Hazards and Consequences

by

M.G. Seitz
DEPARTMENT OF ENERGY
PLUTONIUM ES&H VULNERABILITY ASSESSMENT

ASSESSMENT TEAM TRAINING

April 19–21, 1994
Colorado Springs, Colorado

PLUTONIUM HAZARDS AND CONSEQUENCES

Dr. Martin G. Seitz
PURPOSE

Develop an understanding of the hazards and consequences associated with the handling and storage of plutonium.

Identifying the hazards and consequences of other fissile material in comparison to plutonium.
OUTLINE

Hazards

- Radiolytic/chemical damage to barriers (contamination)
  - Ionizing effects in metals/insulators
  - Radiolysis
  - Reaction of radiolysis products, material degradation

- Pyrophoricity/oxidation – hydration – hydridation
  - Ignition temperatures of metal versus particle size
  - Plutonium hydride
OUTLINE (Continued)

- **Volumetric expansion (explosion, rupture)**
  - Bulk expansion from chemical reaction
  - Gas generation
    - Helium generation
    - $\text{H}_2$, $\text{O}_2$ generation
    - Organic degradation products
    - Plutonium metal gettering

- **Radioactive decay (exposure)**
  - Alpha decay rates
  - Sixty kev gamma radiation and attenuation

- **Criticality (radiation, explosion)**
  - Critical safety operating limits (CSOLs)
  - Shipping limits
OUTLINE
(Continued)

Plutonium-specific consequences

- Contamination
  - Surface contamination
  - Inhalation
  - Injection
  - Ingestion
- Exposure
  - ALARA process
  - Dosimeters
  - Selective alpha air monitors
  - Reporting process
- Environmental insult
  - Soil contamination–spills/drains
  - Air emissions – stacks
  - Air emissions – accidents
HAZARD REFERENCES


FISSILE MATERIALS

Uranium – 233
Uranium – 235
Plutonium – 239
Plutonium – 241
Neptunium – 237

Weapons-grade plutonium
Fuel-grade plutonium

Other plutonium isotopes (Pu–240, Pu–238) are also fissile at higher neutron energies.
RADIOLYSIS

Radiolysis is the breaking of chemical bonds by ionizing radiation (alpha, beta or gamma radiation) and subsequent chemical reactions

**Alpha:** Highly ionizing radiation of short path length (high linear energy transfer)

**Beta:** Moderately ionizing radiation (low linear energy transfer)

**Gamma:** Low ionization. Ionizes by scattering on electrons (low linear energy transfer)
RADIOLYSIS DESTROYS MOLECULES

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Radiolysis Product</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (H₂O)</td>
<td>Hydrogen gas (H₂), oxygen (O₂), peroxide (H₂O₂)</td>
<td>Gases pressurize containers. Products react with plutonium</td>
</tr>
<tr>
<td>Air (N₂O₂)</td>
<td>Nitric oxide (NO), Nitrogen dioxide (NO₂)</td>
<td>Nitric oxide reacts with water to form nitric acid</td>
</tr>
</tbody>
</table>
RADIOLYSIS DESTROYS MOLECULES
(Continued)

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Radiolysis Product</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polypropylene, (-\text{CHCH}_2)-</td>
<td>(\text{C}_2, \text{H}_2, \text{CH}_4)</td>
<td>Plastic turns black and brittle, gas pressurizes container or reacts with plutonium</td>
</tr>
<tr>
<td>(\text{CH}_3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyvinylchloride (PVC) (-\text{CHCH}_2)-</td>
<td>(\text{C}, \text{H}_2, \text{CH}_4, \text{HCl})</td>
<td>Hydrochloric acid reacts with metals to form chlorides</td>
</tr>
<tr>
<td>(\text{CH}_1)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
GETTERING OF REACTIVE GASES BY PLUTONIUM METAL AND OXIDE

Pu, H₂, O₂, H₂O → PuHₓ, PuO₂, Pu (OH)₂
Pu + PuHₓ + O₂ → Pu₂ [O₂ · H]
PuO₂ + H₂O → PuO₂ · H₂O

CORROSION OF PLUTONIUM METAL AND CANISTERS BY ACIDS

Pu, Fe, HCl, HNO₃ → PuCl₄, FeCl₃, Pu(NO₃)₃, etc.

Results: Expansion of the volume of plutonium metal. Breach of the metal canister.
PYROPHORICITY

**Pyrophoric substance** is one that will ignite in air at or below room temperature in the absence of added heat, shock or friction – Chemical Dictionary

**Pyrophoric plutonium** is plutonium metal that will ignite spontaneously in air at temperature of 150°C or below in the absence of external heat, shock, or friction – Rocky Flats Definition

**Pyrophoric materials** are materials that will ignite in air at conditions of temperature, shock or friction encountered under normal storage and handling conditions – Plutonium Vulnerability (Proposed)
PYROPHORICITY

Measured ignition temperatures of plutonium as a function of specific surface area and metal dimension.

Plutonium metal, as small chips, can ignite in air at temperature of 130°C
PYROPHRICITY

Oxidized metal surfaces of plutonium may contain small-sized metal particles that reduce ignition temperatures to 150°C or lower.

Hydride metal surfaces of plutonium can ignite near room temperature. This condition may exist for plutonium stored in contact with plastics or other compounds of hydrogen.

Large metal pieces can conduct heat from a hot spot and prevent ignition.
## VOLUMETRIC EXPANSION
### BULK EXPANSION

<table>
<thead>
<tr>
<th>Material</th>
<th>Density gm/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plutonium metal (alpha)</td>
<td>19.86</td>
</tr>
<tr>
<td>Plutonium dioxide</td>
<td>11.46 (x-ray density)</td>
</tr>
<tr>
<td>Plutonium dioxide (bulk)</td>
<td>10.5 (sintered), 2.0 (unconfined)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Pu + O₂ → PuO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>239g + 32g → 271g</td>
</tr>
<tr>
<td>Volume</td>
<td>12.0 cm³ → 25 cm³</td>
</tr>
</tbody>
</table>
VOLUMETRIC EXPANSION
GAS GENERATION POTENTIAL

- Helium
  - Helium stays in metals and forms compressed microscopic bubbles at grain boundaries. Helium will stay trapped for 50 years but can move upon heating and be released entirely near the melting point of 640°C.
  - Nearly all helium escapes from oxides
  - Typical storage canister — negligible pressure build up in 10 years. Potentially significant build up after 20 years

Calculation: Plutonium generates $1.05 \times 10^{-4}$ mole helium per kilogram of PuO$_2$ per year. The 4.5 kilogram of PuO$_2$ in a can of volume 1.85 Liter will generate 5.3 psi pressure after 50 years. (Pu Storage, p C1).
VOLUMETRIC EXPANSION
GAS GENERATION POTENTIAL

- Hydrogen gas from water that reacts with metal or oxygen deficient oxides or from degradation of organics
  - Plutonium oxide with a surface area of 200 cm$^2$/g can absorb 30 mg water per gram of oxide
  - Plutonium oxide heated to 650°C in vacuum can retain about 1 mg water per gram of oxide

Calculations: For untreated material containing 30 mg water per gram of oxide, complete reaction would yield $1.67 \times 10^{-3}$ mole hydrogen gas per gram material or, in specific storage of 4.5 kg PuO$_2$ in 1.85 liter volume, a total pressure of 1,695 psia.

For stabilized oxide the maximum is 56.5 psia. Complete reaction of water with PuO$_2$ is difficult to rationalize and may not occur (Pu Storage, p C2).
VOLUMETRIC EXPANSION
GAS GENERATION POTENTIAL

- Hydrogen and oxygen from water by radiolysis
  - \( \text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2} \text{O}_2 \)
  - Calculated pressures are 1.5 times that for chemical reaction

Calculations: For untreated material, 1.5 times 1,695 psia = 2543 psia

For treated material, 1.5 times 56.5 psia equals 84.7 psia (Pu Storage, p C2)
VOLUMETRIC EXPANSION
GAS GENERATION POTENTIAL

- Thermal desorption of water
  - Uncharacterized material can release as much as 20 mg water per gram of material
  - External heat source and uniform heating to 200°C required to realize this release

Calculations: Release and vaporization of 20 mg water per gram of PuO₂, results in vaporization of 1.11 mole of water per kilogram of material. The 4.5 kg of material in a 1.85 liter can results in a pressure rise of 1,130 psia at 200°C (Pu Storage, p C3)
ELECTROMAGNETIC RADIATION FROM PLUTONIUM

- Four sources:
  - Gamma radiation from alpha decay
  - Internal conversion x-rays (beta–gamma radiation)
  - Gamma radiation from spontaneous fission
  - Gamma radiation from fission product decay

- Gamma radiation from alpha decay dominates as the radiation hazard from plutonium
Conclusions: Americium dominates the surface dose rate 2 years after processing, and continues to grow linearly for 10-20 years after processing.

(1) Table (Table 7 of Figure 3, p. 53, T1, thick source)
(2) Table (Table 7 of Figure 3, p. 53, T1, thick source)

<table>
<thead>
<tr>
<th>Days After Chemical Separation</th>
<th>Pu</th>
<th>Am</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4x10^-7</td>
<td>2x10^-1</td>
</tr>
<tr>
<td>0.10</td>
<td>0.10</td>
<td>0.096</td>
</tr>
<tr>
<td>0.004</td>
<td>0.0006</td>
<td>0.0005</td>
</tr>
<tr>
<td>0.001</td>
<td>0.75</td>
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</tr>
<tr>
<td>0.0001</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Activity (Ci/g)</th>
<th>Surface Dose Rate (Rads/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu239</td>
<td>4x10^-7</td>
<td>2x10^-1</td>
</tr>
<tr>
<td>Pu240</td>
<td>1x10^-6</td>
<td>2x10^-5</td>
</tr>
<tr>
<td>Pu241</td>
<td>1x10^-6</td>
<td>2x10^-6</td>
</tr>
<tr>
<td>Pu242</td>
<td>1x10^-6</td>
<td>2x10^-6</td>
</tr>
<tr>
<td>Pu243</td>
<td>1x10^-6</td>
<td>2x10^-6</td>
</tr>
<tr>
<td>Pu244</td>
<td>1x10^-6</td>
<td>2x10^-6</td>
</tr>
<tr>
<td>Am241</td>
<td>1x10^-6</td>
<td>2x10^-6</td>
</tr>
</tbody>
</table>

Plutonium Isotopes and Americium Daughter Gamma (From Alpha Decay) Radiation From
**GAMMA (FROM ALPHA DECAY) RADIATION FROM FISSILE ISOTOPES**

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Source of Surface Dose Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium – 233</td>
<td>Alpha decay</td>
</tr>
<tr>
<td>Uranium – 235</td>
<td>Nearly stable</td>
</tr>
<tr>
<td>Plutonium – 239</td>
<td>Alpha decay</td>
</tr>
<tr>
<td>Plutonium – 241</td>
<td>Dominated by Americium – 241 Daughter after 2 years</td>
</tr>
<tr>
<td>Neptunium – 237</td>
<td>Dominated by short lived protoactinium (Pa–233) Decaying to Uranium–233</td>
</tr>
</tbody>
</table>
CRITICALITY

OPERATIONAL CONTROLS

- Packaging and transportation

DOE Order 5480.3 Subject: Safety requirements for the packaging and transportation of hazardous materials, hazardous substances, and hazardous wastes.

Example References:

Title 10 CFR 71, "Packaging of Radioactive Material for Transport"

Title 49 CFR 109 – 199 "Hazardous Materials Regulations"

PACKAGING AND TRANSPORTATION

Shipping: categories and limits

- Fissile Class I: packages that may be transported in unlimited numbers and in any arrangement

- Fissile Class II: packages with a fissile content that may be transported in any arrangement but in numbers that do not exceed a transport index of 50. For nuclear criticality control, packages may have a transport index of not less than 0.1 and not more than 10.

- Fissile Class III: shipments of packages that are controlled in transportation by special arrangements between shipper and carrier to provide nuclear criticality safety
CRITICALITY
OPERATIONAL CONTROLS

- Operations: criticality safety operating limits (CSOLs)
  - Areas of operation
  - Postings
PLUTONIUM – SPECIFIC CONSEQUENCES
CONTAMINATION

- Surface contamination
  - Vulnerabilities
  - Surveys and findings. Over 25% of occurrences within material deficiencies are contamination

- Events leading to contamination
  - Historical operations leave residues that may surface as contamination
  - Stored materials with loss of barriers
  - Deactivation/shutdown operations that disrupt immobilized plutonium

- Stack monitors: Radiological monitoring complying with the Clean Air Act
PLUTONIUM – SPECIFIC CONSEQUENCES EXPOSURE

- As Low As Reasonably Achievable, ALARA
  - Process: Apply improvements to reduce dose to workers following a specified cost–benefit number
  - Spend up to 1,000 dollars to reduce worker exposure by 1 rem per year (RFP ALARA, 7/15/91, ALARA Program Manual)
  - However, this is not a DOE–wide policy. The RADCON Manual is the DOE document for ALARA
PLUTONIUM – SPECIFIC CONSEQUENCES EXPOSURE (Continued)

- Badge dosimeter
  - Ionizing radiation detector
  - Slow neutron detector
  - Inability to measure alpha activity

- Selective alpha air monitor
  - Position air flow to draw activity to the detector
  - Portable monitors to validate the safety of new operations
PLUTONIUM – SPECIFIC CONSEQUENCES
ENVIRONMENTAL INSULT

- Pathways
  - Soil contamination through spills and defective drains
  - Air emissions through stacks
  - Air emissions through accidents

- Environmental monitoring
  - Instruments
  - Detection limits
  - Historical record
# Inhalation Dose Factors and Air Emersion Dose Rate Factors for Plutonium and Other Isotopes*

<table>
<thead>
<tr>
<th>Radio-Nuclide</th>
<th>Specific Activity (Ci/g)</th>
<th>Inhalation Dose Factors</th>
<th>Air Emersion Dose Rate Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CEDE (rem/ci)</td>
<td>CEDE (rem/g)</td>
</tr>
<tr>
<td>U-233</td>
<td>5.81E+07</td>
<td>9.64E-03</td>
<td>1.30E+08</td>
</tr>
<tr>
<td>Np-237</td>
<td>7.82E+08</td>
<td>7.04E-04</td>
<td>4.90E+08</td>
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<tr>
<td>Pu-236</td>
<td>1.04E+03</td>
<td>5.32E+02</td>
<td>1.60E+08</td>
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<tr>
<td>Pu-237</td>
<td>4.53E+01</td>
<td>1.22E+04</td>
<td>1.60E+03</td>
</tr>
<tr>
<td>Pu-238</td>
<td>3.20E+04</td>
<td>1.71E+01</td>
<td>4.60E+08</td>
</tr>
<tr>
<td>Pu-239</td>
<td>8.81E+06</td>
<td>6.20E-02</td>
<td>5.10E+08</td>
</tr>
<tr>
<td>Pu-240</td>
<td>2.39E+06</td>
<td>2.28E-01</td>
<td>5.10E+08</td>
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<tr>
<td>Pu-241</td>
<td>5.26E+03</td>
<td>1.03E+02</td>
<td>1.00E+07</td>
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<tr>
<td>Pu-242</td>
<td>1.37E+08</td>
<td>3.94E-03</td>
<td>4.80E+08</td>
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<tr>
<td>Am-241</td>
<td>1.58E+05</td>
<td>3.43E+00</td>
<td>5.20E+08</td>
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<tr>
<td>Am-242m</td>
<td>5.55E+04</td>
<td>9.72E+00</td>
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<tr>
<td>Cm-242</td>
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<td>3.31E+03</td>
<td>1.70E+07</td>
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<tr>
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<td>1.04E+04</td>
<td>5.16E+01</td>
<td>3.50E+08</td>
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<tr>
<td>Cm-244</td>
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<td>8.09E+01</td>
<td>2.70E+08</td>
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<tr>
<td>Cm-245</td>
<td>3.10E+06</td>
<td>1.72E-01</td>
<td>5.40E+08</td>
</tr>
<tr>
<td>Cm-246</td>
<td>1.73E+06</td>
<td>3.07E-01</td>
<td>5.40E+08</td>
</tr>
<tr>
<td>Cm-247</td>
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<tr>
<td>Cm-248</td>
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<td>4.24E-03</td>
<td>1.90E+09</td>
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<tr>
<td>Cf-248</td>
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<tr>
<td>Cf-250</td>
<td>4.78E+03</td>
<td>1.09E+02</td>
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<tr>
<td>Cf-251</td>
<td>3.29E+05</td>
<td>1.58E+00</td>
<td>5.60E+08</td>
</tr>
<tr>
<td>Cf-252</td>
<td>9.64E+02</td>
<td>5.37E+02</td>
<td>1.30E+08</td>
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<tr>
<td>Cf-253</td>
<td>1.78E+01</td>
<td>2.90E+04</td>
<td>3.00E+06</td>
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<tr>
<td>Cf-254</td>
<td>6.05E+01</td>
<td>8.49E+03</td>
<td>2.80E+08</td>
</tr>
</tbody>
</table>

1. Specific Activity
2. Committed Effective Dose Equivalent
3. Effective External Dose Rate

* Ref: DOE/EH-70 External Dose Rate Conversion Factors for Calculation of Dose to the Public
   DOE/EH-71 Internal Dose Conversion Factors for Calculation of Dose to the Public
A.5.8

Plutonium Packaging and Storage Case Studies

by

J.M. Haschke
DEPARTMENT OF ENERGY
PLUTONIUM ES&H VULNERABILITY ASSESSMENT
ASSESSMENT TEAM TRAINING

April 19–21, 1994
Colorado Springs, Colorado

PLUTONIUM PACKAGING AND STORAGE
CASE STUDIES

John M. Haschke
CASE STUDIES IN PLUTONIUM STORAGE

Safe and secure storage of weapons grade plutonium will be necessary until a final disposition option is implemented.

- awareness of potential hazards
- use risk-reducing practices
- vigilant attitude

Valuable resources are available.

- extensive experience from storage of metal in pits
- other experience gained from storing plutonium as metal and oxide (case studies)
CONTRIBUTORS TO VULNERABILITY IN STORAGE

Knowns

A. Material Form and Properties
B. Storage Configuration
C. Operational Configuration

Unknowns

A. Inadequate Knowledge
   - Material form and properties
   - Storage and operational configurations
     - existence and accuracy of labeling and information
     - possible changes and the kinetics of those changes

B. Possible Consequences of Diagnostic and Remediative Actions (fire, criticality etc)

Capabilities (to address unknowns and to remediate knowns)

A. Technical
   - Diagnosis and characterization
   - Technology development and procedures
   - Facilities and specific equipment

B. Administrative
   - Resources (fiscal and personnel)
   - Permitting and compliance requirements
RELEVANT CHEMICAL PROPERTIES

Plutonium Metal (Pu):
- reacts slowly (not pyrophoric) with oxygen in air to form oxide
- reacts readily with hydrogen to form hydride
- hydride reacts rapidly with oxygen (hydrogen-catalyzed oxidation)
- oxidation of Pu accompanied by more than 100% increase in solid volume

Plutonium Dioxide (PuO$_2$):
- molecules (e.g. water, organic compounds) adsorb on surfaces of oxide particles
- surface molecules desorb when heated
- surface molecules radiolyze / react to form gases (e.g. hydrogen, methane) that do not adsorb
- desorption, radiolysis and reaction generate gas pressure
HAZARD ASSESSMENT

Primary storage hazard is the potential for dispersing plutonium oxide particles.

Metal:
- not a dispersible material form -- must first be converted to oxide
- oxidation (expansion) in storage container can cause rupture and release

Oxide:
- normally exists as a highly dispersible powder
- pressurization of storage container by gases can cause rupture and release

Can such processes actually cause releases from storage containers?
Plutonium Storage - Case Study #1
December 1992

Incident: Rupture of container in storage.

- Initial configuration -
  [Diagram showing initial configuration of the container]

- early processes -
  [Diagram showing processes like breathing and pinhole]

- catastrophic failure -
  [Diagram showing PuO₂ and the contaminated storage bin]

Exterior of Al inner can contaminated
Double-bagged in PVC
Latex seal on "food-pack" can
Packaged/stored in air
2.2 kg, 20% 240-Pu
Packaged in 1985

Radiolytic decay of bagging
Oxidation/hydriding of Pu
Atmospheric "breathing" aids
Gas and particle transport
Corrosive products (HCl) amplify problem
3 g mass gain by 1990

Pu totally oxidized
Radial pressure exerted by oxide
Inner can destroyed
Outer can ruptured
Wedged in storage shelf
Storage bin contaminated

One-point failure (of food-pack can seal)

Direct cause: Oxidation of Pu metal ingot within a confined space.

Underlying factors: Many. Use of organic material, failure to provide adequate free volume, inadequate seal, failure to certify seal, others.
Plutonium Storage - Case Study #2
January 1993

Incident: Energetic release of material on opening.

- initial configuration -
  Polyethylene bagging, probably two layers
  Lead-lined outer can, tape sealed
  5 kg Pu metal
  Packaged in 1984

- early processes -
  Radiolytic decay of bagging creates hydrogen
  Hydrogen reacts with Pu to form PuH_{2+x}
  Bag embrittles

- catastrophic release -
  Oxide
  Opened in hood (air)
  Pulling embrittled bag causes massive breach
  Hydride spontaneously reacts with oxygen
  Hood, operator contaminated

No physical failure mechanism, intrinsic errors in packaging

Direct cause: Exposure of pyrophoric hydride to air

Underlying factors: Many. Use of organic material, 'first surface' of organic material, handling in oxidizing environment, short-term storage extended to long-term with no repackaging, inadequate documentation, others.
Plutonium Storage - Case Study #3
August 1979

Incident: Breach of storage container in shipping.

- initial configuration -
- shipping configuration -
- as opened configuration -

PuO₂, calcined from nitrate (several kg)
Reactor-grade, higher 238 content than previous shipments
PVC bagging
"Food-pack" outer can
Packaged just prior to shipment

AL-M6 shipping container (55-gallon drum)
150 °C max on liner surface
42 W max heat load

Pressurization of container
Container ruptured
Thermal desorption/pyrolysis of impurities
Insulation of container aggravated problem
All procedures and limits satisfied

No physical failure mechanism, intrinsic errors in packaging
Direct cause: Pressurization of primary storage container
Underlying factors: excessive adsorbates on oxide, inadequate heat transfer
during shipment, inadequate technical assessment, false-sense of security
from compliance, others.
**Plutonium Storage - Case Study #4**

1986

**Incident:** Unexpected ignition and complete oxidation of Pu metal component.

- **Sample Process History**
  - Hollow sphere of plutonium metal
  - Oil-filled for criticality testing
  - Oil remained in sphere for at least several days
  - Oil drained from sphere on completion of tests

- **Interim Storage Configuration**
  - Sphere bisected, no cleaning attempted
  - Hemisphere stored on cork-ring stand in ambient air glovebox (thermal insulator)
  - Hydrogen from radiolytic decay reacts with Pu
  - Pyrophoric hydride passivated by film of oil, immediate reaction inhibited
  - Left overnight in this configuration

- **As Found Condition**
  - Oil thins or reacts to a point which no longer inhibits reaction
  - Pyrophoric hydride burns rapidly in air
  - Heat of reaction raises entire component temperature above 500 °C
  - Bulk metal ignites, burning to completion
  - Heat release sufficient to breach glove, crack window

**No physical failure mechanism, intrinsic errors in handling**

**Direct cause:** Ignition of pyrophoric hydride and subsequent ΔT sufficient to ignite bulk sample

**Underlying factors:** Intimate contact between Pu and organic material for extended period of time, improper interim storage (air environment, thermally insulated), inadequate technical assessment, others.
Plutonium Storage - Case Study #5

January 1981

Incident: violent rupture of oxide storage container in vault

- initial configuration -
- interim storage -
- as found condition -

Packaged in May 1979 (21 months old)
225 grams PuO₂ as pressed compact
"sweepings" added
organic lubricant present from compaction
dual food pack cans
polyethylene bagging

walk-in vault with shelf storage
storage wells for criticality safety
radiolytic decomposition of organics
hydrogen, methane, etc. formed
continuing pressurization

alpha contamination alarm activated
package propelled upward and onto floor
top of outer can dented
visible residue of 1m² area
> 10⁶ DPM over large vault area
clean-up cost: $43k

No physical failure mechanism, intrinsic errors in packaging
Direct cause: Pressurization of primary storage container
Underlying factors: excessive organics with oxide, inadequate sample characterization, inadequate technical assessment, small sample size improperly assessed nonhazardous, others.
CONCLUSIONS AND RECOMMENDATIONS

Potential dispersal hazards exist for both stored metal and oxide.

Case-study evaluations suggest that the risk can be greatly reduced.

- exclude all organic materials from the storage package
- prepare and certify materials for storage
- require certified seals for containers
- provide capability for surveillance, repackaging and emergency (problems will occur despite our best efforts)
  - research and development (our current knowledge is incomplete)
  - facility for extracting and processing (extraction will be needed because of problems, political decisions and several disposition options)
  - competent personnel (knowledgeable and experienced people are essential)

These recommendations are consistent with the excellent experience of storing plutonium metal in pits.
A.5.9

Airborne Release Fraction

by

D. Bennett
DEPARTMENT OF ENERGY
PLUTONIUM ES&H VULNERABILITY ASSESSMENT

ASSESSMENT TEAM TRAINING

April 19-21, 1994
Colorado Springs, Colorado

AIRBORNE RELEASE FRACTION

Dr. David Bennett
AIRBORNE RELEASE FRACTIONS

QUALITATIVE OVERVIEW

FRACTION OF SOURCE RELEASED TO ATMOSPHERE
KEY FACTOR FOR ESTIMATING DOSE
AVAILABLE FOR ATMOSPHERIC TRANSPORT TO TARGET

COMPLEX PHENOMENA & PROCESSES
CHEMICAL
PHYSICAL
AERODYNAMIC
MULTIPLE RELEASE FRACTION DEFINITIONS

SEVERAL DEFINITIONS USED

FRACTION OF TOTAL (ORIGINAL) SOURCE QUANTITY
RELEASED TO ATMOSPHERE

OR

FRACTION OF DISPERSIBLE SOURCE QUANTITY
RELEASED TO ATMOSPHERE

DISPERSIBLE SOURCE QUANTITY
USUALLY SMALL FRACTION OF TOTAL QUANTITY

ALL USED IN VARIOUS ASSESSMENTS
RELEASE SEQUENCE

SOURCE QUANTITY

LOSS OF CONFINEMENT

FRACTION RELEASED FROM SOURCE

TRANSPORT FROM SOURCE TO ATMOSPHERE

ULTIMATE FRACTION RELEASED TO ATMOSPHERE

ATMOSPHERIC TRANSPORT

UPTAKE BY TARGET

DOSE
RELEASE PHENOMENOLOGY

COMPLEX & COMPETING PROCESSES

PARTICLE SIZE DISTRIBUTIONS
  DISPERSIBLE FRACTION
  RESPIRABLE FRACTION

CHEMICAL & PHYSICAL FORMS

ENERGY SOURCES (FIRES, ETC)
  AFFECT BOTH PARTICLES AND THEIR MOVEMENT

INITIAL MATERIAL CHARACTERISTICS
  METAL, OXIDE, SOLUTION
  DO NOT REMAIN CONSTANT DURING THE RELEASE

ACCIDENT ENVIRONMENTS
  TEMPERATURE, TURBULENCE, HUMIDITY, ETC
  INTENSITY, DURATION
AEROSOL TRANSPORT WITHIN FACILITY

PARTICLE SIZE DISTRIBUTION
Each bin (size range) can behave differently

COMPETING PROCESSES DURING TRANSPORT
Addition and removal mechanisms for each bin

DEPENDENT ON TRANSPORT CONDITIONS
Flow velocity
Plateout surfaces
Humidity, static, etc

MULTIPATH TRANSPORT

INTERACTION WITH OTHER AEROSOLS
AEROSOL PROCESSES

AGGLOMERATION

CONDENSATION

DIFFUSION

SEDIMENTATION - SETTLING

RESUSPENSION

COMBUSTION & OXIDATION

ADHESION ON SURFACES - PLATEOUT
   SURFACE CHARACTERISTICS, STATIC

IMPACCTION
   UNDER HIGH VELOCITY FLOW CONDITIONS
AEROSOL PROPERTIES

AFFECT AERODYNAMIC BEHAVIOR
IN FLOW STREAM, SETTLING

NOT JUST HIGH DENSITY PLUTONIUM OXIDE PARTICLES
ADHESION, AGGLOMERATION WITH OTHER AEROSOLS
WATER, SMOKE

COMPLEX SHAPES
ESPECIALLY SMOKE PARTICLES (CARBON CHAINS)
LARGE, BUT LOW DENSITY
BUT NEED SMALL PARTICLES FOR DEEP LUNG DEPOSITION

FINAL CHEMICAL FORM AFFECTS UPTAKE BY TARGET
SOLUABLE/INSOLUABLE
RELEASE FRACTION SUMMARY

FOR MOST ACCIDENTS
COMPLEX PHENOMENA
COMPETING PROCESSES

MANY REMOVAL MECHANISMS

HIGH LEVEL, QUALITATIVE OVERVIEW
A.5.10

Airborne Release Fraction

submitted by

J. Mishima
DEPARTMENT OF ENERGY
PLUTONIUM ES&H VULNERABILITY ASSESSMENT

ASSESSMENT TEAM TRAINING

April 19-21, 1994
Colorado Springs, Colorado

AIRBORNE RELEASE FRACTION

Jofu Mishima
**MAR** = Material-at-Risk, inventory in a physically definable, separate location/space, curies.

**DR** = Damage Ratio, that fraction of the **MAR** that is impacted by the event.

**ARF** = Airborne Release Fraction, the fraction of the ([MAR] [DR]) that is made airborne at point of origin.

**RF** = Respirable Fraction, the fraction of the **ARF** that is respirable. For particles (solid and liquid), particles that are 10 micrometers Aerodynamic Equivalent Diameter (AED) and less. AED is the sphere of density 1 g/cm³ that has the same terminal velocity (aerodynamic behavior) as the particle. All materials in the gaseous state (non-condensable gases or vapors) are transportable and respirable and, for the purposes of analysis, the **RF** is 1.0.

**LPF** = Leak Path Factor, the fraction of the **ARF** transported to the containment/confine ment - ambient atmosphere interface. For particles in the respirable size range, assuming an infinite duration, essentially all the particles will be released depending on the physical configuration of the containment/confine ment. For directional air exhaust systems, airborne materials are assumed to be attenuated if a collection device specifically design for the material (e.g. HEPA filter, impregnated-charcoal or silver substituted-zeolite, cryogenic removal) are in the flow path.
* radionuclides separated from ambient atmosphere by barriers - facility structure, gaseous effluent treatment system, enclosures, equipment, containers, etc.

* source term generated by interaction between two complex physicochemical processes - event initiator & material response.

* characteristics of physicochemical processes determine material generation - conditions that result in penetration/breach of barriers and fragmentation/deagglomeration and suspension of material-of-concern.
PHYSICAL FORMS

* NON-CONDENSIBLE GASES - ASSUME LOSS OF CONTAINMENT OR GENERATION. RELEASES ALL MATERIALS IN GASEOUS STATE. NOT ALWAYS EASY.

* VOLATILE - PHYSICOCHEMICAL ENVIRONMENT FOR GENERATION VAPOR.

* LIQUIDS - AQUEOUS OR ORGANIC (COMBUSTIBLE); SOLUTIONS, SLURRIES, VISCIOUS.

* SOLIDS - METAL, BRITTLE, POWDER.

* CONTAMINATED MATERIALS - COMBUSTIBLE OR NON-COMBUSTIBLE SOLID SUBSTRATE, LIQUIDS, COLLECTION DEVICES, STRUCTURAL SURFACES.
INITIATOR EVENTS/STRESSES

* EARTHQUAKE/VIBRATION

* TORNADO/EXTERIOR PRESSURE

* EXPLOSIONS -
  - DETONATION & PHYSICAL ANALOGUE/SHOCK & BLAST EFFECTS
  - DEFLAGRATION & PHYSICAL ANALOGUE/BLAST EFFECTS

* FIRE/HEAT AND GASEOUS PRODUCTS (PRESSURE)

* AERODYNAMIC ENTRAINMENT, RESUSPENSION -
  - HOMOGENEOUS (THICK BED > 2 PARTICLE DIAMETER DEEP)
  - HETEROGENEOUS (SPARSE BED, CONTAMINATION)

* OTHERS/FREE-FALL SPILLS
### SUMMARY TABLE
AIRBORNE RELEASE FRACTIONS (ARFs) AND RESPIRABLE FRACTIONS (RFs)
FOR ACCIDENT ANALYSIS

<table>
<thead>
<tr>
<th>LIQUIDS</th>
<th>&quot;Best Estimate&quot; ARF/ARR; RF</th>
<th>&quot;Bounding&quot; ARF/ARR; RF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aqueous Solutions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>*** Thermal Stress**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- evaporation/simmering</td>
<td>6E-7; 1.0</td>
<td>3E-5; 1.0</td>
</tr>
<tr>
<td>- boiling</td>
<td>1E-3; 1.0</td>
<td>2E-3; 1.0</td>
</tr>
<tr>
<td>*** Releases by Explosions**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Shock Effect</td>
<td>-</td>
<td>g inert: g TNT Eq</td>
</tr>
<tr>
<td>- Blast Effect</td>
<td>-</td>
<td>4E-3/hr X t; 1.0</td>
</tr>
<tr>
<td>*** Venting of Pressurized Liquids**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Failure Below Liquid Level</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) liquid below boiling point of water</td>
<td>-</td>
<td>1E-4; 1.0</td>
</tr>
<tr>
<td>(b) 50° to 100° C superheat</td>
<td>2E-2; 0.7</td>
<td>1E-1; 0.7</td>
</tr>
<tr>
<td>(c) &gt; 100° C superheat</td>
<td>2E-2; 0.7</td>
<td>0.33 (MF)0.91</td>
</tr>
<tr>
<td>- Failure Above Liquid Level</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) Dissolved gases in equilibrium with gases in free volume</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Pressure 0.345 MPa or less</td>
<td>5E-5; 0.8</td>
<td></td>
</tr>
<tr>
<td>- Pressure 0.345 &lt;Pa to 3.5 MPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- density 1.0 g/cm³</td>
<td>2E-3; 0.3</td>
<td></td>
</tr>
<tr>
<td>- density 1.3 g/cm³</td>
<td>1E-3; 0.4</td>
<td></td>
</tr>
<tr>
<td>(b) Liquids greater than 50° C superheat</td>
<td>-</td>
<td>(see above)</td>
</tr>
<tr>
<td>- Rapid pressurization-depressurization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) Greater than Critical Freeboard Height</td>
<td></td>
<td>(negligible)</td>
</tr>
<tr>
<td>(b) Less than Critical Freeboard Height</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Free-Fall Spill of Liquids</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Solutions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) fall distance &lt;3m</td>
<td>4E-5; 0.7</td>
<td>2E-4; 0.7</td>
</tr>
<tr>
<td>(b) fall distance &gt;3m</td>
<td>-</td>
<td>(see text)</td>
</tr>
<tr>
<td>- Slurries, &lt;3m fall distance, &lt;50% solids</td>
<td>2E-5; 0.7</td>
<td>5E-5; 0.8</td>
</tr>
<tr>
<td>- Viscous liquids, &gt; 8 cp, &lt;3m</td>
<td>6E-6; 0.8</td>
<td>3E-5; 0.7</td>
</tr>
</tbody>
</table>

* - - evaporation/simmering
- - boiling
* - - Shock Effect
- - Blast Effect
* - - Failure Below Liquid Level
(a) liquid below boiling point of water
(b) 50° to 100° C superheat
(c) > 100° C superheat
- - Failure Above Liquid Level
(a) Dissolved gases in equilibrium with gases in free volume
   - Pressure 0.345 MPa or less
   - Pressure 0.345 <Pa to 3.5 MPa
     - density 1.0 g/cm³
     - density 1.3 g/cm³
   (b) Liquids greater than 50° C superheat
- Rapid pressurization-depressurization
   (a) Greater than Critical Freeboard Height
   (b) Less than Critical Freeboard Height
* - - Free-Fall Spill of Liquids
- Solutions
   (a) fall distance <3m
   (b) fall distance >3m
- Slurries, <3m fall distance, <50% solids
- Viscous liquids, > 8 cp, <3m
**Aerodynamic Entrainment/Resuspension**

- Indoors, hard unyielding surface, nominal air velocities - 4E-7/hr; 1.0
- Indoors, cover debris or static conditions - 4E-8/hr; 1.0
- Outdoors, large pool, windspeed < 30 mph - 4E-6/hr; 1.0
- Outdoors, soil, windspeed < 50 mph - 4E-5/hr; 1.0
- Outdoors, hard unyielding surface, windspeed < 50 mph - 4E-3/hr; 1.0

Organic, Combustible Liquids

**Thermal Stress (combustion with/without aqueous sublayer)**

- Volatiles, under all conditions - 1E+0; NA
- Non-volatiles
  (a) Small pool fire, quiescent burning #6E-3; 1.0 1E-2; 1.0
  (b) Large pool, vigorous burning - 3E-2; 1.0
  (c) Burned to dryness 1E-2; 1.0 1E-1; 1.0
  (d) Outdoors, aq. soln or a.d. salts under burning fuel, non-heat conducting surface - #5E-3; 0.4
  (e) Outdoors, aq. soln. or a.d. salts under burning fuel, heat conducting surface - #2E-1, 0.3

[See response aqueous solutions above for comparable stresses for remaining phenomenon.]

**SOLIDS**

**Metal that can self sustain oxidation at elevated temperature**

**Thermal Stress**

- Plutonium
  (a) corrosion, room temperature
    unalloyed Pu, dry air 2 X 10^-4 micrograms Pu/cm^2-hr
    unalloyed Pu, 100% RH 7 X 10^-3 micrograms Pu/cm^2-hr
    delta-phase Pu, dry air 7 X 10^-4 micrograms Pu/cm^2-hr
    delta-phase Pu, 100% RH 6 X 10^-4 micrograms Pu/cm^2-hr
  (b) oxidation at elevated temperature 3E-5 X fract. oxid.; 1.0
  (c) self sustained oxidation 1E-5; 0.5 5E-4; 0.5
  (d) falling molten drops/disturbed surface 4E-3; 1.0 1E-2; 1.0
  (e) explosive airborne reaction molten metal, rapid
vapor formation
- Uranium
  (a) complete oxid. metal, 0 to 20 cm/s gas flow, >500° C
    "median" 1E-4; 1.0 - 95% "Y" class + 5% "D" class
    "bound" 1E-3; 1.0 - 95% "Y" class + 5% "D" class
  (b) falling molten drops/disturbed surface
    "median" 2E-3; 1.0 - 50% "Y" class + 50% "D" class
    "bound" 6E-3; 1.0 - 50% "Y" class + 50% "D" class
  (c) explosive dispersal of molten metal
    "bound" 1E+0; 1.0 - 50% "Y" class + 50% "D" class

* Releasing by Explosions
  - Shock Effects
  - Blast Effects (no significant effect postulated)

* Venting of Pressurized Gases Over Metal
  (see Venting Pressurized Powders for fraction of loose corrosion products present
  that can be made airborne)

* Free-Fall Spill
  (see Thermal Stress, falling molten drops for Pu and U metal, above)

* Aerodynamic Entrainment/Resuspension
  (see Aerodynamic Entrainment of Powders for fraction of loose corrosion that
  can be airborne.)

Powders

* Thermal Stress, oxidation & suspension by
  - Non-Reactive Compounds - 6E-3; 0.01
  - Reactive Compounds - 1E-2; 0.001
  - PuF₄ - 1E-3; 0.001

* Explosive Releases
  - Shock Effect 0.8 g inert/g TNT Eq, RF 0.25
  - Blast Effects
    (a) parallel to surface - 5E-3; 0.3
    (b) deflagration above, limited - 1E-1; 0.7
    (c) deflagration above, large - 1E+0; -
      volume reactants, "unconfined" vapor cloud
      strong flow directly impacts material, severe turbulence

* Venting Pressurized Powders
  (a) pressure 0.17 MPa or
      and less - 5E-3; 0.3
  (b) pressure >0.18 MPa but
      3.5 MPa or less 5E-2; 0.4 1E-1; 0.5

* Free-Fall Spill
  (a) slug flow of powder
      fall distance <3m 4E-4; 0.5
      fall distance >3m 3E-3; 0.6
      (see text)
(b) dispersed powder flow into flowing air ($U =$ local windspeed in m/s)
(c) suspension powder by impact of powder held in a can 
(d) turbulence generated by falling debris 
(e) mechanical shock-vibration

* Aerodynamic Entrainment/Resuspension
(a) thin layer powder
(b) thin layer powder, buried under debris or indoors static volume
(c) vehicular traffic, through or by freshly deposited powder

SURFACE CONTAMINATION (sparse contamination, < 2 $D_p$, thick bed over < 25% surface)

Solid, Combustible Substrate

* Thermal Stress
- Contained mixed waste
- Uncontained (a) mixed waste
(b) cellulosics
(c) polychloropene (elastomer, rubber)
(d) polymethylmethacrylate (Lucite, benex)
(e) polystyrene (polyethylene, IX resin)

* Explosive Releases
- Shock Effect (no significant release postulated)
- Blast Effect

* Free-Fall Spill/
Mechanical Shock

* Venting of Pressurized Gas over Contamination (no data)

* Aerodynamic Entrainment/Resuspension
- nominal flow conditions, < 5 m/s
- buried under debris, indoors static conditions

Solid, Non-Combustible Substrate (hard, unyielding surface)

* Thermal Stress (effect loose corrosion products on exposed surfaces)
* **Explosive Releases**
  - Shock Effect
  - Blast Effect
  
  loose contamination on exposed surfaces

* **Venting of Pressurized Gases Over Material**
  
  loose contamination on exposed surfaces

* **Free-Fall Spill/Brittle Fracture**

* **Mechanical Shock-Vibration**
  
  (loose contamination on exposed surfaces)

* **Aerodynamic Entrainment/Resuspension**
  - nominal flow conditions
  - buried under debris, indoor

  static conditions

**HEPA Filters**

* **Thermal Stress**
  
  (passage of hot gases)

* **Explosive Releases**
  - Shock Effect
  - Blast Effect

* **Free-Fall Spill/Crush-Impact**
  a. uncontained (direct impact by
  b. contained (not directly impacted

  g inert/g TNT Eq
  (use powder values)

  2E-11 [rho] [g] [h]

  1E-3; 0.2

  4E-5/hr; 1.0

  4E-6/hr; 1.0

  1E-4; 1.0

  2E-6; 1.0

  9E-3; 1.0

  1E-2; 1.0

  5E-4; 1.0
Effect of Surface Area on Plutonium Ignition Temperatures

Dependence of Uranium Ignition on Specific Area (Baker, Schnizlein and Bingle 1966)
A.5.11

An Overview of Applicable Standards/Orders

by

J.L. Boccio
DEPARTMENT OF ENERGY
PLUTONIUM ES&H VULNERABILITY ASSESSMENT

ASSESSMENT TEAM TRAINING

April 19–21, 1994
Colorado Springs, Colorado

AN OVERVIEW OF APPLICABLE STANDARDS/ORDERS

John L. Boccio
MODULE PURPOSE

- Provide a general overview
  - Plutonium facilities orders

- Instill awareness
  - Current operations
  - Future operations/transition
  - Mission changes
  - Safety envelope (existing/modified)

- Enhance knowledge base for vulnerability assessment
  - Not a compliance audit
STANDARDS, WHAT ARE THEY?

Standards – expressed expectations for performance of
- Health/safety activities
- Safeguard/security activities
- Environmental protection activities

Use of applicable standards
- Reduces uncertainty
- Controls hazards
- Increases predictability
  - Work plans
  - Schedule estimates
  - Safety precautions
  - Other control activities

Types of Standards
- Technical
- Management
- Performance
Technical standards
- Expectations that relate to the performance of physical systems
- Include highly prescriptive regulations
- Establish measurable compliance criteria
- Examples
  - Material properties
  - Testing methods

Management standards
- Expectations that define administrative controls necessary for efficient, safe, reliable, and cost-effective operation
- Include systems to assess effectiveness of organization
- Provide corrective actions
- Examples
  - Occurrence reporting systems
  - Self assessment
  - Document control

Performance standards
- Expectations that relate to performance of individuals
- Examples
  - Conduct of operations/maintenance
  - Safeguards/security
  - Quality assurance
LEVEL 1 DOE ORDERS

- Protect health/safety
  - Worker
  - Public

- Protect environment

- Provide specific requirements

- Invoke other laws/standards
  - Consensus standards such as
    American National Standards Institute
    National Electric Code
    National Fire Protection
<table>
<thead>
<tr>
<th>DOE Orders for environmental control</th>
<th>5400 series</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOE Orders for nuclear safety</td>
<td>5480 series</td>
</tr>
<tr>
<td>DOE Orders for security interests</td>
<td>5600 series</td>
</tr>
<tr>
<td>DOE Orders for emergency preparedness</td>
<td>5500 series</td>
</tr>
</tbody>
</table>

Summaries provided in backup material
DOE ORDERS FOR SECURITY PROTECTION

MAINLY 5600 ORDER SERIES

- DOE Order 5632.2A, "Physical Protection of Special Nuclear Material and Vital Equipment," established the DOE policy for the protection of special nuclear material (SNM) and critical equipment, including nuclear reactors and baselines requirements and standards for those security interests.

- DOE Order 5660.1A, "Management of Nuclear Materials," establishes requirements that cover preparation of the materials management plan (MMP), a planning document providing analyses of available nuclear materials and those required for multi-year planning periods.

- DOE Order 5633.3A, "Control and Accountability of Nuclear Materials," prescribes the DOE minimum requirements and procedures for control and accountability of nuclear materials of DOE-owned and leased facilities and DOE-owned nuclear materials of other facilities which are exempt from licensing by the NRC.
SUMMARY

Many federal laws and DOE orders affect activities at plutonium facilities. The orders highlighted (not inclusive) were categorized as:

- Administrative/facilities
- Environmental compliance
- Safeguards and security
- Emergency preparedness
- Waste management

An awareness of the requirements in these orders will help in the assessment process.
A.5.12

Safety Analysis Report (SAR) Review Process

Findings Related to Plutonium Vulnerabilities

by

J.L. Boccio
SAFETY ANALYSIS REPORT (SAR) REVIEW PROCESS
-FINDINGS RELATED TO PLUTONIUM VULNERABILITIES-

John L. Boccio
MODULE PURPOSE

To provide attendees with an overview of current issues that may pertain to plutonium storage facilities that were identified through the SAR review process

To provide attendees with an awareness of the general nature of these issues and steps being taken for resolution

To provide, via examples, how these issues were identified through the DOE safety assurance process
SAFETY ANALYSIS

- Assessment of facility hazards, including identification of dominant accident scenarios
- Demonstration of adequate level of safety for workers, public, environment
- Analysis of potential upset conditions and corrective or compensatory measures taken
### THE THREE BASIC RISK ASSESSMENT QUESTIONS

- **WHAT CAN HAPPEN?**
- **HOW LIKELY IS IT?**
- **WHAT IS THE DAMAGE?**

<table>
<thead>
<tr>
<th>ANALYSIS METHOD</th>
<th>SCENARIO DEFINITION</th>
<th>SCENARIO QUANTIFICATION</th>
<th>CONSEQUENCE ASSESSMENT</th>
<th>FORM OF RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUALITATIVE</td>
<td>SYSTEMATIC LISTS</td>
<td>JUDGMENTAL ESTIMATES OF THE FREQUENCY RANGE</td>
<td>JUDGMENTAL ESTIMATES OF THE DAMAGE LEVEL</td>
<td>RANKED SCENARIO LISTS</td>
</tr>
<tr>
<td>QUANTITATIVE</td>
<td>COMPREHENSIVE LOGIC MODELS</td>
<td>SCENARIO FREQUENCY AND CONFIDENCE LEVEL CALCULATED</td>
<td>DAMAGE MAGNITUDE AND CONFIDENCE LEVEL CALCULATED</td>
<td>RISK CURVES WITH RANKED CONTRIBUTORS</td>
</tr>
</tbody>
</table>
SAFETY ENVELOPE

Safety envelope defines the condition under which the facility can be operated safely
- Design basis
- Safety analyses

Technical safety requirements (TSRs) define and document these conditions
- Safety limits
- Operating limits (LCO)
- Surveillance requirements
- Administrative controls

Safety management
- Conduct of operations
- Management structure
- Radiation protection
- Emergency preparedness
- Document control
DOE MECHANISM OF SAFETY ASSURANCE

Performance of the following linked activities
(1) Hazard identification
(2) Hazard evaluation
(3) Quantitative accident analyses
(4) Reviews of safety analysis reports (SARs)

Activities define facility control in
(1) Safety structures, system and components
(2) Technical safety requirements
(3) Programmatic commitments, e.g., QA program

Activities performed in accordance with
(1) DOE Order 5480.23 – Nuclear Safety Analyses Reports
(2) DOE-STD-1027-92 – Hazard categorization and accident analyses technique or compliance with DOE Order 5480.23, Nuclear Safety Analysis Report
(3) Select industrial references, e.g., AICLE – Guidelines for Chemical Process Quantitative Risk Analyses
SAFETY ANALYSIS REPORT (SAR) REVIEW GUIDANCE

- Source – document #NS–20.1, 4 October 1991

- Guidance element categories
  - Verify conformance with appropriate DOE Orders
  - Assess adequacy of SAR content
  - Verify SAR hazard classification
  - Determine acceptability of OSRs and LCOs
  - Determine appropriateness of modeling assumption
  - Review process/waste management plan
  - Review fire/material hazard analyses
ACCEPTABILITY OF OSRs/LCOs
- BASIC CONSIDERATIONS -

- Design features for facility/process systems/safety systems
- Compatibility of process variable with design
- Minimum set of functional variables required to control normal and upset conditions
- Process variables that could initiate DBA conditions
- Operational readiness/availability/reliability of confinement barriers that prevent uncontrolled release
- Support system dependencies that could affect front-line system performance
ACCEPTABILITY OF OSRS AND LCOS
- BASIC CONSIDERATIONS -

- Are they properly developed from safety analysis results?
  - Consider design features of facility/process/safety systems

- What is the basis of OSR?
  - Determine correctness
  - Compatibility of process variables with process design
  - Verify if objectives are met
DETERMINING ACCEPTABILITY OF OSRs AND LCOs
- BASIC CONSIDERATIONS -
(Continued)

- What is the minimum set of functional variables required?
  - Normal
  - Abnormal
  - Accident

- What are the contingency plans for cases where limits not met?

- What process variables could:
  - Initiate DBAs conditions
  - Challenge system integrity
  - Degrade liability of passive safety supplies (barriers)
DETERMINING ACCEPTABILITY OF OSRs AND LCOs – SUPPLEMENTARY CONSIDERATIONS –

- Are process flow diagrams consistent and with OSR/LCO requirements?
- Are support system adequately addressed?
- Does building configurations reflect current seismic calculations?
- Do proposed effluents comply with guidelines?
SAR REVIEW/WALKDOWN PROCESS
- LESSONS LEARNED -

- Perceived efficiency of aged HEPA fillers under accident conditions
  - Studies underway to enhance database
- Visual fissile material accumulation in glovebox exhaust
  - Condition monitoring program development
- Vulnerabilities to single failures of components
  - Ineffective CAS monitoring/surveillance procedures
  - Lack of redundancy of tank isolation systems
SUMMARY

The vulnerability assessment process should utilize information and knowledge gained from past studies in evaluating safety assurance. The SAR review process as delineated by NS was instrumental in these fact finding endeavors.
<table>
<thead>
<tr>
<th>Key Element</th>
<th>Requirements Summary</th>
</tr>
</thead>
</table>
| Security Requirements for Category I Quantities of SNM | 1. SNM shall be handled only in a material access area or in a controlled and alarmed process enclosed within a protected area.  
2. SNM shall be stored only in SNM vaults or vault-type rooms protected with DOE-approved intrusion alarm systems.  
3. SNM shall be used or handled under material surveillance procedures.  
4. A sufficient number of security inspectors shall respond to a verified intrusion alarm to contain and/or neutralize the adversaries within the specified time delays.  
5. SNM shall be controlled to prevent theft or diversion by a single authorized individual.  
6. Any individual who could steal sabotage, divert or conceal Category I quantity of SNM shall have a "Q" access authorization. |
### Security Requirements for Category II Quantities of SNM

<table>
<thead>
<tr>
<th>Security Requirement</th>
<th>Key Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. SNM shall be handled in a protected area.</td>
<td></td>
</tr>
<tr>
<td>2. SNM shall be stored only in SNM vaults or vault-type rooms protected with DOH-approved intrusion alarm systems.</td>
<td></td>
</tr>
<tr>
<td>3. SNM shall be used or handled under material surveillance procedures.</td>
<td></td>
</tr>
<tr>
<td>4. Security inspections shall respond to verified intrusion alarms per the site security plan or MSSA.</td>
<td></td>
</tr>
<tr>
<td>5. SNM shall be controlled to prevent theft or diversion by a single authorized individual.</td>
<td></td>
</tr>
<tr>
<td>6. Any individual who could steal equipment, divert or conceal Category I quantities of SNM shall have an &quot;O&quot; access authorization.</td>
<td></td>
</tr>
</tbody>
</table>
### Security Requirements for Category III Quantities of SNM

<table>
<thead>
<tr>
<th>Key Element</th>
<th>Requirements Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. SNM shall be handled in a protected area or other security area with:</td>
<td></td>
</tr>
<tr>
<td>a. clearly defined perimeter barriers</td>
<td></td>
</tr>
<tr>
<td>b. personnel and vehicle access controlled by a security personnel</td>
<td></td>
</tr>
<tr>
<td>c. personnel identification per DOE 5632.9</td>
<td></td>
</tr>
<tr>
<td>d. visitors log</td>
<td></td>
</tr>
<tr>
<td>e. signs prohibiting trespassing posted at the perimeter</td>
<td></td>
</tr>
<tr>
<td>f. signs prohibiting the introduction of prohibited articles and authorizing inspections/searches of vehicles, packages, or persons entering or exiting.</td>
<td></td>
</tr>
<tr>
<td>2. SNM can be left unattended in a locked DOE approved security container or within a locked room with DOE approved intrusion detection system, or patrolled at least every 2 hours. Or if the container is located in a protected area.</td>
<td></td>
</tr>
<tr>
<td>3. SNM can handled by properly cleared employees or escorted visitors.</td>
<td></td>
</tr>
<tr>
<td>4. Protective forces shall respond to a verified security alarm per the site safeguards and security plan or MSSA.</td>
<td></td>
</tr>
<tr>
<td>Security Requirements for Category IV Quantities of SNM</td>
<td>Key Element</td>
</tr>
<tr>
<td>--------------------------------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>1. SNM can be handled per the security plan.</td>
<td></td>
</tr>
<tr>
<td>Requirements Summary</td>
<td></td>
</tr>
<tr>
<td>dated 2-9-88 with update of 1-17-89</td>
<td></td>
</tr>
<tr>
<td>&quot;Physical Protection of Special Nuclear Material and Vulnerable Equipment&quot;</td>
<td></td>
</tr>
<tr>
<td>DOE Order 5632.2A</td>
<td></td>
</tr>
<tr>
<td>Key Element</td>
<td>Requirements Summary</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Miscellaneous Security Requirements</td>
<td>1. Access controls, intrusion detection shall be in accordance with paragraph 12</td>
</tr>
<tr>
<td></td>
<td>2. Intrusion detection and assessment systems shall be in accordance with paragraph 12.b</td>
</tr>
<tr>
<td></td>
<td>3. Communications equipment shall be in accordance with paragraph 12.c</td>
</tr>
<tr>
<td>Key Element</td>
<td>Requirements Summary</td>
</tr>
<tr>
<td>-------------------------------------------------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Security Requirements for Vital Equipment</td>
<td>1. All vital equipment shall be protected from hostile activities under all conditions, a sufficient number of security inspectors shall respond to a verified intrusion alarms to contain and/or neutralize the adversaries within the specified time delays.</td>
</tr>
<tr>
<td></td>
<td>2. All vital equipment shall be contained within a defined vital area within a protected area.</td>
</tr>
<tr>
<td></td>
<td>3. Access controls, intrusion detection shall be in accordance with paragraph 12 of 5632.2A</td>
</tr>
</tbody>
</table>
### General Security Requirements

**PURPOSE:** To "prescribe the DOE policy for the protection of special nuclear material (SNM) and vital equipment, including nuclear reactors, and to establish baseline requirements and standards for those security interests."

<table>
<thead>
<tr>
<th>Key Element</th>
<th>Requirements Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. <strong>SNM facility approval</strong> approval shall be obtained before any SNM can be received, used, processed, or stored at a facility.</td>
<td>1. SNM facility approval shall be obtained before any SNM can be received, used, processed, or stored at a facility.</td>
</tr>
<tr>
<td>2. <strong>The security provided shall be consistent with the guidance issued by the</strong> Assistant Secretary for DP.</td>
<td>2. The security provided shall be consistent with the guidance issued by the Assistant Secretary for DP.</td>
</tr>
<tr>
<td>3. <strong>Physical protection systems within each category of SNM shall be established with considerations of ease of accessibility and concealment, portability, radioactivity, or other controlling factors.</strong></td>
<td>3. Physical protection systems within each category of SNM shall be established with considerations of ease of accessibility and concealment, portability, radioactivity, or other controlling factors.</td>
</tr>
<tr>
<td>4. <strong>Security of SNM and vital equipment shall be against:</strong> a. theft or unauthorized removal of SNM from a material access or protected area, or from a shipment</td>
<td>4. Security of SNM and vital equipment shall be against: a. theft or unauthorized removal of SNM from a material access or protected area, or from a shipment</td>
</tr>
<tr>
<td>b. diversion, unauthorized placement of SNM within a material access or protected area</td>
<td></td>
</tr>
<tr>
<td>c. radiological sabotage of SNM or vital equipment</td>
<td></td>
</tr>
<tr>
<td>d. industrial sabotage of SNM or vital equipment</td>
<td></td>
</tr>
<tr>
<td>5. <strong>An interface between physical security and nuclear material control needs to be satisfied per DOE 5633.3.</strong></td>
<td>5. An interface between physical security and nuclear material control needs to be satisfied per DOE 5633.3.</td>
</tr>
<tr>
<td>6. <strong>The protection afforded SNM shall be graded according to the NM safeguards category per DOE 5633.3A.</strong></td>
<td>6. The protection afforded SNM shall be graded according to the NM safeguards category per DOE 5633.3A.</td>
</tr>
<tr>
<td>7. <strong>Vital equipment shall be identified by the field element.</strong></td>
<td>7. Vital equipment shall be identified by the field element.</td>
</tr>
<tr>
<td>8. <strong>Nuclear reactors and fuel shall be protected from theft, diversion, sabotage consistent with the SNM's category.</strong></td>
<td>8. Nuclear reactors and fuel shall be protected from theft, diversion, sabotage consistent with the SNM's category.</td>
</tr>
<tr>
<td>Key Element</td>
<td>Requirements Summary</td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>---------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>10. The potential for the theft of Category II quantities of SNM from more than one location that could result in a Category I quantity shall be analyzed. The number of actions and time required for these actions shall be determined.</td>
</tr>
<tr>
<td></td>
<td>11. Sufficient protective force personnel shall be available to man access control points and alarm stations and to perform required security functions per DOE 5632.7.</td>
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<td></td>
<td>12. Security related equipment shall be protected from unauthorized access.</td>
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<td>13. Emergency backup power shall be provided for security systems protecting Category I and II SNM and vital equipment.</td>
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<td></td>
<td>14. All SNM shall be protected per its Category classification.</td>
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<td>15. Controls shall be established to deter unauthorized access to security areas or removal of SNM or vital equipment.</td>
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<td>16. Access shall be limited to personnel with appropriate authority and who require access.</td>
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<td></td>
<td>17. Any attempts, suspected attempts, or actual removal or sabotage of SNM or vital equipment shall be reported per DOE 5631.5.</td>
</tr>
</tbody>
</table>
**DOE Order 5633.3A**

"Control and Accountability of Nuclear Materials."
dated 2-12-93; supersedes 5633.3 dated 2-3-88

<table>
<thead>
<tr>
<th>Key Element</th>
<th>Requirements Summary</th>
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<tbody>
<tr>
<td>General Guidance</td>
<td>PURPOSE: &quot;prescribe the DOE minimum requirements and procedures for control and accountability of nuclear materials at DOE-owned and leased facilities and DOE-owned nuclear materials at other facilities which are exempt from licensing by the NRC&quot;. EXCLUSIONS: Nuclear materials at DOD or foreign facilities. KEY DEFINITIONS:</td>
</tr>
</tbody>
</table>
|                      | MC&A: Material control and accountability  
|                      | RIS: Reporting Identification Symbol  
|                      | VA: Vulnerability Assessment  
|                      | SNM: Special Nuclear Materials  
|                      | NM: Nuclear Materials  
<p>|                      | MBA: Material Balance Area |</p>
<table>
<thead>
<tr>
<th>Requirement Summary</th>
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<tbody>
<tr>
<td>Contol and Accountability of Nuclear Materials</td>
<td>DOE Order 5633.4</td>
</tr>
<tr>
<td>M66A Program</td>
<td>1</td>
</tr>
<tr>
<td>Program Planning and Management</td>
<td>Performance Criteria</td>
</tr>
<tr>
<td>Material accountability system</td>
<td>Physical Inventories</td>
</tr>
<tr>
<td>Material accountability system</td>
<td>Measures tailored to implementation for each facility following:</td>
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<tr>
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<td>An approved, graded M66A program for the control of nuclear</td>
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<td>materials (including inside) with separable multiphase</td>
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<td>Surplus</td>
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<td>Containment</td>
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<td>Anomaly resolution</td>
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<tr>
<td>Initial data and accountability system access control</td>
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<tr>
<td>Security when M66A system components are inappropriate</td>
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<tr>
<td>Time</td>
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<tr>
<td>Loss detection controls</td>
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Date: 12-93

Supersedes 5633.4 dated 2-93

"Contol and Accountability of Nuclear Materials"
<table>
<thead>
<tr>
<th>Key Element</th>
<th>Requirements Summary</th>
</tr>
</thead>
</table>
| MC&A Program | 2. Administrative assurances for MC&A plans shall include:  
Procedures reviews and approvals  
Limiting access to nuclear materials accounting system and data  
Identification of data entry problems and any responsible person(s)  
Determination of nuclear materials accounting system completeness  
Review and assessment of MC&A system integrity and quality  
Reviews of new and changed facilities or operations prior to start-up  
Audits of facility MC&A by an organization independent of the MC&A.  
Responsibilities for MC&A functions shall be documented. A 3 letter RIS shall be assigned to each facility.  
A documented performance testing program per DOE 5630.16  
One facility management official shall be designated as being responsible for the MC&A. |
<p>|             | 3. The SNM Category level shall be determined for each location per DOE 5633.3A. |
|             | 4. New and renovated facilities shall incorporate state-of-the-art MC&amp;A technologies, systems and approaches. |</p>
<table>
<thead>
<tr>
<th>Key Element</th>
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<tbody>
<tr>
<td>MC&amp;A Program</td>
<td>5. SNM can be removed from the inventory and MC&amp;A books per DOE 5633.3A. It shall be removed to a storage or disposal area containing only discardable material.</td>
</tr>
<tr>
<td></td>
<td>6. MC&amp;A shall be maintained during a decommissioning, closure, or deactivation and can be terminated only when remaining material has an attractiveness of E and all of the other material has been written off the MC&amp;A books.</td>
</tr>
<tr>
<td></td>
<td>7. Each facility shall report occurrences as Emergency, Unusual Occurrence, or Off-Normal Occurrence per DOE 5000.3B.</td>
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<td></td>
<td>8. The MC&amp;A plan requirements for the Category III and IV facilities will be determined by the Manager, Field Office.</td>
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<td></td>
<td>9. Facility emergency plans shall consider the loss of control of SNM per DOE 5500.1B.</td>
</tr>
<tr>
<td></td>
<td>10. Appropriate ATSM and ANSI standards shall be used for NM control, measurement and measurement control, accounting, and statistical methods, except when directed by DOE. IAEA and NRC standards shall be used when appropriate.</td>
</tr>
</tbody>
</table>
### Materials Management Plan

This order covers the preparation of the Materials Management Plan (MMP), a planning document prepared annually providing analyses of available nuclear materials and those required over the ensuing multi-year planning period. The preparation of the MMP is the responsibility of the DOE with input from the contractors.

### Key Definitions:

- **Scrap NM** is unirradiated but is not usable in its existing form, i.e. it requires chemical treatment to render it useful.
- **Usable Excess NM** is not suitable for any programmatic use in its existing form. It usually covers spent fuel and scrap.
- **Usable Excess NM** is suitable for use in its present form.

- **"E" Material** is unusable excess nuclear material for which DP-27 has the management responsibility. Usually sources: (1) economically recoverable unirradiated scrap or (2) spent fuel not scheduled for recovery.

- **"M" Material**. Usable excess NM in a form suitable for direct introduction into production processes for which DP-27 has management responsibility.

This order consists of 8 chapters dealing with:

1. **Forecasting Nuclear Material Requirements**
   - This Chapter describes the procedures for preparing the future requirements for nuclear material, a Field Office responsibility.

2. **Materials Management Plan**
   - The field offices shall determine a Materials Management Plan covering 11 ensuing fiscal years.

3. **Studies and Plans**
   - Guidelines for DOE requested studies.

4. **Nuclear Materials Allotments**
   - Determines how much NM is assigned to each B... field office for either management purposes or projects.

5. **Optimization of Nuclear Material Inventories**
   - Determine the most cost-effective flow of material to maintain inventories appropriate with DOE programs. This is a Field Office and HQ responsibility.
<table>
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<tr>
<th>Key Element</th>
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</table>
| Materials Management Plan         | 6. Inactive Materials  
Field Offices shall identify excess materials as "E" or "M". All excess or inactive material shall be returned to the inventory ASAP.  
7. Materials Management Appraisals  
Field Offices and contractors shall be subject to periodic review and evaluation of its Materials Management.  
8. Miscellaneous Activities  
Miscellaneous handling activities by the contractors.  
The MMP determines the supply and usage schedules for nuclear materials for each of the 11 fiscal years that the MMP covers. There are three main aspects to the plan:  
1. NM Supply Schedules include:  
   Beginning inventory  
   Reactor production  
   Receipts  
   Removals (losses and transfers)  
   Ending inventory  
2. NM Usage Schedules include: *  
   Beginning inventory  
   Receipts  
   Removals *  
   Ending inventory  
3. Materials Reported and Units include:  
The type of material handled and its weight. |
The Materials Management Appraisals of the contractors by the Field Offices is to provide management with feedback concerning:

- The effectiveness of the Management Plan
- The quality of the performance
- The adequacy and effectiveness of established policies and procedures and actions necessary to improve the program.
- An assurance that the contractors' staff understand the MMP and the appraisal
- A determination that the contractors are utilizing the NM optimally and within the MMP
- A determination of the effectiveness of the contractors program.

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<td>Materials Management Appraisals</td>
<td>The Materials Management Appraisals of the contractors by the Field Offices is to provide management with feedback concerning:</td>
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<td>- The adequacy and effectiveness of established policies and procedures and actions necessary to improve the program.</td>
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<td>- A determination of the effectiveness of the contractors program.</td>
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<td>Key Element</td>
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<tr>
<td>Effective (including cost effectiveness) NM management is attained through contractors' administrative procedures.</td>
<td>1.</td>
</tr>
<tr>
<td>A 10 character Project Number shall be assigned by DOE which provide a link between nuclear material quantities and related financial data. The Nuclear Materials Management and Safeguards System at Oak Ridge, Tennessee shall maintain a master list of project numbers and titles. The list shall be distributed annually or when major changes are made.</td>
<td>2.</td>
</tr>
<tr>
<td>The Nuclear Materials Management and Safeguards System at Oak Ridge, Tennessee shall maintain a data base of the DOE's NM inventory. This data base contains the list of the inventory, coded to indicate the NM's status and present use.</td>
<td>3.</td>
</tr>
<tr>
<td>For Pu all aspects of management control apply which includes Inventory Reporting, Requirements Forecasts, Materials Management Plan, Allocation Control, Inventory Assessment, and Appraisals.</td>
<td>4.</td>
</tr>
<tr>
<td>General Guidelines</td>
<td>Requirements Summary</td>
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<tr>
<td><strong>PURPOSE:</strong> To provide general design criteria (GDC) for use in the acquisition of the Department’s facilities and to establish responsibilities and authorities for the development and maintenance of these criteria.</td>
<td>1. Packaging materials and packaged materials shall be kept to a minimum.</td>
</tr>
<tr>
<td><strong>Applicability:</strong></td>
<td>2. No hazardous gases or liquids shall be used in PSFs.</td>
</tr>
<tr>
<td>All general requirements in Section 1300 apply to Plutonium Storage Facilities (PSFs)</td>
<td>3. Only storage related materials and equipment shall be stored in the PSF.</td>
</tr>
<tr>
<td>The PSFs section 6430.1A applies to PSFs that will contain a Category I quantity of Plutonium.</td>
<td>4. Combustible packaging materials shall be stored in metal containers away from the PSF where a fire would not endanger the PSD.</td>
</tr>
<tr>
<td><strong>Exemptions:</strong></td>
<td>5. Inadvertent entry to hazardous areas shall be controlled with visual or auditory alarms, or other warning systems or interlocks.</td>
</tr>
<tr>
<td>Material in process or in use.</td>
<td>6. An automated vault surveillance system shall be provided where excessive radiation exposure would result from entering for material control and accountability purposes.</td>
</tr>
<tr>
<td>Material packaged per DOE 5480.3 and is awaiting transportation or has been received and is awaiting disposition.</td>
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<td>Key Element</td>
<td>Requirements Summary</td>
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<tr>
<td>Nuclear Criticality Safety</td>
<td>1. StandardANS 8.6 shall apply.</td>
</tr>
<tr>
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<td>2. Designs shall be consistent with NRC Reg. Guide 3.43.</td>
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<tr>
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<td>3. Favorable geometry is the preferred method for limiting criticality potential.</td>
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<td>4. Fixed neutron absorbers shall be considered.</td>
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<td>Rack design shall assure continued effectiveness.</td>
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<td>Prevention of removal by mechanical or chemical action.</td>
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<td></td>
<td>5. Storage racks shall continue to function following a DBE or any DBA.</td>
</tr>
<tr>
<td></td>
<td>6. Liquid waste storage tanks and transfer lines shall have concentrations below critical limits.</td>
</tr>
<tr>
<td>Key Element</td>
<td>Requirements Summary</td>
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<td>-----------------------------------</td>
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</tr>
<tr>
<td>Special Storage Requirements</td>
<td>1. Aqueous solutions of Pu can be stored if instrumentation is provided to detect precipitate solids buildup, if they are expected to occur, and if the solids can be removed.</td>
</tr>
<tr>
<td></td>
<td>2. Storage racks shall be noncombustible</td>
</tr>
<tr>
<td></td>
<td>3. Storage racks shall be designed to securely hold storage containers in place, ensure proper separation of containers, and maintain structural integrity under normal operations, anticipated operational occurrences, and DBA conditions.</td>
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<tr>
<td></td>
<td>4. Storage racks shall be designed as safety class items.</td>
</tr>
<tr>
<td></td>
<td>5. Bumpers shall provide rack protection from handling equipment.</td>
</tr>
</tbody>
</table>
General Confinement Considerations

1. The confinement guidelines of Section 1305-5.1 give general provisions. The actual confinement design requirements is determined on a case-by-case basis.

2. Shall suit the most restrictive hazards anticipated.

3. Single barrier confinement may be suitable for material in a form that is not readily dispersible.

4. Multiple barrier confinements are required if the form of the plutonium is readily dispersible.

5. Qualified shipping packages may not be considered to be barriers.

6. For the most restrictive cases, the use of 3 confinement systems shall be considered:
   - Primary - Storage container or cladding
   - Secondary - Individual compartments with ventilation
   - Tertiary - Building structure with ventilation

7. Operation of support and protection systems, such as fire protection shall not promote the failure of the principal confinement systems.

8. Cooling systems shall be provided as needed.

9. Exhaust ventilation systems shall be provided with HEPA filtration.

10. Inlet ventilation systems shall be provided with either HEPA filtration or fail-safe backflow prevention.

11. PSF systems, components, and structures shall be designed to provide confinement of radioactive materials under normal operations, anticipated operational occurrences, and the DBA conditions they are required to withstand. Releases to the environment shall be meet the guidelines of DOE 6430.1A, section 1300-1.4.

<table>
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<tr>
<td>General Confinement Considerations</td>
<td>1. The confinement guidelines of Section 1305-5.1 give general provisions. The actual confinement design requirements is determined on a case-by-case basis.</td>
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<td>2. Shall suit the most restrictive hazards anticipated.</td>
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<td>3. Single barrier confinement may be suitable for material in a form that is not readily dispersible.</td>
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<td></td>
<td>4. Multiple barrier confinements are required if the form of the plutonium is readily dispersible.</td>
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<td></td>
<td>5. Qualified shipping packages may not be considered to be barriers.</td>
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<td>6. For the most restrictive cases, the use of 3 confinement systems shall be considered: Primary - Storage container or cladding Secondary - Individual compartments with ventilation Tertiary - Building structure with ventilation</td>
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<td></td>
<td>7. Operation of support and protection systems, such as fire protection shall not promote the failure of the principal confinement systems.</td>
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<td>8. Cooling systems shall be provided as needed.</td>
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<td>9. Exhaust ventilation systems shall be provided with HEPA filtration.</td>
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<td>11. PSF systems, components, and structures shall be designed to provide confinement of radioactive materials under normal operations, anticipated operational occurrences, and the DBA conditions they are required to withstand. Releases to the environment shall be meet the guidelines of DOE 6430.1A, section 1300-1.4.</td>
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<td>Requirements Summary</td>
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<tr>
<td>Primary Confinement</td>
<td>1. Consists of shielding or storage containers</td>
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<td>2. Shall provide primary containment during normal operation, anticipated operational occurrences, and for all of its DBAs.</td>
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<td>3. Shall prevent a corrosion resistant confinement for fuel assemblies</td>
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<td>4. Handling systems shall ensure safe introduction, removal, and handling of stored plutonium.</td>
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### Secondary Confinement

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<tr>
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<th>Requirements Summary</th>
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<tbody>
<tr>
<td>1.</td>
<td>Shall be consist of compartments within a building</td>
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<tr>
<td>2.</td>
<td>The level of compartmentalization needed to keep the quantity of stored materials within safe limits shall be determined by a safety analysis.</td>
</tr>
<tr>
<td>3.</td>
<td>Shall be designed to function during normal operations, anticipated operational occurrences, and all of its DBAs.</td>
</tr>
<tr>
<td>4.</td>
<td>Shall be designed as safety class and capable of performing its necessary functions following a DBE.</td>
</tr>
<tr>
<td>5.</td>
<td>Penetrations shall have positive seals to prevent migration of contamination.</td>
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<tr>
<td>6.</td>
<td>Safety analysis shall be used to determine any special ventilation needs.</td>
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<tr>
<td>7.</td>
<td>Each compartment shall have ventilation from the building system and shall have a pressure negative with respect to the building.</td>
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<tr>
<td>8.</td>
<td>Exhaust ventilation shall be sufficient to ensure an adequate ventilation flow in the event of a credible breach in the compartment barrier.</td>
</tr>
<tr>
<td>9.</td>
<td>Access through compartment barriers shall be through the use of access ways such as airlocks and enclosed vestibules.</td>
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<td>Key Element</td>
<td>Requirements Summary</td>
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<tr>
<td>Tertiary Confinement</td>
<td>1. This is made up of the facility building and its ventilation system.</td>
</tr>
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<td></td>
<td>2. The building is not required to be protected from missiles but shall be designed to prevent a massive collapse of building structures or the dropping of heavy objects onto the stored plutonium as a result of building structural failures.</td>
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<td></td>
<td>3. It shall be designed to remain functional to the extent that the guidelines in DOE 6430.1A section 1300-1.4.2 are not maintained.</td>
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<tr>
<td></td>
<td>4. Penetrations shall have positive seals to prevent migration of contamination.</td>
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<td></td>
<td>5. Air locks or enclosed vestibules shall be provided for access through confinement barriers.</td>
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### Key Element: Facility Layout

<table>
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<tbody>
<tr>
<td>1. The design shall accommodate all planned plutonium handling activities.</td>
</tr>
<tr>
<td>2. Unpacking activities (from shipping containers) shall occur in unpackaging room(s).</td>
</tr>
<tr>
<td>3. PSFs shall not be heated directly with natural gas, unless heating occurs in a separate, isolated building.</td>
</tr>
<tr>
<td>4. Layout shall provide for efficient cleaning, maintenance, and inspection.</td>
</tr>
<tr>
<td>5. Facility design shall facilitate identification, inventory, placement, and retrieval of storage containers.</td>
</tr>
<tr>
<td>6. Door locations shall be coordinated with aisles to facilitate access, loading and unloading operations, for use of fire fighting equipment, and for compliance with NFPA 101.</td>
</tr>
<tr>
<td>7. Layout shall accommodate taking of inventories including any measurements required for verification or confirmation per DOE 5633.3.</td>
</tr>
<tr>
<td>Key Element</td>
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<td>---------------------------------</td>
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</table>
| Effluent Control and Monitoring | 1. Solid material contaminated with radioactive material shall be handled, stored, and packaged for transport in a safe manner including: Collection, Packaging, Inventory, Storage, Assay equipment, Appropriate facilities for volume reduction, Monitoring.  
2. Liquid industrial wastes, such as mop sink discharge, shall be collected and transferred to a liquid waste treatment, or equivalent, facility.  
3. Liquid treatment shall be per DOE 5400 series.  
4. Decontamination wastes shall be collected and monitored near the source of generation before transfer to the liquid waste treatment facility or area.  
5. Liquid waste storage tanks lines shall have: Stirrers or mixing devices, Sampling devices, Volume measuring devices, Transfer systems, Leak detection and containment.  
6. Waste transfer lines shall have: Leak detection and containment, Inspection/collection pits which are gravity fed, Double walled or multi-pipe encasements per DOE 6430.1A, Section 1300-7.4.  
7. Confinement ventilation systems shall be designed to remove particulate material, vapors, and gases as needed per DOE 6430.1A, Section 1300-1.4.3.  
8. If an outlet may contain plutonium it shall be provided with two monitoring systems per DOE 6430.1A, Section 1589-99.0.1. |
PROCESS EVALUATION FOR NUCLEAR CRITICALITY SAFETY SHALL:
1. be performed for subcriticality under both normal and credible conditions prior to starting new or revised operation.
2. determine and explicitly identify the controlled parameters and their associated limits.
3. be documented with sufficient detail, clarity, and lack of ambiguity to allow independent judgements of the results.
4. be confirmed by independent assessment.
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<tr>
<td>Technical Practices</td>
<td>1. The mass and distribution of the nuclear and surrounding materials, that control the effective multiplication shall be managed to key the system subcritical.</td>
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<td>2. Double Contingency Principle: The system shall be designed so that at least two unlikely, independent and concurrent changes would occur that would allow the system to become critical.</td>
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<td>3. Equipment shall be designed for the control of dimensions, so that critical assemblies cannot be created.</td>
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<td>4. Neutron absorbers can be used, but strict control shall assure their continued presence and effectiveness.</td>
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<td>5. Subcritical limits shall be determined, preferably by experimental data. If experimental data does not exist, then validated calculations can be used.</td>
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<tr>
<td>Validation of Calculational Methods</td>
<td>1. Correlation of results with criticality experiments.</td>
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<td>2. Margins of subcriticality shall include uncertainties in the parameters along with uncertainties in the extensions beyond the areas of validation.</td>
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<td>3. Computer programs should have the mathematical operations confirmed. After changes, the programs shall be reconfirmed.</td>
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<td>4. The areas of the calculations' applicability may be extended beyond the validated areas if trends in the results can be established. If the extension is large, other calculational methods should be used for comparison.</td>
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<td>5. Nuclear properties, such as cross sections, shall be consistent with experimental measurements.</td>
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<td>6. Validation of the computer programs shall be reported in writing. The report shall include:</td>
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<td>a. Sufficient detail and clarity to allow independent duplication of results.</td>
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<td>b. A statement of the computer programs used along with the methodology for choosing mesh points, cross section sets, and any other numerical inputs.</td>
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<td>c. Identification of experimental data used for validation.</td>
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<td>d. A statement of the area(s) of applicability.</td>
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<td></td>
<td>e. A statement of the bias and prescribed margin of subcriticality over the area(s) of applicability.</td>
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<td>f. A basis for the margin of subcriticality.</td>
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<tr>
<td>Key Element</td>
<td>Requirements Summary</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>----------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Management Responsibilities</td>
<td>MANAGEMENT:</td>
</tr>
<tr>
<td></td>
<td>1. shall accept overall responsibility for safety of operations. Continuing interest in safety should be evident.</td>
</tr>
<tr>
<td></td>
<td>2. shall formulate criticality safety policy and make it known to all employees involved in operations with fissile material.</td>
</tr>
<tr>
<td></td>
<td>3. shall assign responsibility and delegate authority to implement established policy.</td>
</tr>
<tr>
<td></td>
<td>4. shall provide personnel familiar with the physics of nuclear criticality and with associated safety practices to furnish technical guidance appropriate to the scope of operations.</td>
</tr>
<tr>
<td></td>
<td>5. shall establish a means for monitoring the criticality safety program.</td>
</tr>
<tr>
<td></td>
<td>6. shall participate in periodic audits of the overall effectiveness of the criticality safety program.</td>
</tr>
<tr>
<td></td>
<td>7. may use consultants and criticality safety committees to achieve the objectives of the criticality safety program.</td>
</tr>
<tr>
<td>Requirement Summary</td>
<td>Key Element</td>
</tr>
<tr>
<td>---------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Supervisory Responsibilities</td>
<td>1. Shall accept responsibility for the safety of operations under his control.</td>
</tr>
<tr>
<td></td>
<td>2. Shall be knowledgeable in those aspects of critically safety relevant to operations under his control.</td>
</tr>
<tr>
<td></td>
<td>3. Shall ensure personnel are trained and knowledgeable of procedures and safety considerations so their functions can be performed without undue risk.</td>
</tr>
<tr>
<td></td>
<td>4. Shall maintain records of training activities and verification of personnel understanding.</td>
</tr>
<tr>
<td></td>
<td>5. Shall help develop written procedures for operations under their control.</td>
</tr>
<tr>
<td></td>
<td>6. Shall verify compliance with critically safety specifications for new or modified equipment before its use.</td>
</tr>
<tr>
<td></td>
<td>7. Shall require compliance with good safety practices.</td>
</tr>
</tbody>
</table>
**NUCLEAR CRITICALITY SAFETY STAFF:**

1. staff shall provide technical guidance for designing equipment and processes and for developing operating procedures.

2. shall maintain familiarity with current developments in criticality safety standards, guides, and codes.

3. should consult with knowledgeable individuals to obtain technical assistance as needed.

4. shall maintain familiarity with all operations within the organization requiring criticality safety controls.

5. shall assist supervision in training personnel.

6. shall conduct or participate in audits of criticality safety practices and compliance with established procedures.

7. shall examine reports of procedural violations and other deficiencies for possible improvement of practices and procedures; shall report their findings to management.
Operating Procedures

<table>
<thead>
<tr>
<th>Key Element</th>
<th>Requirements Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Procedures</td>
<td>ESTABLISHED OPERATING PROCEDURES:</td>
</tr>
<tr>
<td>1.</td>
<td>purpose is to facilitate safe and efficient conduct of the operation. Succinct procedures should be organized and presented for convenient use by operators.</td>
</tr>
<tr>
<td>2.</td>
<td>shall include those controls and limits significant to the nuclear criticality safety of the operation.</td>
</tr>
<tr>
<td>3.</td>
<td>shall be supplemented and revised as needed.</td>
</tr>
<tr>
<td>4.</td>
<td>shall be reviewed periodically by supervision.</td>
</tr>
<tr>
<td>5.</td>
<td>shall be reviewed by the nuclear criticality staff, as appropriate, when new or revised procedures are effected.</td>
</tr>
<tr>
<td>6.</td>
<td>should be supplemented by posted nuclear criticality safety limits incorporated in operating check lists or flow sheets.</td>
</tr>
<tr>
<td>7.</td>
<td>if deviations from operating procedures or alterations in conditions affect criticality safety then they shall be documented, promptly investigated, and reported to management; action shall be taken to prevent a recurrence.</td>
</tr>
<tr>
<td>8.</td>
<td>shall be reviewed frequently to ascertain that procedures are being followed and that process conditions have not been altered so as to affect the criticality safety.</td>
</tr>
</tbody>
</table>
for "Administrative Practices for Nuclear Criticality Safety"

<table>
<thead>
<tr>
<th>Key Element</th>
<th>Requirements Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process Evaluation</td>
<td>PROCESS EVALUATION FOR NUCLEAR CRITICALITY SAFETY SHALL:</td>
</tr>
<tr>
<td></td>
<td>1. be performed for subcriticality under both normal and credible conditions</td>
</tr>
<tr>
<td></td>
<td>prior to starting new or revised operation.</td>
</tr>
<tr>
<td></td>
<td>2. determine and explicitly identify the controlled parameters and their</td>
</tr>
<tr>
<td></td>
<td>associated limits.</td>
</tr>
<tr>
<td></td>
<td>3. be documented with sufficient detail, clarity, and lack of ambiguity to</td>
</tr>
<tr>
<td></td>
<td>allow independent judgements of the results.</td>
</tr>
<tr>
<td></td>
<td>4. be confirmed by independent assessment.</td>
</tr>
</tbody>
</table>
for "Administrative Practices for Nuclear Criticality Safety"

<table>
<thead>
<tr>
<th>Key Element</th>
<th>Requirements Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials Control</td>
<td>1. The movement of fissile materials shall be controlled.</td>
</tr>
<tr>
<td></td>
<td>2. Appropriate labeling and area posting shall be maintained specifying material identification and all limits on parameters that are subject to procedural control.</td>
</tr>
<tr>
<td></td>
<td>3. Neutron absorbing materials which help control criticality shall be maintained.</td>
</tr>
<tr>
<td></td>
<td>4. Access to areas where fissile material is handled, processed, or stored shall be controlled.</td>
</tr>
<tr>
<td></td>
<td>5. Spacing, mass, density, and geometry of fissile material shall be maintained to assure subcriticality under all normal and credible conditions.</td>
</tr>
</tbody>
</table>
DOE ORDERS FOR ENVIRONMENTAL CONTROL

- DOE Order 5400.1, "General Environmental Protection Program" — Establishes environmental protection program requirements, authorities, and responsibilities for DOE operations to ensure compliance with applicable environmental protection laws, regulations, orders, and policies.

- DOE Order 5400.5, "Radiation Protection of the Public and the Environment" — Establishes revised radiation protection standards for DOE environmental activities.

- DOE Order 5440.1D, "National Environmental Policy Act Compliance Program" — Establishes hazardous waste management procedures for DOE operations that result in the generation, transportation, treatment, storage, or disposal of hazardous waste.


- DOE Order 5480.4, "Environmental Protection, Safety and Health Protection Standards" — Defines codes and standards to be applied to the design and construction of new facilities and major facility modifications.

- DOE Order 5820.2A, "Radioactive Waste Management" — Establishes policies, guidelines and minimum requirements for management of radioactive and mixed waste and contaminated facilities.
DOE ORDERS – NUCLEAR SAFETY

- DOE Order 5480.5, "Safety of Nuclear Facilities: -- establishes nuclear facility safety program requirements.
- DOE Order 5480.19, "Conduct of Operations Requirements for DOE Facilities" -- requires a graded approach to management, organization, and conduct of operations at DOE facilities to ensure an acceptable level of safety.
- DOE Order 5480.21, "Unreviewed Safety Questions," -- ensures that DOE has advance opportunity to review and approve activities that might result in an accident or malfunction.
- DOE Order 5480.22, "Technical Safety Requirements" -- ensures that DOE nuclear facilities operate within the assumptions contained in the accident analysis in their Safety Analysis Report (SAR).
- DOE Order 5480.23, "Nuclear Safety Analysis Reports" -- requires SARs to document that a facility can be operated with an acceptable degree of safety.
DOE ORDERS – FACILITY MANAGEMENT

- DOE Order 4320.2, "Capital Asset Management Process"
- DOE Order 4330.4A, "Maintenance Management Plan"
- DOE Order 4700.1, "Project Management System" — establishes a DOE project management system
- DOE Order 5480.19, "Conduct of Operations" — formalizes the methodology for conducting operations at DOE nuclear facilities
- DOE Order 6430.1A, "General Design Criteria: -- requires facilities to be designed and constructed to be reasonable and adequate for their intended purpose and consistent with health, safety, security, and environmental protection requirements
DOE ORDERS FOR OCCUPATIONAL SAFETY/HEALTH

- Priority from DOE Order 5483.1A
- Supporting orders in:
  - Industrial safety
  - Industrial hygiene
  - Construction safety
  - Occupational health

DOE Order 5483.1A: Invoices requirements of the OSHA regulations as codified in the 29 Code of Federal Regulations
<table>
<thead>
<tr>
<th>IAEA Documents</th>
<th>DOE Documents</th>
</tr>
</thead>
<tbody>
<tr>
<td>IAEA Safety Series 9 - Basic Safety Standards for Radiation Protection</td>
<td>DOE Order 5480.11 - Radiation Protection for Occupational Workers, DOE N 5480.6 - Radiation Control Manual</td>
</tr>
<tr>
<td>IAEA Safety Series 14 - Basic Requirements for Personnel Monitoring</td>
<td>DOE Order 5480.4 - Environmental, Protection Safety and Health Protection Standards, DOE Order 5480.8A Contractor Occupational Health Program, DOE N 5480.5 Imposition of Proposed Nuclear Safety Requirements, DOE N 5480.6 - Radiological Control</td>
</tr>
<tr>
<td>IAEA Safety Series 18 - Environmental Monitoring in Emergency Situations</td>
<td>40 CFR 61.93, ANS N 13.1, DOE Order 5480.11 - Radiation Protection for Occupational Worker</td>
</tr>
<tr>
<td>IAEA Safety Series 38 - Radiation Protection Procedures</td>
<td>DOE N 5480.6 - Radiation Control Manual</td>
</tr>
<tr>
<td>IAEA Safety Series 39 - Safe Handling of Plutonium</td>
<td>DOE Order 6430.1A - General Design Criteria; Chapter 13 - Plutonium Facilities</td>
</tr>
<tr>
<td>IAEA INFCIRC/225/Rev 2 - The Physical Protection of Nuclear Material</td>
<td>DOE Order 5632.2A - Physical Protection of Special Nuclear Material and Vital Equipment, DOE Order 5660.1A - Management of Nuclear Materials</td>
</tr>
</tbody>
</table>
Compliance with project storage requirements of SNM is an essential part of criticality control measures.

<table>
<thead>
<tr>
<th>Specific Requirements</th>
<th>Appropriate Orders/Standards</th>
</tr>
</thead>
</table>
| Compliance with project storage requirements of SNM is an essential part of criticality control measures. | DOE Order 5480.24, "Nuclear Criticality Safety," states that fissionable material shall be produced, processed, stored, transferred, disposed, or handled in such a manner that the probability of a criticality incident is acceptably low. The Order also provides requirements for a criticality safety program including the storage and transportation of fissile materials. Additional information concerning control of nuclear materials can be found in DOE N 5480.6, "Radiation Control Manual;" DOE Order 5633.2, "Control and Accountability of Nuclear Materials, Responsibilities, and Authorities;" DOE Order 5480.3, "Safety Requirements for the Packaging and Transportation of Hazardous Material, Hazardous Substances, and Hazardous Wastes," and DOE Order 1540.2, "Hazardous Material Packaging for Transport-Administrative Procedures."

The double-contingency principle is also invoked. This principle requires that two unlikely, independent and concurrent changes in process conditions must occur before a criticality accident is possible and that no single failure shall result in the potential for a criticality accident.
PURPOSE: This document establishes regulations for the safe transport of radioactive material.

EXEMPTIONS:

- Material that is an integral part of the means of transport.

- Within establishments where the radioactive material is produced, used or stored (except where it is stored as part of the transport),

- Human beings with radioisotope powered medical devices or treated with radiopharmaceuticals.

- If a manufactured item contains radioactive material (clocks, smoke detectors, etc) it is exempted from packaging requirements if it meets the requirements set forth in SS6.

- Any amount of natural uranium or thorium or depleted uranium can be used in a manufactured item if it is enclosed in a sheath made of metal or other suitable material.

COVERAGE:

- Sets limits for the amount of each radioactive element that can be contained in a package for transport. The limits are determined in part by the ease that the material can be dispersed. Extra criteria are listed for fissile material.

- Sets limits for the amount of package surface contamination that is allowable.

- Sets definitions of the different packaging types (type A, B, etc) and the required design considerations.

- Sets requirements for defining the transport index.

- Sets general provisions for accidents involving radioactive material, quality assurance programs, compliance assurance, radiation protection, emergency responses and special arrangements.

- Sets requirements for inspections of packages prior to shipment.

- Sets requirements for dealing with leaking packages.

- Sets requirements for marking and labeling.

- Sets requirements for transporters concerning short term storage, segregation of packages, and any special considerations for rail, road, vessels, air and other modes of transport.

- Sets testing requirements for materials and packagings.

- Sets administrative requirements for shipping.
<table>
<thead>
<tr>
<th>Key Element</th>
<th>Requirements Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PURPOSE:</strong></td>
<td>To establish safe plutonium handling techniques and facility design. This did not cover facilities handling fissionable quantities of material.</td>
</tr>
<tr>
<td><strong>COVERAGE:</strong></td>
<td>The first two chapters of this document deal with chemical and biological aspects of plutonium.</td>
</tr>
<tr>
<td><strong>FACILITY DESIGN FEATURES:</strong></td>
<td>Stairs and doors should be kept to a minimum (to avoid spills)</td>
</tr>
<tr>
<td></td>
<td>Partitions should be made of concrete, steel, or other non-flammable material that are moisture resistant and easily decontaminated.</td>
</tr>
<tr>
<td></td>
<td>Partitions define ventilation areas, so good air seal is needed.</td>
</tr>
<tr>
<td></td>
<td>Plumbing, electrical and air lines and connections should be considered as permanent structures.</td>
</tr>
<tr>
<td></td>
<td>Only one entrance per controlled area.</td>
</tr>
<tr>
<td></td>
<td>Emergency exits should be equipped with air locks.</td>
</tr>
<tr>
<td></td>
<td>Working areas should be designated with a zone number, 1 to 4. The zones should be color coded as white for Zone 1, green for Zone 2, orange/amber for Zone 3, and red for Zone 4.</td>
</tr>
<tr>
<td>Key Element</td>
<td>Requirements Summary</td>
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</tr>
</tbody>
</table>
| FACILITY DESIGN FEATURES: (continued) | Zone 1 Only minimal or no radioactivity allowed. This is for offices, counting room, mechanical services room, blower room, dark room, etc.  
Slight positive pressure, a few mm of \( \text{H}_2\text{O} \) with respect to Zone 2 with an air-lock between Zones 1 and 2. 
Zone 2 This is the support area for specialized types of work involving plutonium containing glove boxes.  
Glove boxes should be 20-50 mm \( \text{H}_2\text{O} \) negative pressure with respect to Zone 2.  
Free standing glove boxes shall use bagging for transfer of material in and out.  
\( \mu \)g quantities of Pu can be used in fume hoods with ventilation at least 50m/min.  
Zone 3 This area is for transport of materials along with maintenance and modification of glove boxes.  
Work in Zone 3 requires protective clothing.  
Ventilation should be negative with respect to zone 2, 5-10mm \( \text{H}_2\text{O} \).  
Light fixtures should not be in direct contact with Zone 3 air. Service should be from Zone 2.  
An in-line glove box arrangement shall have Zone 3 a component structure. |
<table>
<thead>
<tr>
<th>Key Element</th>
<th>Requirements Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 4 The glove boxes make up this area.</td>
<td>Primary containment shall be vessels within the glove boxes. The glove boxes are secondary containment.</td>
</tr>
<tr>
<td></td>
<td>Materials or equipment that could cause a fire, explosion, or corrosion should be minimal in zone 4.</td>
</tr>
<tr>
<td></td>
<td>The operators shall have good visibility from zone 2 or 3 into zone 4.</td>
</tr>
<tr>
<td></td>
<td>The floor of the glove box shall be as free as possible of equipment, so the floor can be inspected.</td>
</tr>
<tr>
<td></td>
<td>Ventilation should be negative 15-40 mm H₂O with respect to zones 2 and 3.</td>
</tr>
<tr>
<td>Key Element</td>
<td>Requirements Summary</td>
</tr>
<tr>
<td>------------------------</td>
<td>--------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>CHANGE ROOM:</td>
<td>Access from zone 1 to 2 and 3 shall be through a change room.</td>
</tr>
<tr>
<td></td>
<td>Workers in zone 2 or 3 shall wear appropriate protective clothing per IAEA</td>
</tr>
<tr>
<td></td>
<td>Safety Series No. 22.</td>
</tr>
<tr>
<td></td>
<td>The change room should contain a sink, shower, hand-and-foot monitor, and</td>
</tr>
<tr>
<td></td>
<td>lockers for personal and protective equipment.</td>
</tr>
<tr>
<td></td>
<td>If the glove boxes are arranged in-line, then a change room shall be provided</td>
</tr>
<tr>
<td></td>
<td>between zones 2 and 3.</td>
</tr>
<tr>
<td></td>
<td>All water from sinks and showers shall be collected and tested prior to disposal.</td>
</tr>
<tr>
<td>DECONTAMINATION ROOM:</td>
<td>For decontaminating equipment and possible laundering of contaminated clothing.</td>
</tr>
<tr>
<td></td>
<td>All liquids shall be collected in a retention tank and tested prior to disposal.</td>
</tr>
<tr>
<td></td>
<td>Equipped for packaging of solid wastes.</td>
</tr>
<tr>
<td>Key Element</td>
<td>Requirements Summary</td>
</tr>
<tr>
<td>------------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>VENTILATION:</td>
<td>Reference IAEA Safety Series 17 and 122.</td>
</tr>
<tr>
<td></td>
<td>Zone 1 inlet air should be filtered.</td>
</tr>
<tr>
<td></td>
<td>Discharge air shall be adequately filtered.</td>
</tr>
<tr>
<td></td>
<td>Fans should have adequate reserve capacity for adverse conditions.</td>
</tr>
<tr>
<td></td>
<td>Properly filtered air can be recirculated.</td>
</tr>
<tr>
<td></td>
<td>All penetrations (electrical, plumbing, etc) shall be adequately sealed.</td>
</tr>
<tr>
<td></td>
<td>Louvers between zones should be used to keep opening easily.</td>
</tr>
<tr>
<td></td>
<td>Accidents, including major fires, shall be considered when designing the ventilation, to ensure continued operation of filters.</td>
</tr>
<tr>
<td></td>
<td>Airborne dust should not be allowed to collect in ducts.</td>
</tr>
<tr>
<td></td>
<td>Volume change rates:</td>
</tr>
<tr>
<td></td>
<td>Zone 1 4 volume changes/hr</td>
</tr>
<tr>
<td></td>
<td>Zone 2 6-8 volume changes/hr</td>
</tr>
<tr>
<td></td>
<td>Zone 3 8-15 volume changes/hr</td>
</tr>
<tr>
<td></td>
<td>Exhaust ducts shall be independent until the filter plenum.</td>
</tr>
<tr>
<td></td>
<td>Filters shall conform to IAEA Technical Reports Series No. 122.</td>
</tr>
</tbody>
</table>
Chapter 4 provides 25 pages of glove box design and technique.

A continuous monitoring control panel and alarm shall be provided to provide surveillance over critical equipment, ventilation and life detection.

Smoke and/or fire detectors should be properly placed. These should be throughout zones 2 and 3 to allow evacuation and emergency work.

An auxiliary emergency power supply should be readily available.

EMERGENCY POWER SYSTEMS

EMERGENCY WARNING

A report from the IAEA panel of experts meeting November 1971

SAFE HANDLING OF PLUTONIUM, 1974

IAEA SAFETY SERIES No. 39 (contingued)
### HEALTH SURVEILLANCE:

Internal and external radiation exposure from plutonium handling needs to be monitored. These are to be performed with standard dosimetry and bioassay techniques.

Air monitoring is problematic in that the maximum permissible concentration is $2 \times 10^{-12}$ Ci/m$^3$ for readily transportable forms and $4 \times 10^{-11}$ Ci/m$^3$ for non-transportable forms. This is low for most monitoring systems and usually must be accumulated on filter paper for 4 days.

Continuous air monitoring is needed in case of single large releases.

For surface monitoring refer to IAEA Technical Reports Series No. 120.

Indirect monitoring can include dry smears, wet smears, large area swabs, adhesive tape samples, and autoradiography; the smears, swabs, etc being counted for activity.

Direct monitoring includes alpha counting no more than 0.5 cm from the surface.

### EMERGENCY RESPONSES:

Emergency plans should be prepared beforehand to cover any foreseeable conditions such as fires, (especially plutonium fires) spills, explosions, failure of a glove box, failure of ventilation, power failure to critical equipment.
A.5.13.

Radiological Hazards of Plutonium and Other Fissile Materials

by

M. Goldman
DEPARTMENT OF ENERGY
PLUTONIUM ES&H VULNERABILITY ASSESSMENT

ASSESSMENT TEAM TRAINING

April 19-21, 1994
Colorado Springs, Colorado

RADIOLOGICAL HAZARDS
OF
PLUTONIUM AND OTHER FISSIONABLE MATERIALS

Marvin Goldman
<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Nuclear Properties of Environmentally Significant Transuranium Radionuclides</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Radionuclide</td>
</tr>
<tr>
<td>Cm-242</td>
<td>Am-241</td>
</tr>
<tr>
<td></td>
<td>Pu-239</td>
</tr>
<tr>
<td></td>
<td>Pu-240</td>
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<td>Pu-241</td>
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<td>Np-239</td>
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<td>Np-237</td>
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<td>Am-241</td>
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<td>U-235</td>
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<td>U-236</td>
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<td></td>
<td>U-238</td>
</tr>
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<td></td>
<td>U-234</td>
</tr>
</tbody>
</table>

**TABLE 4-4**
PLUTONIUM
Chemical Properties

- A chemically reactive silvery white transuranic heavy metal (actinide series) mp=640°C bp=3327°C
  - Similar in appearance to stainless steel when freshly machined
- Oxidized easily in moist air (PuO₂)
  - Will turn brown or black
  - Valance states (+3 to +7) +4 most stable in physiological conditions
  - PuO (olive green powdery surface) most commonly shipped and stored in this form
- Generally forms insoluble oxides, hydroxides, and fluorides
  - Environmentally inert
  - No significant concentration mechanism important to human pathways
  - Solubility in H₂O dependent on redox, pH, presence of organic ligands
RADIOLOGICAL TERMS AND DEFINITIONS

- LET: Linear Energy Transfer (keV/μm)
  - High LET: α, p⁺, n
  - Low LET: β⁺, β⁻, x-rays & gamma

- RBE: Relative Biological Effectiveness
  - RBE vs. LET

- Biological significance of Bragg Peak
RADIOLOGICAL TERMS AND DEFINITIONS

Energy Deposited: (Physical and Chemical)

Magnitude of Molecular Damage

Modifier for Tissue Specific Stochastic Risk

Dose: Energy/Mass (ergs/gm) RAD

Energy Deposited

Dose Equivalent = Dose × QF  Unit: REM

Quality Factor (QF) for

α : 20
n : 2-10

B⁺, B⁻, x and γ rays : 1

QF also called "Radiation Weighting Factor" (Wₐ) ICRP

Effective Dose Equivalent

Dose Equivalent × tissue weighting factor (Wt)

- Gonads  0.25
- Breast  0.15
- Red marrow  0.12
- Lungs  0.12
- Thyroid  0.03
- Bone surface  0.03
- Remainder  0.03 (0.06 × 5)
MECHANISM OF RADIOBIOLOGICAL DAMAGE

Direct Effect: Critical target damaged directly by ionizing radiation (most common with high LET radiation)

Indirect Effect: Critical target damaged indirectly via free radical formation (most common with low LET radiation)
- Free radical: An atomic or molecular species with an unpaired electron
- Free radicals deposit their energy rapidly ($<10^{-6}$ sec) and locally ($<40 \ \mu m$)
# Plutonium Contamination

<table>
<thead>
<tr>
<th>Types of Contamination</th>
<th>Clinical Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inhalation</td>
<td>Most</td>
</tr>
<tr>
<td>Contaminated wounds</td>
<td></td>
</tr>
<tr>
<td>Ingestion</td>
<td></td>
</tr>
<tr>
<td>Intact skin</td>
<td>Least</td>
</tr>
</tbody>
</table>
PLUTONIUM CONTAMINATION

Biological Transport

- Rate of Plutonium Translocation is dependent upon:
  - Deposition site
  - Physical and chemical form
  - Specific activity

- Biological Transport is dependent upon bonding to biomolecules
  - Pu cannot exist in free ionic form if pH>1
  - Transferrin, citrates, amino acids, phospholipids
  - Polymers (0.01-1 μm): Particulates formed by hydrolysis deposit on cell surfaces (phagocytosis)

- Ultimate deposition site via blood to
  - Bone (45%)
  - Liver (45%)
  - Other tissues (10%)
BIOLOGICAL PATHWAYS OF PLUTONIUM

- Inhaled
  - Exhaled
  - Deposited in Bone and Liver
  - Deposited in Bone and Liver
- Swallowed
  - Soluble
  - Insoluble
  - Eliminated
  - Eliminated

*Slight increase chance of developing cancer*

*Most soluble plutonium that is swallowed is not absorbed*
<table>
<thead>
<tr>
<th>Intake</th>
<th>Oral Intake: (F&lt;sub&gt;i&lt;/sub&gt;: GI → Blood)</th>
<th>Inhalation</th>
<th>Lung Clearance</th>
<th>T&lt;sub&gt;1/2&lt;/sub&gt; Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soluble Forms</td>
<td>10&lt;sup&gt;-5&lt;/sup&gt; (0.001%)</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insoluble Forms</td>
<td>10&lt;sup&gt;-4&lt;/sup&gt; (0.01%)</td>
<td></td>
<td></td>
<td>W (10-100 days)</td>
</tr>
</tbody>
</table>
Biological Characteristics of Soluble Blood Born Plutonium

- **Systemic Transfer Fraction:** (Blood → Organ)
  - Bone 0.45 (endosteal surfaces of mineral bone)
  - Liver 0.45 (RE system)
  - Other 0.10

- **Biological $T_{1/2}$**
  - Bone ~ 100 years
  - Liver ~ 40 years
PLUTONIUM INHALATION

- Most likely route of internal contamination (75% of industrial exposures).
- Initial pulmonary deposition driven by particle size (not chemistry).
- Deposition in the deep lung varies inversely with the particle diameter.
- Final deposition driven by initial deposition site and chemistry.
TABLE 3-5

ANNUAL DOSE RATE TO VARIOUS LUNG COMPARTMENTS FROM CHRONIC EXPOSURE TO PLUTONIUM-239 AEROSOLS

Concentration: 1.0 fCi/m³  
Particle AMAD: 0.05, 1.0 and 5.0 Microns

<table>
<thead>
<tr>
<th>Duration of Exposure (Years)</th>
<th>Pulmonary Tracheobronchial</th>
<th>Nasopharyngeal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.05u 1.0u 5.0u</td>
<td>0.05u 1.0u 5.0u</td>
</tr>
<tr>
<td>1</td>
<td>3.9 1.5 .7</td>
<td>2.7 1.1 6.1</td>
</tr>
<tr>
<td>5</td>
<td>9.1 3.5 1.7</td>
<td>3.7 1.5 7.9</td>
</tr>
<tr>
<td>10</td>
<td>9.8 3.8 1.8</td>
<td>3.8 1.6 8.1</td>
</tr>
<tr>
<td>70</td>
<td>9.9 3.8 1.8</td>
<td>3.8 1.6 8.1</td>
</tr>
</tbody>
</table>
DOSE RATE TO ORGANS AS A FUNCTION OF TIME DUE TO CHRONIC INHALATION OF ONE MICRON (AMAD) PLUTONIUM PARTICLES AT A CONCENTRATION OF 2.6 fCi/m³. EQUILIBRIUM DOSE RATE TO PULMONARY LUNG 1 MRAD PER YEAR ADULT REFERENCE MAN — BREATHING RATE $2.3 \times 10^4$ LITERS PER DAY.

FIGURE 3-2
TABLE 3-6

AEROSOL CONCENTRATIONS IN fCi/m³ PRODUCING A 1 MRAD/YEAR EQUILIBRIUM DOSE RATE TO THE PULMONARY REGION OF REFERENCE MAN (Class Y Clearance)

<table>
<thead>
<tr>
<th>Aerosol AMAD (μm)</th>
<th>Pu-238</th>
<th>Pu-239</th>
<th>Pu-240</th>
<th>Pu-241*</th>
<th>Am-241</th>
<th>Cm-244</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>330</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>0.10</td>
<td>1.1</td>
<td>1.2</td>
<td>1.2</td>
<td>390</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>0.30</td>
<td>1.6</td>
<td>1.7</td>
<td>1.7</td>
<td>540</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>0.50</td>
<td>1.8</td>
<td>1.9</td>
<td>1.9</td>
<td>630</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>1.0</td>
<td>2.5</td>
<td>2.6</td>
<td>2.6</td>
<td>850</td>
<td>2.4</td>
<td>2.5</td>
</tr>
<tr>
<td>2.0</td>
<td>3.4</td>
<td>3.5</td>
<td>3.5</td>
<td>1,100</td>
<td>3.3</td>
<td>3.4</td>
</tr>
<tr>
<td>3.0</td>
<td>4.1</td>
<td>4.3</td>
<td>4.3</td>
<td>1,400</td>
<td>4.0</td>
<td>4.1</td>
</tr>
<tr>
<td>5.0</td>
<td>5.2</td>
<td>5.4</td>
<td>5.4</td>
<td>1,800</td>
<td>5.1</td>
<td>5.2</td>
</tr>
</tbody>
</table>

* only alpha dose rate due to Am-241 daughter is considered
Precancerous changes:
- Some have observed localized radio dermatitis and
  self-limiting translocation.
- Tissues volume → module formation → encapsulation
  energy of alpha can deliver very high dose to very small
  mostly fibrosis. High
- Foreign body /issue reaction → more readily absorbed
  Burns/abrasions/dermatitis/or other skin lesions: Absorption
  compounds.
- Soluble compounds more readily absorbed than insoluble
  Absorption increases as pH ↑
  Generalizations:
  - Human data 0.01% to 0.0002% total uptake
  - Conditions in animals (intact skin)
  - Maximum uptake > 0.05%/hr under ideal absorption
  - Intact skin is an excellent barrier to absorption

SKIN/WOUND TRANSPORT
PLUTONIUM
PULMONARY CLEARANCE OF PLUTONIUM

3 mechanisms of bronchial tree clearance of inhaled particles

- Tracheal/bronchial clearance to the pharyngeal junction → GI
  Two components:
  1. rapid mechanical ciliary action clearing in 1 day.
  2. slow cellular (macrophage) mechanical phase clearing the deeper (alveolar) spaces: clearance 1 month → 1 year

- Clearance to the tracheal/bronchial lymph nodes
  • Retention >90%

- Clearance to blood
  • Rapid for soluble fraction
ICRP LUNG MODEL

- 3 compartments of respiratory tract
  - Nasopharyngeal:
    - Ciliated columnar cells
    - Mucin secreting goblet cells
  - Tracheobronchial
    - Trachea → Bronchi → Terminal → Bronchioles
  - Pulmonary
    - Non-ciliated gas exchange tissues
    - Respiratory bronchioles → Alveolar ducts → Atria
      → Alveolar sacs → Terminal alveoli

- A complex lymphatic system accompanies all blood vessels (drain into tracheobronchial, hilar and mediastinal lymph nodes.)
PLUTONIUM BIOASSAY

- Pu-239 most difficult
  (low specific activity & weak x & y)

- Urine
  - Recommended LLD 0.06 pCi/sample
    (ANSI N13.30)
  - Maximum yield ~ 2-3 weeks

- Feces
  - Recommended LLD ~ 0.5 pCi/sample
  - Maximum yield ~ 24 - 48 hrs.
PLUTONIUM BIOASSAY (continued)

- **Chest (lung) Counters**
  - Large NaI detectors and long counting intervals (Am-241 impurity @ 1200 ppm)
  - LLD ~ 500 pCi

- **Nasal Smears**
  - ASAP (within 1st hour)
  - Q-tip (dry) each nostril separately
  - Used as a screening tool
PLUTONIUM DETECTION

- Several Types of Survey Meters Available
  - Alpha scintillation (ZnS) thin mylar window (very fragile: not useful as field instrument)
  - GM counters with thin windows (α, β, γ)
  - Thin NaI (TI) crystal scintillators (γ & X-ray)

- Realistic goal in field is detection rather than quantitation due to interference from variable overburden (e.g. dust, dirt, moisture)

- Am-241 (decay product of Pu-241 with 60 KeV gamma) normally in trace quantities with weapons grade plutonium is easier to detect. Most successful field detection approach.
ENVIRONMENTAL SAMPLING
Air Sampling

- Start ASAP
- Early phase of accident not available
  (typically measuring resuspension)
- Hi-Vol air samples w/HEPA filter
  (e.g. 1000 CFM w/filter ≤ 0.5 μ)
- Sampling time
  - Rapid assessment 5-10 min (1000 cf air minimum)
  - Continuous over 24 hours with filter
    change at regular intervals
ENVIRONMENTAL SAMPLING
(continued)

- Soil
  - Typically measured by gamma spectroscopy
  - Sample $\sim 2$ Kg soil ($1 \text{ ft}^2 \times 3''$ deep)

- Water
  - Typically measured by gamma spectroscopy
  - Sample drinking water and discharge sources
  - Sample size $\sim 1$-2 liters
ENVIRONMENTAL SAMPLING
(continued)

- Vegetation
  - Sample size: \(~3\) liters densely packed and double bagged

- Swipes
  - Assay for removable contamination
  - Typically use filter paper (dry) over \(100\ \text{cm}^2\)
  - Placed in individual envelope labeled with appropriate collection information
PLUTONIUM

Radiation Dosimetry/Biology
ANNUAL LIMIT ON INTAKE (ALI)

- Committed Effective Dose Equivalent (CEDE)
  
  $\downarrow 50y \downarrow Wt \downarrow \text{erg/gm} \downarrow QF(W_r)$

- Intake by "reference man" via inhalation or ingestion which will result in a dose equivalent equal to the most limiting of the following:

<table>
<thead>
<tr>
<th>Dose</th>
<th>Location</th>
<th>Effect</th>
<th>Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 REM</td>
<td>Whole Body</td>
<td>Stochastic</td>
<td>CEDE</td>
</tr>
<tr>
<td>15 REM</td>
<td>Lens of Eye</td>
<td>Non-stochastic</td>
<td>CDE</td>
</tr>
<tr>
<td>50 REM</td>
<td>Other Organs</td>
<td>Non-Stochastic</td>
<td>CDE</td>
</tr>
</tbody>
</table>
# Plutonium Inhalation Dose (mrem/nCi)

<table>
<thead>
<tr>
<th></th>
<th>Pu-238</th>
<th></th>
<th>Pu-239</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W (10^-3)</td>
<td>Y (10^-5)</td>
<td>W (10^-3)</td>
<td>Y (10^-5)</td>
</tr>
<tr>
<td>Gonad</td>
<td>0.004</td>
<td>0.002</td>
<td>0.003</td>
<td>0.002</td>
</tr>
<tr>
<td>Breast</td>
<td>68</td>
<td>1184</td>
<td>64</td>
<td>1195</td>
</tr>
<tr>
<td>Lung</td>
<td>562</td>
<td>215</td>
<td>625</td>
<td>243</td>
</tr>
<tr>
<td>R Marrow</td>
<td>7030</td>
<td>2683</td>
<td>7807</td>
<td>3038</td>
</tr>
<tr>
<td>B Surface</td>
<td>0.004</td>
<td>0.001</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>Thyroid</td>
<td>260</td>
<td>101</td>
<td>280</td>
<td>112</td>
</tr>
<tr>
<td>Remainder</td>
<td>392</td>
<td>288</td>
<td>429</td>
<td>308</td>
</tr>
<tr>
<td>CEDE</td>
<td>7</td>
<td>20</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>ALI (nCi)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inhalation (W 10^{-3})</td>
<td>Ingestion (W 10^{-3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------------</td>
<td>-------------------------</td>
<td>-----------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CEDE (mrem/nCi)</td>
<td>429</td>
<td>3.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALI (nCi)</td>
<td>6</td>
<td>800</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**GENERALIZATION**

\[
\text{RISK: } \frac{\text{Inhalation}}{\text{Ingestion}} > 100 \times 's
\]
<table>
<thead>
<tr>
<th></th>
<th>Tc-99m</th>
<th>Plutonium-238</th>
<th>Curium-250</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALI (nCi)</td>
<td>80,000,000</td>
<td>7</td>
<td>0.3</td>
</tr>
<tr>
<td>Route</td>
<td>Ingestion</td>
<td>Inhalation</td>
<td>Inhalation</td>
</tr>
<tr>
<td>$f_1$ (fraction to blood)</td>
<td>$\sim 0.8$</td>
<td>$10^{-3}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Dose limiting organ</td>
<td>Whole body</td>
<td>Bone surface</td>
<td>Bone surface</td>
</tr>
<tr>
<td>Dose to organ (mrem/nCi)</td>
<td>$3.3 \times 10^{-5}$</td>
<td>7030</td>
<td>170,570</td>
</tr>
</tbody>
</table>

**RISK**

**Plutonium vs. Other Radionuclides**

**ALI RISK:**
- 5 rem Stochastic = 0.25% ↑ cancer risk (normal: 33%)
- 15 rem Non-Stochastic = lens of eye (cataract threshold $\sim 250$ rem)
- 50 rem Non-Stochastic = Bone surface
### PLUTONIUM RISK

Relative Toxicity

<table>
<thead>
<tr>
<th>Substance</th>
<th>Criterion</th>
<th>Species</th>
<th>Quantity</th>
<th>Route</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu-239 (PuO₂)</td>
<td>LD₅₀/₃₀</td>
<td>Dog</td>
<td>0.32 mg/kg</td>
<td>IV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(~20 nCi/kg)</td>
<td></td>
</tr>
<tr>
<td>Pu-239 (PuO₂)</td>
<td>LD₅₀/₃₀</td>
<td>Dog</td>
<td>1.3 mg/kg</td>
<td>INH</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(~80 nCi/kg)</td>
<td></td>
</tr>
<tr>
<td>Tetanus toxin</td>
<td>LD 50</td>
<td>Mouse</td>
<td>0.1 ng/kg</td>
<td>IPR</td>
</tr>
<tr>
<td>Cause</td>
<td>Total Number of Deaths</td>
<td>Individual Risk (Probability/yr)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------------</td>
<td>------------------------</td>
<td>----------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Accidents</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor Vehicle</td>
<td>52,411</td>
<td>$2.4 \times 10^{-4}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air Transport</td>
<td>1,880</td>
<td>$8.6 \times 10^{-6}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Railway</td>
<td>602</td>
<td>$2.8 \times 10^{-6}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Falls</td>
<td>13,690</td>
<td>$6.3 \times 10^{-5}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fire</td>
<td>6,163</td>
<td>$2.8 \times 10^{-5}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drowning</td>
<td>5,784</td>
<td>$2.7 \times 10^{-5}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industrial</td>
<td>5,168</td>
<td>$2.4 \times 10^{-6}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrocution</td>
<td>984</td>
<td>$4.5 \times 10^{-6}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Explosion</td>
<td>562</td>
<td>$2.6 \times 10^{-6}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Firearms</td>
<td>1,806</td>
<td>$8.3 \times 10^{-6}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Diseases</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cardiovascular</td>
<td>964,000</td>
<td>$4.4 \times 10^{-3}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Malignancies</td>
<td>396,720</td>
<td>$1.8 \times 10^{-3}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Influenza/Pneumonia</td>
<td>58,230</td>
<td>$2.7 \times 10^{-4}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diabetes</td>
<td>33,800</td>
<td>$1.6 \times 10^{-4}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Natural Events</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lightning</td>
<td>160</td>
<td>$7.3 \times 10^{-7}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tornadoes</td>
<td>118&lt;sup&gt;b&lt;/sup&gt;</td>
<td>$5.4 \times 10^{-7}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hurricanes</td>
<td>90&lt;sup&gt;c&lt;/sup&gt;</td>
<td>$4.1 \times 10^{-7}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) Based on total U.S. Population
(b) 1953-75 average
(c) 1901-71 average
TABLE 3-11
ANNUAL DOSE RATE DUE TO CHRONIC INGESTION OF PLUTONIUM-239 OXIDE, AMERICIUM-241, PLUTONIUM-241, & CURIUM-244

*Annual Intake = 1000 pCi/Year*

<table>
<thead>
<tr>
<th>Duration of Ingestion (Irratal)</th>
<th>Red. Marrow</th>
<th>Bone</th>
<th>Endostal</th>
<th>Lilor</th>
<th>Plutonium-239 oxide</th>
<th>Americium-241</th>
<th>Plutonium-241/Americium-241</th>
<th>Lilor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.4</td>
<td>2.4</td>
<td>3.1</td>
<td>2.5</td>
<td>4.5</td>
<td>12.8</td>
<td>1.3</td>
<td>1.2</td>
</tr>
<tr>
<td>5</td>
<td>3.4</td>
<td>2.4</td>
<td>3.1</td>
<td>2.5</td>
<td>4.5</td>
<td>12.8</td>
<td>1.3</td>
<td>1.2</td>
</tr>
<tr>
<td>10</td>
<td>3.4</td>
<td>2.4</td>
<td>3.1</td>
<td>2.5</td>
<td>4.5</td>
<td>12.8</td>
<td>1.3</td>
<td>1.2</td>
</tr>
<tr>
<td>20</td>
<td>3.4</td>
<td>2.4</td>
<td>3.1</td>
<td>2.5</td>
<td>4.5</td>
<td>12.8</td>
<td>1.3</td>
<td>1.2</td>
</tr>
<tr>
<td>30</td>
<td>3.4</td>
<td>2.4</td>
<td>3.1</td>
<td>2.5</td>
<td>4.5</td>
<td>12.8</td>
<td>1.3</td>
<td>1.2</td>
</tr>
<tr>
<td>50</td>
<td>3.4</td>
<td>2.4</td>
<td>3.1</td>
<td>2.5</td>
<td>4.5</td>
<td>12.8</td>
<td>1.3</td>
<td>1.2</td>
</tr>
<tr>
<td>70</td>
<td>3.4</td>
<td>2.4</td>
<td>3.1</td>
<td>2.5</td>
<td>4.5</td>
<td>12.8</td>
<td>1.3</td>
<td>1.2</td>
</tr>
</tbody>
</table>
PLUTONIUM
ENVIRONMENTAL ASPECTS

- Atmospheric Testing (1945-1962 USA, Great Britain, Soviet Union) released ~0.3 - 0.6 MCi (5 to 10 tons) of Pu-239 and 240. Some after by France and China
  - Mostly northern hemisphere
  - Soil: most in top 10 cm
  - Ocean: ~50% below the thermocline
  - ~1% increase in natural α activity (US)
    (Artificial radioactivity in US ~16 KCi Pu & 4KCi Am vs ~1600 KCl of naturally occurring α activity.)
PRINCIPAL PATHWAYS OF THE TRANSURANIUM ELEMENTS THROUGH THE ENVIRONMENT TO MAN

FIGURE 1-5
PLUTONIUM
ENVIRONMENTAL HEALTH CONSIDERATIONS
FROM A WEAPONS ACCIDENT

- Doses to population
  - As high as several hundred rem (lung) from inhalation (initial cloud passage).
  - Doses from resuspension will be 100 - 1000 times less.
- Sheltering is primary protective action
  - Stay indoors
  - Turn off A/C
  - Resuspension is primarily a problem around accident site.
  - Do not consume plants/vegetables until radiological assays are completed.
PLUTONIUM
ENVIRONMENTAL ASPECTS
(continued)

- Accidents
  - 1964 satellite carrying ~1 Kg Pu-238 (Indian Ocean)
  - Airplane accidents with atomic weapons
    - 1966 Palomares Spain ~2 km² contaminated
      (only ~30g [~525 Ci] remain following decon.)
    - 1968 Thule, Greenland ~0.1 km² contaminated
      (only ~400g [7,000 Ci] remain following decon.)
PLUTONIUM
ENVIRONMENTAL ASPECTS (continued)

- Bioaccumulation is negligible
  - $10^{-3}$ in plants
  - $10^{-4}$ in animals
  - $10^{-5}$ in milk
  - $10^{-4}$ in man (soluble e.g. Pu nitrate)
  - $10^{-6}$ in man (insoluble e.g. PuO$_2$)

- Concentration Factors:
  - soil $\rightarrow$ plant ($\sim 10^{-3}$ to $10^{-6}$)
  - soil $\rightarrow$ plant $\rightarrow$ animal ($\sim 10^{-8}$)
  - soil $\rightarrow$ plant $\rightarrow$ animal $\rightarrow$ man ($\sim 10^{-11}$ to $10^{-12}$)
PLUTONIUM
ENVIRONMENTAL ASPECTS (continued)

- Resuspension Factors ($10^{-5}$ to $10^{-8}$)
  - $10^{-5}$ more appropriate for fresh deposition of finely distributed plutonium
  - $10^{-8}$ fixed to soil for long periods (e.g. Trinity Test Site, Alamagordo, New Mexico)

- Pu is typically in the tetravalent (+4) form and quickly forms positively charged polymers which are readily complexed to soil components.

- Fixation high in humus and clay soils (ion exchange)
- Fixation lower in sandy soils
**TABLE 5-1**

**FACTORS AFFECTING RESUSPENSION**

**METEOROLOGICAL FACTORS**

- Wind Frequency Distribution:
  - Mean Wind Speed
  - Wind Direction
- Intensity of Gusts
- Vertical Turbulent Exchange
- Air Density (Temperature-Pressure)
- Frequency and Amount of Rain/Snowfall

**GROUND-SURFACE PROPERTIES**

- Soil Characteristics
  - Soil Type
  - Moisture Content
  - Density
  - Texture
- Particle Characteristics
  - Shape
  - Density
  - Size Distribution
  - Cohesiveness
- Land Use
- Surface Roughness
- Type and Amount of Vegetative Cover
- Topography/Terrain Irregularities
- Soil Disturbance Activities
### TABLE 3-14

**OCCUPATIONAL EXPOSURE**

**ANNUAL LIMIT OF INTAKE (ALI) AND DERIVED AIR CONCENTRATION (DAC)**

**FOR THE MORE IMPORTANT TRANSURANIUM NUCLIDES**

From Federal Guidance Report No. 11 - EPA 520/1-84-003

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Class</th>
<th>ALI $\mu$Ci</th>
<th>DAC $\mu$Ci/m$^3$</th>
<th>Ingestion ALI $\mu$Ci</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neptunium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Np-236</td>
<td>W 10^4</td>
<td>0.82</td>
<td>9 $10^{-4}$</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>5 $10^4$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Np-237</td>
<td>W 10^4</td>
<td>0.004</td>
<td>2 $10^{-4}$</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>2.14 $10^4$</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Np-238</td>
<td>W 10^4</td>
<td>0.6</td>
<td>3 $10^{-4}$</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>2.117 d</td>
<td></td>
<td></td>
<td>1000</td>
</tr>
<tr>
<td>Np-239</td>
<td>W 10^4</td>
<td>2000</td>
<td>9 $10^{-4}$</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>2.155 d</td>
<td></td>
<td></td>
<td>2000</td>
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<tr>
<td>Plutonium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pu-239</td>
<td>W 10^4</td>
<td>0.007</td>
<td>3 $10^{-4}$</td>
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<tr>
<td></td>
<td>27.5 y</td>
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<td>8 $10^{-4}$</td>
<td>1 $10^{-4}$</td>
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<tr>
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<td>W 10^4</td>
<td>0.006</td>
<td>3 $10^{-4}$</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>30065 y</td>
<td>0.02</td>
<td>7 $10^{-4}$</td>
<td>1 $10^{-4}$</td>
</tr>
<tr>
<td>Pu-239</td>
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<td>3 $10^{-4}$</td>
<td>0.001</td>
</tr>
<tr>
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<td>6537 y</td>
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<td>Pu-241</td>
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<td>0.3</td>
<td>1 $10^{-4}$</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>14.4 y</td>
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<td>3 $10^{-4}$</td>
<td>1 $10^{-4}$</td>
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<tr>
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<td>0.001</td>
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<tr>
<td></td>
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<tr>
<td>Americium</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Am-241</td>
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<td>1 $10^{-4}$</td>
</tr>
<tr>
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<td>0.8</td>
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<td>1 $10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>152 y</td>
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<td>0.8</td>
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<tr>
<td>Am-242m</td>
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<td>0.006</td>
<td>3 $10^{-4}$</td>
<td>1 $10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>1.62 h</td>
<td>0.01</td>
<td>4 $10^{-4}$</td>
<td>1 $10^{-4}$</td>
</tr>
<tr>
<td>Am-243</td>
<td>W 10^4</td>
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<td>7.288 y</td>
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<td>3 $10^{-4}$</td>
<td>1 $10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>18.1 h</td>
<td>0.01</td>
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<td>1 $10^{-4}$</td>
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<tr>
<td>Am-244m</td>
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<td>1 $10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>25 m</td>
<td></td>
<td></td>
<td>4 $10^{-4}$</td>
</tr>
<tr>
<td>Curium</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Cm-242</td>
<td>W 10^4</td>
<td>0.5</td>
<td>1 $10^{-4}$</td>
<td>1 $10^{-4}$</td>
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<tr>
<td></td>
<td>16.3 d</td>
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<td>30</td>
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<tr>
<td>Cm-244</td>
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<td>0.01</td>
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<td>1 $10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>18.11 y</td>
<td></td>
<td></td>
<td>1</td>
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</tbody>
</table>

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A.5.14.1

Criticality Safety

by

T. McLaughlin
DEPARTMENT OF ENERGY
PLUTONIUM ES&H VULNERABILITY ASSESSMENT

ASSESSMENT TEAM TRAINING

April 19–21, 1994
Colorado Springs, Colorado

CRITICALITY SAFETY

Tom McLaughlin
### CATEGORIES OF CRITICALITY ACCIDENTS

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Assemblies/Reactor</td>
<td>App. 50,000 experiments</td>
</tr>
<tr>
<td>Experiments</td>
<td>App. 30 accidents total</td>
</tr>
<tr>
<td></td>
<td>7 fatalities</td>
</tr>
<tr>
<td>Process Line</td>
<td>8 accidents</td>
</tr>
<tr>
<td></td>
<td>All solutions</td>
</tr>
<tr>
<td></td>
<td>7 US-1 UK</td>
</tr>
<tr>
<td></td>
<td>2 fatalities</td>
</tr>
</tbody>
</table>
PROCESS CRITICALITY ACCIDENTS

All involved solutions

Total Reported = 8

Worker Fatalities = 2

Public exposures = not measured; negligible risk

Environmental contamination = not measured negligible
Process Criticality Accidents

-- All Involved SNM in Solution --

YEAR

NUMBER

Table 1.

Fissile Material Atom Densities

<table>
<thead>
<tr>
<th>Material</th>
<th>Density</th>
<th>Element or Isotope</th>
<th>Weight Percent</th>
<th>Atom Density, atoms / barn-cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plutonium</td>
<td>19.86</td>
<td>$^{239}$Pu</td>
<td>95</td>
<td>0.04753</td>
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<td></td>
<td></td>
<td>$^{240}$Pu</td>
<td>5</td>
<td>0.00249</td>
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<td>Stainless Steel</td>
<td>7.92</td>
<td>Cr</td>
<td>19.0</td>
<td>0.01743</td>
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<tr>
<td>(Keno mix = 200)</td>
<td></td>
<td>Fe</td>
<td>69.5</td>
<td>0.05935</td>
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<tr>
<td></td>
<td></td>
<td>Ni</td>
<td>9.5</td>
<td>0.00772</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mn</td>
<td>2.0</td>
<td>0.00174</td>
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<tr>
<td>Carbon Steel</td>
<td>7.82</td>
<td>C</td>
<td>1.0</td>
<td>0.00392</td>
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<td>(Keno mix=100)</td>
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<td>Fe</td>
<td>99.0</td>
<td>0.08349</td>
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<tr>
<td>Ordinary Concrete</td>
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<td>Al</td>
<td>3.4</td>
<td>0.00175</td>
</tr>
<tr>
<td>(Keno mix=301)</td>
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<td>Ca</td>
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<td></td>
<td></td>
<td>Fe</td>
<td>1.4</td>
<td>0.00035</td>
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<td>H</td>
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<td>0.01374</td>
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<tr>
<td></td>
<td></td>
<td>O</td>
<td>53.2</td>
<td>0.04606</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Na</td>
<td>2.9</td>
<td>0.00175</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Si</td>
<td>33.7</td>
<td>0.01662</td>
</tr>
</tbody>
</table>
Table 2.

Multiplication Factors for Storage Array
Two 8 x 83 x 6 Arrays (7,968 units)

<table>
<thead>
<tr>
<th>Density of Fissile Material in Inner Container, g/cc</th>
<th>Array Multiplication Factor $k_{\text{eff}} + 3\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.86</td>
<td>0.81</td>
</tr>
<tr>
<td>14.895</td>
<td>0.77</td>
</tr>
<tr>
<td>9.93</td>
<td>0.72</td>
</tr>
<tr>
<td>4.965</td>
<td>0.62</td>
</tr>
<tr>
<td>2.23</td>
<td>0.54</td>
</tr>
</tbody>
</table>
Figure 1. Illustration of Array in TA-55, PF-41 Bavs
Figure 2. Storage Shroud, as Modeled
Figure 3. Single Storage Container
Modeling Details
Figure 3A. Single Storage Container
Additional Modeling Details
Figure 4. Multiplication Factors for 8 by 83 by 6 (x, y, z) Arrays

Values are for units of constant mass (4,500 grams)
A.5.14.2

Additional Reading on Criticality Safety
ADDITIONAL READING
ON
CRITICALITY SAFETY
CRITICALITY
SAFETY
MANAGER/ENGINEER

By
Health Physics Training
Every Westinghouse Hanford Company employee has the responsibility for criticality safety. Operations involving fissionable material have in-depth envelopes of safety designed into them. This design incorporates research and lessons learned from past errors and will prevent personnel injury and equipment damage when followed. When individuals fail to follow the procedures, the envelope of safety becomes eroded and the potential for serious accidents becomes unacceptable. We must be alert to the gradual erosion of safe practices and procedures to the point where exceptions become the normal mode of operation.

This training has been developed to give you an awareness of the procedural requirements and the envelope of safety used when working with fissionable materials.

Terminal Goal

Following this training in Criticality Safety the student will have the basic knowledge and confidence to do his or her assigned task in a safe and proficient manner.

Terminal Objective

Upon completion of the training the student will be able to pass a written examination with 80% accuracy.
I. PRESENTATION

A. Nuclear Theory and Reactions

1. Fission

   a. Definition: Splitting of a nucleus

   b. Process: U-235 or Pu-239 + neutron → fission product₁ + fission product₂ + 2-3 neutrons + γ + β + heat

   c. Produces:
      (1) At least _____ new nuclei (fission products)
      (2) Heat released or given off
      (3) Radiation released or generated
      (4) Free neutrons released

2. Fissile material

   a. Material that will sustain a chain reaction by slow neutron induced fission; e.g., U—, U-233, Pu—, and Pu-241.

3. Fissionable material

   a. Material that can sustain a neutron induced chain reaction; e.g., all fissile materials plus Np-237, Pu-238, Am-241 and Cm-244. These are the most common and the list is not all inclusive.

      (1) All fissile material is also fissionable material but not all fissionable material is fissile.

   b. _____ is the only fissionable isotope that occurs naturally in commercial quantities.
Objective: d. Identify the two interactions that free neutrons undergo and why they are important in criticality safety.

4. Neutrons

a. Free neutrons are constantly being released through several nuclear reactions.

b. Neutrons only interact with the _____ of other atoms.

c. There are two ways a neutron can interact with an atom's nucleus

(1) Scattering
(2) Absorption

d. Scattering reactions occur when the neutrons strikes and bounces off the nucleus. This takes energy away from the neutron causing it to slow down. Slow neutrons are more likely to be absorbed.

e. Absorption occurs when the nucleus of an atom captures a neutron.

(1) Some atoms become radioactive by the absorption of a neutron.

f. Fission may occur when a neutron is captured by the nucleus of a fissionable material causing it to split into two parts.

(1) Fission releases additional neutrons that may result in more fissions.

(2) Fission neutrons are "born" as fast neutrons (high energy) and are more likely to escape from the system. After they have leaked out they are not available to cause more fissions.
5. A chain reaction is a series of fission reactions caused by the released neutron from the previous fission events.

a. The magnitude and duration of a chain reaction is dependent upon the multiplication factor (k).

(1) __________ factor shows whether the number of fissions is increasing or decreasing.

(2) $k = \frac{\text{# of fission neutrons in current generation}}{\text{# of neutrons in preceding generation}}$

(3) k=1 __________

(4) k>1 supercritical

(5) k<1 subcritical

b. Assuring that fissionable material is keep subcritical is what criticality safety is all about.
B. Criticality Characteristics

1. Prompt high levels of
   a. Immediate ultra-high radiation dose rate, poses greatest hazard to personnel.
   b. Neutrons will cause activation of materials. Metals are most likely to become activated, for example sodium within the body.
   c. Nearby individuals may perceive a blue flash.
   d. The magnitude and duration of the criticality will determine the radiation level.

2. The fission products continue to produce radiation after criticality stops.
   a. Fission products are very radioactive.
   b. Contamination of the area is possible with uncontained material or if rupture of containment occurs during criticality.

3. Generation of
   a. Kinetic energy of the fission products imparts energy to the surrounding materials and an increase in temperature results.
C. Factors Affecting Criticality - Parameters - mass, geometry, reflection, moderation, enrichment, concentration, heterogeneity, density, volume, interaction, and poisons.

1. _______ is the most important single factor (most often used).
   a. _______ mass - the mass of fissionable material that can reach criticality under specified conditions.
   b. Minimum critical mass - the smallest amount of fissionable material that can reach criticality under ideal conditions.

2. Geometry/shape
   a. _______ is optimum for criticality but bad for criticality prevention. This is because of the small surface area/volume ratio of a sphere will result in the fewest possible neutrons leaking out of the system.
   b. Fissionable material in a spherical geometry has the lowest possible neutron _______.
      (1) Cubes - approach sphere - bad shape
          Small shapes that can be tightly stacked together have more potential for criticality.
          Rectangular vs. spheres
      (2) Cylinders: If the diameter is equal to the height then this is possibly a bad shape.
c. Any geometry that is thin will be a good shape for criticality safety, liquids less than two (2) inches.

d. The neutron leakage will increase if the surface area to volume ratio is (increased/decreased).

   (1) Flattening of bad geometries will increase surface area/volume ratio.
   (2) Elongation of a bad geometry will increase the surface area/volume ratio.

   (a) Increases neutron ______

e. Increased neutron leakage means ______ (decreased/increased) chance of criticality.
3. Materials that cause the neutrons to change direction without being absorbed.
   a. (increase/decrease) neutron leakage
   b. More neutrons are available to cause ________.
   c. If you put solid fissionable material (not powders) into a container of liquid the effects of reflection will be more than the moderation effects.
   d. Introducing a reflector results in decreasing the critical mass by ________.

4. Materials that absorb significant energy from neutrons during collisions.
   a. Thermal neutrons (slow neutrons) are up to ________ times more likely to cause fission.
   b. Materials with a ________ atomic mass, ≤ 12, make best moderators.
   c. The following is a list of common moderators:
      (1) __________
      (2) __________
      (3) Hydrocarbons - very good
      (4) ________ is common and readily available.
d. Layering a moderator with a fissile material (intermixing) is like having material in solution.

e. A ______ will also act as a ______ when it surrounds the system. A good reflector is not necessarily a good moderator, i.e., steel, U, lead, etc.
5. The percentage of the material that is fissile. Natural uranium is 0.71% U-235 and 99.29% U-238.

a. The _______ (higher/lower) the enrichment, the less it takes for a critical mass in a given situation.

b. The higher the enrichment, the more controls that will need to be imposed to prevent an accidental criticality. Only 810 g of 100% U-235 is needed for a minimum critical mass of uranium.

c. Natural _______ is almost impossible to make critical without extensive engineering because of its low enrichment. For this reason natural or depleted (< .71% U-235) are not usually a criticality concern.
6. The mass of fissile material in a given volume.

   a. \( H/X \) - The moderator to fissile ratio (\( H/X \)) can be used to understand why the curve of a graph of the critical mass to the concentration is the shape it is.

   b. 30 g/l concentration of \(^{239}\text{Pu}\) nitrate solution is the point where minimum critical mass occurs and has a \( H/X = 850 \). This is the concentration with OPTIMUM MODERATION.

   c. \(<30\ \text{g/l over moderated} - H/X \text{ "too high" } > 850\)

   d. \( >30\ \text{g/l under moderated} - H/X \text{ "too low" } < 850\)

   e. \( H/X \) ratio \(<2\) considered dry

   f. \( H/X \) ratio \(<20\) is slightly moderated

   g. Typically when setting controls, solutions are considered fully moderated.

   h. Change in concentration can cause a solution to go critical or if its critical, to go subcritical.

7. Heterogeneity - The non homogeneous distribution of fissionable material due to chemical and physical properties of the material.

   (1) Two immiscible liquids in the same container can result in fissile material shifting from one liquid to the other due to different
solubility potential. Thus low concentration in one liquid may become highly concentrated in the other liquid.

(2) Fissionable material may precipitate out of solution thus forming a sludge on the bottom of the container.
8. ___________ – How close together the atoms of fissionable material are.
   
a. ______ (high/low) density means less material needed to achieve criticality
b. ______ (high/low) density means more neutrons will escape.
9. __________ - The amount of solution in a container.
   a. __________ is a subcritical volume for plutonium solutions. There will not be enough fissile material for a criticality to occur.
   b. Any container that will hold a basketball or more may contain enough plutonium solution to cause criticality safety concerns.
   c. Containers - Any vessel capable of containing fissionable material.

10. __________ - Neutrons interact between units (containers, pins, fuel assemblies, batches, etc.) of fissionable material.
   a. Spacing of fissionable material is used to minimize the neutrons that escape from one batch and entering another.
   b. Examples where spacing is used.
      (1) In some facilities yellow lines on the room floor ___ (1/2/3/4) feet from a wall are used to minimize fissionable material interacting with other fissionable material that may be on the other side.
      (2) Spacing requirements inside a glove box.
      (3) Spacing requirements for batches or unit masses.
      (4) Spacing designed into carts, storage boxes, shipping containers, fissionable material storage locations, etc.
11. ___________ - A material that absorbs neutrons but does not fission.
   a. Common - __________, __________, Gadolinium, Samarium
   b. Poisons will decrease the neutron population thus decreasing the chance of criticality.
   c. Borated Raschig rings are used as poisons in some storage tanks.

12. Using the parameters/factors to control the number of ___________ in the system and their energy is what criticality safety is all about.
   a. Fissions are always occurring in fissionable materials.
   b. If neutron multiplication can be controlled, $K < 1$, there will be no criticality.
13. Shutdown mechanisms for accidental criticality

(1) Increasing the ___________ leakage caused by changes in physical properties in the system. For example, as the heat released by the criticality will cause the material to expand. This means that the nuclei of the atoms are further apart and therefore there is more neutron leakage.

(2) Liquid systems may pulse or cycle. The nature of liquids allow for the system to more readily return to original conditions.

(a) Subsequent criticalities may be only ___________ (time unit) apart.

(b) Heat released from the criticality will cause changes in the ___________ properties of the system.

(c) Increases neutron ___________ making the system subcritical.

(d) System cools down and then goes critical, etc.

(e) After several criticalities the system could boil and this may eventually change the concentration of the system.

(f) Other shut down mechanisms are possible.

* Denotes material covered in the Manager/Engineer class but not in the Fissionable Material Handler class.
D. Review of criticality accidents/near accidents

1. General Electric near criticality at Wilmington, North Carolina.

   a. The event involved an inadvertent transfer of high concentration uranium from a solvent exchange process to a waste treatment process. Due to improper maintenance of a control valve and operations response (trying to control process with manual valve) solution containing \( >150 \text{ ppm} \) of U was transferred to a tank with a limit of \( <150 \text{ ppm} \). This resulted in solution in a large tank (20,000 gal) containing solution with a concentration of 2,333 ppm.

   b. Proposed changes would be authorized only by license amendments. Licensee did not consider this as a limit to their ability to unilaterally change the process and controls under the administrative provisions of their license. NRC inspections were predicated on the same understanding. An example of this was the safety basis for the facility was demonstrated for U enriched to 5% but licensee authorized U to 6%.

   c. In '86 density monitors set point changed from 280 g U/l to 350 g U/l. This concentration was determined not to be a risk in the feed preparation system, but the downstream systems do not appear to have been considered.

   d. In '87 density monitor for tank V-103 (20,000 gal) was approved for deletion because remaining controls met license requirements. This included a set point alarm and automatic closure of a transfer block and bleed valve.

   e. Process control was not considered to be a criticality safety contingency by operation. There was no distinction between process control and criticality control instrumentation. This significantly weakened the safety margin because of only a single point sampling system.

   f. Licensee lacked a multidisciplinary approach to identify: 1) each route to a criticality scenario, 2) necessary contingencies for each scenario, and 3) formal controls necessary for each contingency.

   g. Computer control system was routinely manually bypassed when samples were not taken. Thus mass contingency had been degraded because of management's inattention to the point where it was no longer a valid barrier.

   h. Valve lineup of the "Critical Valves" were not easily identified so that the recirculation alignment could be assured.

   i. 100 kgs of 3.2% uranium was the MCM. 150 kgs was transferred to the V=104 tank (20,000 gal) with an available inventory of .275 kgs.
j. Management's inadequate oversight of the maintenance process, coupled with the facility's production-oriented philosophy, resulted in affording maintenance personnel extensive work latitude without specifying the impact that maintenance activities could have on criticality controls.

k. Changes and modifications had been made to plant equipment and systems without an adequate evaluation of their effect on operations.

(1) Fill time for 600 gal tanks < May '87 10.8 hrs
    May '87 2.3 hrs
    Nov '90 1.4 hrs

(2) The tanks were filled to 90% and then circulated for 15 min. before sampling. The auto-sampling system was not working at this time and was being replaced with new equipment. Manual sampling was necessary for analysis instead of in line analysis.

l. In '89 and '90 loss of criticality control at other NRC facilities also occurred. All three of these had the same underlying causes; 1) inadequate management attention to criticality safety program, 2) lack of mandatory and enforced procedural compliance, 3) inadequate training programs, and 4) the need for additional monitoring devices.

2. Wood River Junction 1964 - In this accident the person poured a solution of highly enriched and high concentration uranium from a geometrical safe container to an 18 inch diameter tank. The solution went critical and the person received a lethal dose of radiation. A second criticality was caused when personnel tried to recover from the first accident.

a. There was no written procedure for the way the operation was conducted.

b. The containers were poorly marked.

c. Transferred high concentration solution from safe to an unsafe geometry.

d. Person had not been assigned to do this job, but since he had time he went ahead and did the job.

e. The second accident was caused because personnel did not understand all the factors that effect criticality control.

f. Similar scenario has occurred twice within the last few years at commercial facilities because of improper training. There is a tendency to assume that dilute material is harmless, so no precautions are needed. This sloppiness also contributed to the mis-identification of concentrated solutions.
E. Criticality Prevention

1. Reason
   a. Primary reason is the prevention of _______________________.
   b. Secondary reason is to avoid damage to the plant.
      (1) Cost of repair
      (2) Cost of decon
      (3) Loss of facility use
      (4) Loss of jobs
2. Controls for criticality safety are of one of two types either administrative or engineering.

a. DOE Order 5480.5 - Safety of nuclear facilities

   (1) Purpose is "That consideration is given to all potential criticality hazards associated with fissionable material operations outside nuclear reactors."

b. Westinghouse Hanford Manual (WHC-CM-4-29)

   (1) Covers the general criticality safety requirements for handling fissionable materials. The following organizations or classification are assigned responsibilities that they must be familiar with.

   (a) Operating Organization

   (b) Criticality Safety Representative (CSR)

   (c) Responsibilities for fissionable material handlers

      i) Know the (criticality\radiation) safety requirements established for the operation and handle fissionable material in strict accordance with those requirements.

      ii) Handle fissionable material only after completing the required prerequisite criticality safety training.

      iii) Ask for additional instructions when needed.

      iv) Communicating any criticality safety questions and concerns to the responsible management, the Criticality Safety Representative (CSR) and their co-workers as appropriate.
v) Knowing and following criticality (security/emergency) procedures.

vi) Communicate criticality safety related information to co-workers and responsible management (e.g., at shift turnover).

(d) Engineering

1) Criticality Engineering Analysis

2) Radiological Safety Analysis

(e) Safety

1) Independent Safety Review Organization (Nuclear Facility Safety or Reactor Safety)

(f) Quality Assurance

(g) Transportation and Packaging

(h) Training

(i) Safety and Environmental Advisory Council

(2) Waivers or Deviations (1.5.7) - There may be a better way to do the job. Waivers are possible if the conditions warrant it.
c. Criticality Safety Training

(1) Lists requirements and assigns responsibilities for training employees in criticality safety.

(2) Fissionable Material Handlers and Managers/Engineers are to have:

(a) _________ training every ___ years.

(b) Job-Specific-Training shall be provided to ensure that personnel are familiar with all aspects of their positions every two years and for new job assignments.

(c) Periodic Criticality Safety Training Meetings, 3 required per year. Attendance requirements depend upon job assignment.

1) ____________ (monthly/quarterly/annual) meeting, usually conducted as a safety meeting.

11) ____________ (monthly/quarterly/annual) meeting, required by supervisors of Fissionable Material Handlers. Personnel in a support function within a fissionable material facility are to have an annual meeting. It is the supervisor's responsibility to arrange the meeting for these employees.

(d) The WRAM report will give level of training but only as indicated below. Be sure that each employee you assign to a job has the proper level of criticality training for the job assignment.

1) Fissile = Fissionable Handler or Manager/Engineer courses

11) Non-Fissile = Support Personnel or Non-Fissile courses
Objective: n. Identify the conditions when a Fissile Material Handler may issue a stop work order and the steps needed to lift a stop work order.

d. Declaring and Lifting Stop Work Orders

(1) Upon identifying an unsafe or a condition adverse to criticality safety immediately notify responsible worker/management).

(2) If a work activity represents a CLEAR and IMMINENT DANGER, the work shall be suspended pending management review. If there is a question about compliance with the requirements of this manual or other governing criticality safety documents, it is expected that work will be suspended (or for dynamic systems, stabilized) pending management review of the situation.

(a) The manager or supervisor of the employee raising the concern shall ensure that, if the employee does not agree with the sufficiency of operation's response, the problem is brought to the attention of the independent safety review organization management as soon as possible.

(b) Level 2 and 3 independent safety review managers have authority to issue stop work and shutdown orders in accordance with Management Policies (MP) 1.4, "Shutdown and Stop Work Direction".

(3) Lifting A Stop Work Order

(a) Work may be resumed if the facility operations management, the facility Criticality Safety Representative (CSR), and the employee who stopped the work agree that the system is operating correctly and within its design safety limits. Stop work orders issued by safety organizations are lifted in accordance with MP 1.4.

(b) If the facility operations management and CSR agree that the system is within limits and operating safely, but are unable to establish the safety system to the satisfaction of the employee who stopped the work, then the employee's concern will be resolved in accordance with Management Requirements and Procedures (MRP) 4.14, "Resolution of Employee Concerns". Work may be resumed during the concern resolution process with the approval of the Independent Safety Review Organization.
Objective: e. Explain the double contingency principle.

e. Control of Fissionable Material

(1) **Double Contingency Principle**

(a) **Contingency** is an unlikely action, event, or occurrence that can cause a change in operating conditions, such that a prescribed safe operating condition or limit to be exceeded.

(b) Requires at least two (2) unlikely, independent and concurrent changes in process conditions before an accidental criticality is possible.

(c) In criticality safety ___________ need to be anticipated to determine if situation will be subcritical.

(d) No ___________ (single/double) error or equipment malfunction shall result in a criticality.

(2) Criticality parameters and controls of physical characteristics shall be incorporated into the design, operation, and administration of a fissionable material facility.
f. The following administrative controls must be in place before a WHC organization can have custody of fissionable material outside of a reactor core.

(1) Criticality Safety Evaluation Report (CSER) – Required for any operation which involves greater than exempt quantities of fissionable material.

(2) Criticality Prevention Specification (CPS) – Required for all Fissionable Material Facilities and may be required for some Limited Control Facilities.

(3) Radiation/Criticality Safety Postings – Required any time work is covered by a Criticality Prevention Specification.

(4) Operating Procedures may contain CPS limits and controls, posting is still required.

g. Criticality Safety Evaluation Report

(1) The purpose of a criticality safety evaluation report is to analyze all aspects of fissionable material operations to maintain the operations at an acceptable subcritical margin.

(a) If you are making design changes to criticality system make sure that those changes are within the CSER. Check with the CSR if there is any doubt or questions.

(b) Requests for Criticality Safety Evaluation (CSE) shall be made to Criticality Engineering Analysis if:

i) If changes to the limits are desired.
ii) Equipment design changes or equipment position changes outside present CSER.
Criticality Prevention Specifications

(1) Criticality prevention specifications are to provide rules for the safe handling of fissionable material. They shall be available for reference by the fissionable material handlers.

(2) A USER document that is controlled by the __________ (manager/CSR) and is reviewed and approved by the Independent Safety Review Organization.

(3) Criticality Prevention Specification Content
   (a) Fissionable material description section specifies the fissionable materials that may be handled and the physical and chemical forms of the materials that are approved for use under the CPS limits.
   (b) Description of operation and equipment section specifies the operations allowed and equipment that may be used.
   (c) Limits section specifies the technical limits that ensure double contingency for the approved operation, equipment, and material.
   (d) Process controls section will provide the additional controls to support the technical limits.
   (e) Supporting information section includes notes to help clarify the limits and process controls.

(4) Must comply with all aspects of the ________________ when working with fissionable material. Also may be written into procedures.

(5) The Criticality Prevention Specification is written from the ________________ Report (CSER) and shall reference this document. Therefore, these specifications are within the double contingency principle.

(6) Failure to comply with any requirement of a CPS is a nonconformance.

(7) If you exceed the Criticality Safety limits the critical status of the system is unknown.
i. Criticality Safety Posting

(1) This document is to supplement operation procedures by providing a ready reference to limits and controls important to criticality safety. Required if fissionable material is under the control of a criticality prevention specification.

(Four Facilities are; exempt, isolated, limited control, and fissionable material)

(2) ____________ Facilities - Containing ≤ 3% of MCM no posting for fissionable materials, they are exempt from most criticality controls.

(3) ____________ Facilities - Containing ≤ 1/3 of MCM. Posting required at entrances into the facility stating that the facility is isolated facility and specify a person to contact before bringing fissionable material into the facility.

(4) ____________ Facility - Containing > 1/3 of MCM but in a form where criticality is not possible. Posting is the same as a Fissionable Material Facility.

(5) ____________ Facilities - Containing > 1/3 MCM.

(a) Criticality Prevention Specification limits and controls that are controllable or observable shall be posted at each work station or storage location.

i) Distinctive in ____________ (color/design) and not easily confused with other posting. Purple boundaries is the preferred design.

ii) Shall be legible and conspicuously posted.

iii) Cannot contain noncriticality limits.

(b) Criticality limits may be documented in controlled operating procedures besides posting.
(c) Exceptions are approved by the Independent Safety Review Organization.

(6) Inventory sheets where required.

(a) __________ at each work station or storage location.

(b) Shall be ______________ by the person making the transfer.

(c) Never have more in the work location then allowed on the ______ posting.
j. Fissionable Material Labeling

(1) This procedure establishes consistent fissionable material labeling to insure positive identification.

(a) Material label shall be used to identify nonprocess containers holding one or more grams of fissionable material.

(b) Standard should be used whenever practical.

(2) The following are examples of nonstandard labeling:

(a) When labeling of individual units is not practical a single posting may be used.

(b) Fuel stored in inaccessible locations may be posted in the immediate vicinity.

(c) When samples are in small containers.

(3) Empty containers are to be labeled "" (full/empty) or "unloaded" as appropriate.

(4) Labeling of material shall be done if mistaken identity is possible.
k. Fissionable Material Storage

(1) All storage shall be conducted with an approved Criticality Prevention Specification.

(2) Use of fissionable material storage area for storage of other materials is prohibited unless the facility is designated as a multipurpose facility.

(3) Fissionable material shall be stored in closed containers and labeled.

(4) Limits for criticality safety shall be posted in conspicuous places near the storage area.

(5) "In Process" materials definition is unique to the facility who have a need for this classification.
   
   (a) The definition requires approval of DOE-RL and WHC Independent Safety Review Organization. Any changes in the definition must have this approval level.

   (b) This is not to be used as a loophole to get out of other requirements.

   (c) This is used to streamline operations.
Objectives:  ab. Identify typical engineering controls used in criticality safety.
ac. Identify the most positive design criteria for nuclear safety equipment.
ad. Identify the approvals that must be in place for changes to fissionable material operations that may impact criticality safety.

1. Plant Configuration Control

(1) Design shall include the most (positive/easiest) practical methods to prevent a criticality accident. Most positive controls are those that take less other controls to maintain criticality safety.

(a) Geometrically safe equipment
(b) Geometrically favorable equipment
(c) Fixed poisons
(d) Nuclear blanks
(e) Instrumentation
(f) Soluble poisons
(g) Administrative controls

(2) Engineering controls are required where appropriate and are preferred over administrative controls.

(a) The above engineering controls are preferred but are not always possible.

(b) The following controls shall be incorporated into the design, operation and administration of a fissionable material facility to the extent necessary to ensure the conformance with the Criteria for Criticality Safety Acceptance (section 1.5.1 of WHC-CM-4-29).

(c) The use of criticality parameters/factors to control the operation activities requiring the use of fissionable material. See section 2.5.2.2 of WHC-CM-2-29 for detail list and description.
(d) Areal Density Control — Restrictions allowed fissionable mass per unit area of a large slab.

(e) Flow Controls —

1) Nuclear Blanks — A barrier in a line to prevent flow besides the valve.

ii) In-line Orifices — Used to control flow of gases or liquids to prevent the development of undesirable conditions.

(f) Placement or Displacement Controls — fuel spacers, raschig rings, poisons, spacing limits, etc.

(g) Control on Material Compounds and Form — Restrictions on allowed composition and allowed physical state for fissionable materials at particular process stages, work stations, or storage locations.

(h) Chemistry controls to prevent material buildup in the system, i.e. pH, concentration, etc.

(3) Criticality Engineering shall provide ____________ (limits/procedures) for the criticality safety arrangement of equipment and procedures.

(4) ____________ (Nuclear Safety/Quality Control) inspects and verifies design parameters as identified in the criticality safety design requirements.

(5) Change control that affects criticality safety shall have:

(a) Approval of ____________ Safety Review Organization

(b) Review by ____________ (HPT/CSR)

* * *

(c) Work authorization (9.5.1.1) system in place that uses:

1) Approved safety equipment list.

* * *

(d) These approvals must be in place before changes can take place.

* * *

(e) The following require a-c above if they affect criticality safety:

1) Maintenance.

* * *

ii) Flowsheets.

* * *

iii) Engineering change notices.
iv) Procedure change authorization.
v) Criticality Safety approval of drawings.
Objective: List the responsibilities of the organization when shipping fissionable materials.

m. Fissionable Material Packaging and Transportation.

(1) The shipping organization is responsible for the safe packaging and shipping of fissionable materials until it is received and accepted by the receiver organization.

(2) Those with responsibilities in this area must read chapter 10 of Nuclear Criticality Safety Manual, WHC-CM-4-29.
Objective: list the purposes of a criticality alarm system

(a) Automatic initiation of an alarm system
(b) Identifies the equipment requirements for an alarm system
(c) Provides continuous detection of high radiological contamination
(d) Establishes the approximate time of a criticality event
(e) Must be at least two detectors for high radiation
(f) In areas where criticality alarms are required, a visual indicator is required
(g) Notify the appropriate personnel when the alarm sounds
(h) Notify the supervisor within 15 minutes of the alarm
(i) Testing of the alarm system is to be tested periodically

Criticality Alarm Systems

(1) The criticality alarm system:

- Provides continuous detection for high radiological contamination
- Establishes the approximate time of a criticality event
- Must be at least two detectors for high radiation
- In areas where criticality alarms are required, a visual indicator is required
- Notify the appropriate personnel when the alarm sounds
- Notify the supervisor within 15 minutes of the alarm
- Testing of the alarm system is to be tested periodically
(2) Emergency Actions

(a) If criticality alarm sounds run out of the facility.

(b) Get at least ________ (100/1000) ft. away from the building and proceed rapidly to the staging area.

(c) Separate into anti-C and nonanti-C clothing groups.

(d) A "Quicksort" will be performed by a HPT to:

   i) Check for __________ (neutron/gamma) activation of sodium (Na) in the body.

   ii) Determine who was close to the criticality accident.

(e) Must have Building Emergency Director's (BED) permission to reenter the building.
0. Criticality Accident Dosimeters

(1) Fixed station dosimetry is required in all fissionable material facilities.

(2) All personnel who enter an area with an installed criticality alarm system shall wear a Personal Nuclear Accident Dosimeter (PNAD).

(a) Both units are to characterize the radiation dose (gamma - neutrons).

(b) PNAD is to be replaced when:
   1) Damaged in any way.
   2) Activation elements or filters become lost or decrease to less than the size of a pencil eraser.
   3) Bar code number becomes illegible.

(c) Return permanently assigned PNAD to WHC Dosimetry when it is no longer needed for work assignment.
p. Firefighting

(1) To prevent criticality accidents the methods use to fight fires are analyzed. Knowledge of the firefighting restrictions are therefore needed by personnel.

(2) Category A - An area with no possibility of criticality if water is used to fight fire. No posting required.

(3) Category B - An area in which the use of water to fight fire may violate a criticality safety limit, however double contingency will be maintained. Posting is optional.

(4) Category C - An area in which fissionable material is present in amounts and configuration that could be made critical by the combination of fire, consequential conditions, the addition of water and concurrent rearrangement of the fissionable material. The only forms of water that may be used are high expansion foam, automatic sprinkler systems, limited water-volume systems, or hose fog nozzles. Posting required.

(5) Category D - An area in which criticality safety requires the exclusion of moderators. Only dry chemicals, gases or high expansion foam may be used. Posting required.
q. Inspections, Audits, and Appraisals

(1) Conducting periodic inspections, audits, and appraisals to ensure that the required procedures have been followed and safety precautions are being taken.

(2) Normal:

(a) Fissionable Material Facility - ________ (weekly/monthly)

(b) Isolated and Limited Control Facilities - quarterly

(3) The inspections shall be often enough to insure safe operations and is based on level of activity at the facility.
r. Recovery from Criticality Prevention Specification (CPS) nonconformance to maintain the safety envelope.

(1) Nonconformance of a CPS: A condition outside the boundaries of a CPS caused either by commission or omission.

(2) Types of nonconformances:

(a) Infraction - A CPS requirement was breached, but double contingency has been maintained and there is no realistic way to cause a criticality.

(b) Violation - A significant loss of control that either breached or had a high probability of breaching double contingency.

(3) Recovery from a known or suspected nonconformance.

(a) Static System - Leave the system as found and secure. The immediate location shall be physically secured against entry by locking, if possible, or cordoned off by ropes or other means. Post warning signs at appropriate locations stating that entry requires permission from the operating organization's manager.

(b) Dynamic System - Promptly take whatever action is necessary to maintain or improve the safety of the system. Take only those actions necessary to stabilize the system. In general, equipment should not be shut down until it is determined that the shutdown can be performed safely. Safe shutdown of operation may be required by the recovery plan. The immediate location shall be physically secured against entry by locking, if possible, or cordoned off and posted as (a) above.

(c) Do Not do anything that could cause an increase in reactivity of the system, increase the chance that a criticality would occur.
Secure against entry and against working with fissionable materials in the problem area.

(d) Immediately notify ___________ (immediate/level 2) manager.

(e) Manager notifies CSR and obtains other technical assistance required to determine if a nonconformance has occurred.

(f) A recovery plan is written according to section 15 of WHC-CM-4-29.
   
   i) If potential for criticality exists, recovery shall be according to section 16.
   
   ii) If recovery could increase reactivity then a written recovery plan shall be prepared.

   iii) If recovery will not increase reactivity, everyone agrees, then recover first. This is to prevent a more serious problem developing while writing the written plan.

(g) A review of the cause(s) of the nonconformance and a long-term corrective action plan shall be developed.
s. Disarming/terminating a critical or potentially critical system.

(1) Take no action to disarm or terminate a criticality except as outlined in section 16, WHC-CM-4-29. Planned by experts after careful review of the situation.

(2) If you suspect a "near miss" exists or an undefined system that could be dangerous. Have the facility evacuated if criticality alarms have not sounded.

(3) Building Emergency Director (BED) has the responsibility to:
   (a) Direct emergency operations at the affected building.
   (b) Assemble a task force to assess the potential hazard and determine the method for disassembly, disarming, or terminating the nuclear chain reaction.
   (c) Must have BED permission to reenter the building.

(4) Area Emergency Director (AED) has the responsibility to:
   (a) Direct emergency operations in the affected area.
   (b) Give permission for the disarming or terminating actions for a critical or potentially critical system.
ANSWER SHEET FOR CRITICALITY SAFETY MANAGER/ENGINEER HANDOUT

P. 2  A. 1. c. (1) two
     2. a. U-235, Pu-239
            b. U-235

P. 3  4. b. nucleus

P. 4  5. (1) Multiplication
            (3) critical

P. 5  B. 1. radiation
     3. heat or energy

P. 6  C. 1. mass
     a. critical
     a. sphere
     b. leakage

P. 7  c. increased
     (2) (a) leakage
     d. decreased

P. 8  3. reflector
     a. decrease
     b. fission
     d. 1/2

4. moderators
     a. 1000
     b. low
     (1) hydrogen
     (2) carbon
     (4) water
P. 9  d. moderator, reflector

P. 10 5. enrichment
   a. higher
   c. uranium

P. 11 6. concentration

P. 13 7. density
   a. high
   b. low

P. 14 9. volume
   10. interaction
   b. (1) three

P. 15 11. poison
   a. boron, cadmium

12. neutrons

p. 16 13. (1) neutron
   (2) (a) seconds
   (b) physical
   (c) leakage

P. 19 1. a. personnel injuries

p. 20 2. b. Nuclear Criticality Safety
   (1) (c) i) criticality
       iii) guidance

P. 21  v) emergency

P. 22 c. (2) (a) formal or classroom, two
        (c) i) quarterly
        ii) annual
p. 23 d. (1) management
P. 24 e (1) (c) contingencies
   (d) single
P. 25 f. (1) Evaluation
   (2) Criticality Prevention Specification
   (3) Criticality
P. 27 h. (2) Criticality Safety Representative
   (4) Criticality Prevention Specification
   (5) Criticality Safety Evaluation
P. 28 i. (2) exempt
   (3) isolated
   (4) limited control
   (5) fissionable material
  1) design
P. 29 (6) (a) maintained
   (b) initialed
   (c) criticality safety
P. 30 j. (1) (a) fissile
   (b) label
   (3) empty
P. 32 l. (1) positive (best)
P. 33 (3) limits
   (4) Quality Control
   (5) a) Independent
       (b) Criticality Safety Representative
P. 36 n. (1) (a) radiation
(e) three

(f) blue

(h) 25

P. 37 (2) (b) 100

(d) 1) neutron

P. 40 q. (2) (a) monthly

P. 42 (d) immediate
A.5.14.3

Nuclear Criticality Safety

by

L. Lowry
Why Do I Need to Know about Nuclear Criticality?

Because nuclear criticality accidents can be injurious and potentially fatal.
YOU ARE RESPONSIBLE FOR YOUR OWN SAFETY

LLNL management takes an active role in assuring the safety of personnel in their work. However, criticality safety is the responsibility of everyone involved in the processing of fissionable material.

The employee is responsible for:
- Learning the job procedure
- Stopping unsafe work
- Alerting management to unsafe conditions
- Taking appropriate action in an emergency.

VERY SPECIAL NUCLEI

You may be working with some very special nuclei, such as uranium-233, uranium-235, or plutonium-239. The fissionable nucleus splits into two new nuclei when it absorbs a neutron, and emits gamma rays and neutrons. If a large number of fissions occur at once, exposure to the flood of gamma rays and neutrons can kill or seriously injure you.
CHAIN REACTIONS...

SUBCRITICAL CHAIN

When a nucleus fissions, it emits neutrons—usually two, but sometimes more. One or more of these neutrons can cause other fissions, thereby giving birth to more neutrons. Thus, a fission chain is started. If, at some point, the last neutrons born in a chain fail to make fissions, the chain reaction dies out. Notice in the illustration that the last two neutrons have not made a fission, so the chain stops. This is called a subcritical chain.

CHAIN REACTIONS...

CRITICAL CHAIN

If one of the neutrons born of each fission causes on the average another fission, and this delicate condition is sustained, then the fission rate stays constant. This happens in nuclear power plants and is described as the reactor running at "just critical" or simply "critical."
CHAIN REACTIONS....
SUPERCRITICAL CHAIN

The chain reaction can increase rapidly if more than one fission is made by the neutrons born from each preceding fission. This is the supercritical condition, the condition that can send the flood of neutrons and gamma rays out in a short, powerful burst. The burst is usually terminated by a sudden expansion of the material.

WHAT IS A CRITICALITY ACCIDENT?

A criticality accident is the unintentional creation of a supercritical condition. Criticality accidents may be of brief durations or may endure for hours.
HOW CAN YOU TELL IF A CRITICALITY ACCIDENT HAS HAPPENED?

Most of the time you can't tell by just looking at it. The configuration of the material will look the same. It looks just like you left it. In some cases, however, certain effects may be noticeable.

WHAT SIGNS OF AN ACCIDENT MIGHT BE NOTICED?

Sometimes, the gamma radiation coming from the fissioning nuclei is intense enough to ionize some of the oxygen and nitrogen of the air. Some of the energy may be emitted in the form of light. You may be able to see a flash.

The gamma rays may dissociate some of the oxygen molecules near the assembly. The free oxygen atoms may then attach themselves to other oxygen molecules to form ozone, a substance which has a distinct odor. You may be able to smell ozone.

You may hear a sound. The energy heats the metal causing it to suddenly expand. Liquid systems are likely to splash.
CRITICALITY ALARMS

Because you may not see, smell, or hear anything that tells you a criticality accident has happened, we make sure you do hear something by providing a criticality alarm—a klaxon. The alarm is triggered by the neutrons or gamma rays that come from the assembly. When you hear it, run out the door! Don’t wait to turn anything off or put anything down. Just drop it, and run!

HEAT AND RADIATION ARE RELEASED IN A CRITICALITY ACCIDENT

When a criticality accident happens, the energy is released throughout the material. The energy of the neutrons and gamma rays is carried out of the material and can reach people standing nearby. This is the effect that can injure people. The heat, on the other hand, is absorbed in the material and usually does little damage. In liquids, however, there can be considerable splash.
IT'S STILL DANGEROUS AFTER THE BURST

When a criticality accident occurs, the initial burst of fissions may be over in a few milliseconds or less. After the period of supercriticality, the system will continue to emit harmful radiation. Staying near the material will increase your radiation dose. So, when you hear the criticality alarm sound (klaxon), run out of the room and stay out until re-entry has been determined to be safe.

DISTANCE LIMITS THE EFFECTS OF AN ACCIDENT

The distance between you and the radiation source is very effective in limiting injurious effects. Radiation dose falls off approximately as the inverse square of the distance. For example, if you are 30 feet away instead of 3 feet, your dose will be reduced to $\frac{1}{100}$th of the rate at 3 feet because 30 feet is 10 times as far as 3 feet and the square of 10 is 100. The dose levels shown here are for a burst of $10^{17}$ fissions.
THE CONSEQUENCES

50 rad: Detectable in the blood.
100 rad: Some of the people would lose hair.
200 rad: Almost everyone would become very sick.
400–500 rad: Death would be possible.
Over 600 rad: Death would be very likely.

HOW DO WE CONTROL PROCESSES SO THAT ACCIDENTS ARE AVOIDED?

Use these six controls

1. Limit the mass.
2. Control the shape.
3. Maintain separation.
4. Control moderation.
5. Control reflection.
6. Use neutron poisons.

Now, let's look at each of these in more detail.
1. **LIMIT THE MASS**

If the amount of fissionable material is small, the neutron may succeed in leaking from the system. Remember, most of what we regard as solid material is really empty space. (For example, if a nucleus In a solid piece of plutonium is represented by a ball one mile in diameter sitting on the surface of the earth, the next nucleus would be out at the distance of the moon. That's a lot of empty space.) As more fissionable material is added, the path through the material gets longer, and the chance for a collision increases. Finally, an amount is reached that makes the assembly critical. The Operational Safety Procedure specifies the maximum amount of fissionable material that can be used. Don't exceed it.

2. **CONTROL THE SHAPE**

Shape controls (affects) leakage. The farther the neutron has to travel through the material before it can escape, the more likely it is that the neutron will collide with a nucleus. Long paths mean a high likelihood of fission; short paths mean a smaller likelihood of fission. The sphere is the most effective shape for achieving criticality, because it has a minimum surface-to-volume ratio. This results in minimum neutron leakage for any mass.
3. MAINTAIN SEPARATION

Maintaining an appropriate spacing between subcritical units of fissionable material will control neutron interaction among the units, and thus prevent criticality. The spacing required is a function of the mass of the individual units and of the total mass of the interacting system.

4. CONTROL MODERATION

Materials that are effective in slowing neutrons down are called moderators. The illustration shows some good moderators which all contain lightweight atoms. Moderation is important because slowly neutrons are about a thousand times as likely to cause fission in uranium or plutonium as are high-speed (fast) neutrons. Consequently, it is possible that a non-critical mass of fissionable material with fast neutrons would be critical in the presence of moderators.
5. CONTROL REFLECTION

Reflectors may return neutrons leaking from a fissionable system, giving the neutrons a second chance to cause fissions. This is the result of neutron scattering in the reflector, which may also moderate the energy of the returned neutrons. Any material near the fissionable material will provide some reflection, even neutron poisons such as cadmium or boron.

6. USE NEUTRON POISONS

Boron and cadmium are the most commonly used neutron poisons in aqueous solutions. The word “poison” is used because it takes only a small amount to “kill” off the neutrons. The neutrons are slowed down by the water and are then easily captured by the boron or cadmium. If, however, the neutrons are fast, as in metal systems, boron and cadmium lose their special effectiveness as poisons.
WHAT'S GOING ON?

To understand what's going on, to know why fissionable material behaves differently as circumstances change, one must examine the behavior of neutrons. Some factors that influence the behavior of neutrons are: mass, shape, separation, moderation, reflection, poisons, and density of fissile material. Each of these factors will be considered in the following discussion.

WHERE ARE THE NEUTRONS?

Neutrons, along with protons, reside in the nuclei of atoms. The nucleus of plutonium-239 contains 145 neutrons and 94 protons. Together, they make up the isotopic weight of the Pu-239 nucleus, that is, $145 + 94$, or 239.
WHERE DO NEUTRONS COME FROM?

The most important source of neutrons, from a criticality safety viewpoint, is through fission. When a nucleus fissions, several neutrons are emitted.

WHAT PROCESSES OTHER THAN FISSION CAN PRODUCE NEUTRONS?

Some nuclei (Pu-238 for example) can fission without outside intervention. They may remain quiescent for an extended period of time, then without warning they split into two pieces, emitting neutrons at the same time.

Energetic nuclear particles often produce neutrons in collisions with nuclei. One important example of this is in collisions between energetic alpha particles and light nuclei, such as beryllium. Another example is in collisions between high-energy cosmic rays and the nuclei of most common materials.
WHAT HAPPENS TO NEUTRONS?

Five important things can happen to neutrons:

1. They can cause fissions.
2. They can be scattered (with an energy loss and a change in direction).
3. They can be captured by a nucleus and simply disappear.
4. If a neutron escapes absorption for a long enough time, it will spontaneously decay into a proton and an electron. The half life for this process is about 10.6 minutes.
5. They can leak from the system and be lost.

NEUTRONS CAN CAUSE FISSIONS

When a neutron is born from fission, it is moving at a very high speed. If it bumped into nothing along the way, it could go over 8000 miles in one second. When a neutron goes through material, however, there are many atoms in the way, about 10,000 billion billion atoms in each cubic centimeter. With so many opportunities for a collision, a fast neutron will typically travel a few cm before striking a nucleus. If the material is fissionable, the collision could result in absorption of the neutron usually followed by a fissioning of the nucleus, producing more high-speed neutrons.
NEUTRONS CAN BE SCATTERED

Scattering occurs when a neutron hits a nucleus and bounces off. This always results in some energy being lost by the neutron. The amount lost depends on the mass of the nucleus. For heavy nuclei the energy loss is small. This is very much like a cue ball hitting a bowling ball. The cue ball bounces off without much loss of speed. On the other hand, if the neutron hits a hydrogen atom, which weighs about the same as a neutron, the neutron can lose a lot of energy. That’s like a cue ball hitting another billiard ball. The cue ball could stop dead.

NEUTRONS CAN BE CAPTURED

If a neutron isn’t scattered when it hits a nucleus, it is absorbed. If fission doesn’t occur, a gamma ray is emitted and the nucleus has permanently captured the neutron. All nuclei, even fissionable ones, capture neutrons to some extent.

Some nuclei, boron and cadmium in particular, are very effective at capturing slow neutrons. Such nuclei are called neutron poisons because they capture so many neutrons in an assembly. But, since they are not particularly good at capturing fast neutrons, poisons are only useful in systems in which neutrons are slowed down.
DEPLETED URANIUM (D-38)

Depleted uranium (D-38) is what’s left of natural uranium after some of the $^{235}$U has been removed. At this point, it is typically 99.75% $^{238}$U. With so much $^{238}$U present, most of the neutrons born from fission in the $^{235}$U are captured in the $^{238}$U without causing fission. Furthermore, the $^{235}$U nuclei are so widely separated because of their low concentration that even a mountain of D-38 is subcritical.
LOW-ENRICHED URANIUM

Many nuclear power plants in the U.S. use low-enriched uranium as fuel. The water used to cool the reactor moderates the neutrons, and the neutrons are then able to cause fissions more readily. This increased likelihood of causing fissions, and the geometrical arrangement of the uranium and water, make it possible to achieve criticality in the presence of so much $^{238}\text{U}$.

NOW LOOK AT SOME MINIMUM CRITICAL MASSES

The materials that concern us are $^{235}\text{U}$, $^{233}\text{U}$, and $^{239}\text{Pu}$. These materials can be critical in very small amounts. In the following Illustrations, the materials will be bare, immersed in water, or dissolved in an aqueous solution. We'll use spherical shapes because they give the smallest critical masses. Notice that under similar conditions $^{235}\text{U}$ always has the largest critical mass and $^{239}\text{Pu}$ always has the smallest.
**SOLID SPHERE IN AIR**

For those neutrons that escape through the surface of the sphere, the air provides almost no reflection or moderation. The neutrons continue to move away from the spheres. Consequently, the critical masses are larger than they would be if reflection or moderation were present.

**SOLID SPHERE IN WATER**

Water reduces the amount of solid, fissionable material needed to go critical by about a factor of two. The neutrons are partially moderated and some are reflected back. Compare these masses with those for air.
SPHERICAL SOLUTIONS IMMERSED IN WATER

When the fissionable material is dissolved in a water/acid solution, the amount needed to go critical is quite small. The neutrons are fully moderated and many are reflected back into the solution. Compare these numbers with the previous ones.

PROCEDURES

In addition to understanding the physics of fission, it is important to have a carefully established set of procedures to follow when handling fissionable material.

The Fissile Material Card at the work station gives the mass and liquid limits. These limits must be obeyed. The Mass Control Record Card, also at the work station, specifies the sequence of steps that must be followed in identifying the fissionable material and verifying its mass before putting it into a glove box.

Careful attention to procedures, and a knowledge of what is happening in the nuclear processes, will help you work safely with fissionable material.
A.5.14.4

Fundamental Concepts and Simple Fissioning Systems

by

T. McLaughlin
FUNDAMENTAL CONCEPTS
AND SIMPLE FISSIONING SYSTEMS

Thomas P. McLaughlin

I. INTRODUCTION

To accommodate the diverse levels of both experimental and theoretical knowledge of nuclear matters of those participating in this course, basic concepts and nomenclature will be introduced, but mathematical developments will, in general, not be presented. References are given for those who may wish to explore the mathematics and physics that underlie the materials covered herein. However, this course has been and will be of interest to people of various backgrounds, and therefore departures from and/or elaborations of this textual material will be made as the questions raised by the participants demand.

Wherever appropriate, the fundamental processes and concepts will be clarified and amplified through examples. Additionally, the tie-in between these somewhat abstract concepts and the real world of criticality safety will be emphasized and reinforced, particularly by the experimental sessions, so that they can later prove useful in guiding your thoughts and decisions concerning the criticality aspects of a particular design, modifications to an existing design, a particular operation, changes in a particular operation, proposed new operating procedures, and so forth. Two important goals of this course are to convey sufficient awareness of factors that affect criticality, and the consequences of accidental nuclear excursions so that realistic, meaningful balances between risk and benefit can be achieved. It is dangerously misleading to imply or believe that risks can be entirely eliminated in any endeavor. What we should strive for is knowledge and perspective which can be applied to maintain risk at an acceptably low level.

II. CRITICALITY SAFETY VERSUS RADIATION SAFETY

The distinction between these two areas of safety concern should be made clear from the outset. There are thousands of radioactive species in the world, most of which have been manmade during the last few decades, but a few are naturally present in our environment, stemming from the origin of our planet. All radioactive materials possess some potential for being hazardous to your health, and thus appropriate care should be exercised when working with them. On the other hand, criticality safety concerns itself with only a few of these radioactive species — for most practical purposes only with plutonium and uranium.

For example, tritium (symbol \(^{3}\text{H}\)) is radioactive and potentially hazardous if it somehow gets into the body. Tritium cannot, however, undergo the fission process (as can uranium and plutonium), and thus the radiation emitted from a fixed quantity of tritium can never increase but can only decrease with time. In contrast, the rate at which radiation is released from uranium or plutonium (due to the fission process) can be increased or decreased by varying its condition or environment, that is, by changes in the geometry of the specimen, addition or removal of surrounding materials (hands, water, etc.), and concentrating or diluting, as with solutions.
Since penetrating radiation (neutrons and gamma rays) is emitted with each fission event, the radiation exposure one is subjected to will rise and fall with the fission rate. Under normal operations involving the handling and processing of plutonium and uranium, the multiplication factor of a system (to be defined later) is kept well below unity (typically in the range 0.1 to 0.8). If during an accident situation the multiplication factor should exceed unity, then the fission rate will rise extremely rapidly with little or no time for an operator to react before inherent, natural mechanisms will reduce the fission rate. If this were to occur, then the radiation exposure could be substantial or lethal even though the duration of exposure will likely be much less than one second and no or minimal mechanical damage will result.

Criticality safety, then, is concerned with planning and conducting operations with uranium and/or plutonium in such a manner that the multiplication factor remains well below unity at all times, i.e., that a nuclear excursion will not occur under both normal and credible abnormal conditions and may reasonably be designed against.

It should be stressed that criticality safety, like other safety areas (vehicular, electrical, falls, fire, etc.), should be taken seriously, but only in proportion to the potential consequences, and further only when weighed against the other areas of safety. For example, if one were to calculate (or even hypothesize) that during an extreme earthquake the uranium/plutonium associated with a certain operation or system could rearrange itself so that the state of criticality of the rearranged material could exceed unity, then one might argue that this situation should be designed against. However, it would not generally be cost effective to spend time and money designing against the criticality if the postulated earthquake is of sufficient severity to destroy the building. The reason for this is twofold: the collapsing building will likely kill any occupants, and the consequences of accidental criticalities are not mechanically damaging and are localized to within a few meters of the event. Thus, personnel even in an adjoining room have never received lethal radiation exposures from a criticality accident.

III. NOMENCLATURE AND BASIC PROCESSES

We are concerned with the behavior of neutrons in material. A neutron is a chargeless particle of approximately the same mass and size as a proton, or if you will, the same as the nucleus of an hydrogen atom; namely,

\[ M_n = 1.7 \times 10^{-27} \text{ kg} \]

and a diameter of

\[ D_n = 2.4 \times 10^{-16} \text{ m}. \]

To put these small quantities in perspective it is useful to consider the relative sizes and masses of neutrons and nuclei of atoms. On a relative scale, the neutron and proton (hydrogen nucleus) have a mass of 1, and all other nuclides have relative masses equal to their mass number. For example, \(^{239}\text{Pu}\) has a mass equal to 239 times the neutron mass, and \(^{12}\text{C}\) has a mass equal to 12 times the neutron mass.

Now consider sizes and distances. For our purposes, we may treat neutrons and atomic nuclei as spheres whose diameters, \( D \), vary according to \( D_A = D_n A^{1/3} \), where \( A \) is the atomic number. Thus, aluminum, which is 27 times as massive
as a neutron \((A = 27)\), has a nucleus whose diameter is only 3 times as great as that of a neutron. The "heavy" elements such as uranium and plutonium have nuclei about 6 times as large as the neutron. Finally, consider distances between atomic nuclei. These are typically \(1-5 \times 10^{-10}\) m. Thus the distance between nuclei is about ten thousand times as large as the size of the nucleus itself! For example, if a neutron were the size of a pea, then the distance between the nuclei of adjacent atoms would be the length of a football field.

Consider a neutron impinging on a slab of aluminum as shown in Figure 1. The neutron may or may not interact in the slab. If no interaction occurs then the neutron is said to have *leaked* from the slab, or the process is referred to as *leakage*. If an interaction does occur, then it may be a *scatter* process or an *absorption* process.

![Figure 1. Basic neutron interaction modes.](image)

During scatter, the neutron's direction and to some extent its energy (speed) change but continues on until finally the neutron is either absorbed or it leaks out of the slab. The absorption process captures or absorbs the neutron. The result of this absorption process is a new, radioactive form of aluminum with a nuclear mass of 28 units. But for our purposes the important fact is that a neutron was lost to the system forever. The subsequent radioactive decay of \(^{28}\text{Al}\) does not release a neutron but instead an electron. The absorption process is often represented in equation form as \( ^1n + ^{27}\text{Al} \rightarrow ^{28}\text{Al} \), where the plus sign (+) signifies absorption.

A simplistic description of the scatter and absorption processes may be to visualize the former as hard sphere collisions, e.g., a marble (the neutron) bouncing

*Fundamentals 3*
off (scattering) a billiard ball (the nucleus of the aluminum atom), while the latter may be thought of as one sticky gumball (one that has been well chewed — the neutron) colliding with and sticking to (being absorbed by) a larger sticky gumball (again, the nucleus of the aluminum atom.) Strange as it may seem, the neutron-nucleus collision may behave like a marble bouncing off a billiard ball one time (i.e., scatter process) and then two sticky gumballs the next (i.e., absorption process).

Although one cannot be sure what the outcome of a particular neutron-nucleus interaction will be, all is not lost. Measurements, aided by theory, have been performed that have told us probabilities or likelihoods of particular modes of interaction per atom.

The various interaction processes have been both measured and theoretically predicted in terms of the probability of a particular event per target atom or in terms of the total probability of all interaction events per target atom. A near-universal name for these probabilities is the term cross section. The cross section (or probability) for a particular event is generally reported in units of barns (1 barn = $10^{-24}$ cm$^2$) and given the symbol sigma ($\sigma$). For most interactions of interest to us, the cross section (per atom) generally lies within the range 0.001 to 1000 b, or $10^{-27}$ to $10^{-21}$ cm$^2$.

Note that $10^{-24}$ cm$^2$ is roughly equal to the geometric cross-sectional area subtended by the nucleus of an atom. However, the similarity ends there. Actual cross sections generally vary substantially:

- from material to material and isotope to isotope,
- with the energy (speed) of the incident neutron, and
- with the type of process (scatter, absorption).

Look at a few examples of cross sections shown in figures 2, 3, and 4. Although it is difficult to make generalizations about cross sections, two that are reasonably consistent are: the absorption cross section rises steeply at low neutron energies, and scatter cross sections are usually slowly varying and reasonably independent of the energy of the neutron.

4 Fundamentals
Figure 2. Fission cross sections for selected isotopes.
Figure 3. Scatter cross sections for selected isotopes.
CAPTURE CROSS SECTIONS

Figure 4. Capture cross sections for selected isotopes.
The fission process, that has not been mentioned until now but is indicated on Figure 5 for $^{236}$U, is actually a subset of the absorption cross section for the heavy elements (uranium, plutonium, thorium and other heavy elements). For these heavy elements, the absorption cross section can be subdivided as:

$$\text{Absorption} = \text{Capture} + \text{Fission (heavy atoms only)}.$$ 

That is, the fission cross section is zero for all other (lighter in atomic mass) elements at neutron energies of interest.

$$\begin{align*}
\text{20\%} & \quad \text{$^{236}$U (Capture)} \\
\text{80\%} & \quad \text{$^{87}$Br + $^{147}$La + 2$^1$n (Fission)}
\end{align*}$$

Figure 5. Neutron interaction with uranium.

The percentages shown indicate that roughly one time in five (20\%) the absorption leads to a $^{235}$U atom, and the remainder of the time (80\%) the neutron, upon being absorbed by the $^{235}$U nucleus, will cause the nucleus to immediately blow apart (fission). The products of this fission event are typically two rather heavy atoms, called fission fragments or fission products, and a few neutrons. The significant result of the fission event is the liberation of neutrons, which can then propagate the fission process in other $^{235}$U nuclei. This propagation is generally referred to as a chain reaction. Expressed differently, then, our goal in criticality safety is designing systems and planning operations such that fission events (which also occur naturally in uranium and plutonium) lead to chain reactions that die away with time rather than grow.

A. NEUTRON ENERGY AND SPEED

Let us turn for a minute to the neutron's energy and its time of emergence subsequent to a fission event. Neutrons are "born", i.e., emerge from a split nucleus, as "fast" neutrons, and have energies in the 1-3 MeV (million electron volt) range. The velocity of a 1-MeV neutron is $\sim 13$ million (1.3 x 10$^7$) meters per second (m/s). At normal room temperature (~20°C), molecular motion energy is only 0.025 eV. If neutrons are slowed down (by way of collisions with other nuclei) to this energy, then their speed is reduced to ~2,000 m/s. That neutrons can be slowed down and the import of this fact to criticality safety will be made clear in subsequent sections.
B. PROMPT AND DELAYED NEUTRONS

Nearly all neutrons that are born as a result of fission events appear essentially instantaneously. That is, within $10^{-15}$ seconds after the fission event is detected, the neutrons may also be found (detected). These neutrons are known as prompt neutrons. The number of prompt neutrons which are released, with any particular fission event may vary from 0 up to about 6, i.e., it has a statistical nature. But one can characterize the average number of prompt neutrons per fission by experimentally observing a large number of fission events. For the two most common fissioning species, these data are:

\[
^{235}\text{U} \sim 2.5 \text{ neutrons per fission}
\]

and

\[
^{239}\text{Pu} \sim 3.0 \text{ neutrons per fission.}
\]

These values depend slightly on the energy of the neutron that causes the fission, but this dependence is generally unimportant for criticality safety purposes.

A very small percentage of the time, however, a neutron may not be born until seconds or tens of seconds after the fission event has occurred. These neutrons arise from the radioactive decay of certain fission products and are known as delayed neutrons.

An example of delayed neutron emission is given (Fig. 6) by the decay scheme for $^{87}$Br. Note that the half-life for $^{87}$Br decay is 55 seconds and that not every decay proceeds from neutron emission. If the decay does follow the route $^{87}$Br to $^{87}$Kr (excited), however, then a neutron will appear almost simultaneously with the $^{87}$Br decay, because the half-life of the $^{87}$Kr (excited) is short compared to 55 seconds.

![Figure 6. Example of delayed neutron emission.](image)
The fractions of all neutrons born subsequent to the fission process which are prompt (and delayed) for $^{235}\text{U}$ and $^{239}\text{Pu}$ are as follows:

<table>
<thead>
<tr>
<th>Element</th>
<th>Prompt</th>
<th>Delayed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{235}\text{U}$</td>
<td>0.993</td>
<td>0.007</td>
</tr>
<tr>
<td>$^{239}\text{Pu}$</td>
<td>0.997</td>
<td>0.003</td>
</tr>
</tbody>
</table>

These are average numbers which result from observing many fission events.

Although this relatively small fraction of neutrons that is delayed is generally not important in criticality safety considerations, it is all important in permitting control of the chain reaction, e.g., in controlling the fission rate in a reactor. Thus its significance will be discussed more fully later and emphasized in the experimental sessions when we actually run our critical assemblies (zero power) here at Pajarito Site.

IV. SIMPLE FISSIONING SYSTEMS

There are many forms in which fissionable material is processed, handled, used, etc. Examples are:

- solid metal (spheres, cubes, cylinders, slabs, etc.),
- ceramics ($\text{UO}_2$, UC, PuC, UBe$_{100}$, UC$_{1000}$ for reactor fuel),
- foils, turnings (from machining operations), and
- solutions (chemical reprocessing).

Although this list is not complete, for illustrative purposes let us consider two extremes: solid metal and hydrogenous solutions. That these are indeed extremes will be brought out later. Ceramics and foils generally possess the neutronic characteristics of solid metal systems; however, if the fissionable material is very dilute, e.g., UC$_{1000}$ or thin foils interspersed between layers of paraffin (hydrogenous), then the system has solution-like characteristics. The determining factor whether or not a system behaves neutronically like a solid metal or solution is the degree of dilution of the fissionable species ($^{235}\text{U}$, $^{239}\text{Pu}$) with other (usually light) atoms. Typical solutions contain H : $^{235}\text{U}$ ratios of a few hundred to one. Obviously, there are systems that lie between these two simplified extremes of solid metal or solution, but knowledge of these two bounds will enable a reasonable understanding of any intermediate system, such as metal turnings in a waste container that was accidentally flooded with water or oil.

There is one further subdivision of these two limiting types of systems that is of interest. Again, for purposes of understanding basic processes and concepts, a system can be considered bare (not reflected) or reflected. The terminology here refers to whether neutrons upon leaving (leaking) from a fissioning system can scatter off surrounding material (actually the nuclei of the atoms thereof) and return to the fissioning system. Although in reality no system can be considered 100% unreflected, since even air will scatter some neutrons, it is convenient to consider this a limiting situation since many systems are for all practical purposes bare. Examples are the Godiva-IV and Jezebel assemblies at Pajarito Site and
reprocessing solutions in thin-walled tanks. Recall that the total interaction cross section is different for each material and is also dependent on neutron energy, but on the average, neutrons will travel from 1- to 10-cm in a dense material before interacting. Idealized systems of these four categories (solid metal and solution both bare and reflected) will be discussed individually in the following sections.

A. SOLID METAL — BARE

Although one generally must speak of average properties of a system, such as the average scattering cross sections or the average number of neutrons per fission, for a moment consider a single neutron and take the neutron's perspective as it travels in a system containing only uranium or plutonium atoms. Recall that a neutron travels only in straight lines between scattering events until it eventually leaks out of the system or is absorbed by a uranium (plutonium) nucleus. Looking at the scattering process on a relative basis, one realizes that since the uranium or plutonium nucleus is ~238 times as massive as the neutron, the situation may be likened to a fast moving marble striking a stationary billiard ball. The latter will not move perceptibly, while the former will bounce off in some direction with essentially the same speed it had before the scatter event.

Now, consider a system consisting of 235U metal pieces, e.g., on a bench and in a geometric arrangement such that the following averages characterize the system:

- Leakage probability = 0.5;
- Absorption probability = 0.5;
- Total "loss" probability = 1.0.

These system probabilities are not to be confused with the microscopic cross sections discussed previously. The distinction is that these system (average) probabilities are determined by both the microscopic cross sections and the physical arrangement of the system. As we mentioned earlier, the cross section is dependent only on the neutron's speed or energy for a given target atom, but obviously whether or not a neutron is absorbed in a 10-kg piece of pure 235U metal or leaks out clearly depends on the shape of the 10-kg of 235U. For example, as a dense sphere about the size of a grapefruit, there is a fair chance that a neutron will be absorbed by a 235U nucleus before leaking from the sphere. On the other hand, that same 10-kg uranium, when made into a thin foil 0.2-cm thick and 10-cm wide, would have a length of 535 cm. Clearly if this foil is laid flat (as opposed to being all coiled up like a watchspring), then a neutron born in the foil by natural radioactive decay will have essentially a 100% likelihood of leaking from the uranium. Note that a neutron may undergo many scatter events before leaking from the system boundaries, but for the purpose at hand, a scatter event is essentially a nonevent, since the neutron changes its direction only, not its energy (speed).

Following this example further, imagine a snapshot to be taken of the system at an instant in time that revealed 100 neutrons to be zipping around within the system boundaries. Although each individual neutron will either be absorbed or will leak out of the system at a slightly different time subsequent to the snapshot, the average lifetime of all the prompt neutrons from their time of birth to either absorption or leakage from the system can be thought of in much the same way we think of human lifetimes and generations.
With the given probabilities, how many second-generation prompt neutrons will arise from these 100 first-generation neutrons?

\[
\text{Leak out} = 100 \times 0.5 = 50 \text{ neutrons} \\
\text{Absorbed} = 100 \times 0.5 = 50 \text{ neutrons}
\]

This accounts for all of the first-generation neutrons; however, of those 50 that are absorbed there will result

\[
\text{Capture} = 50 \times 0.2 = 10 \text{ neutrons}, \\
\text{Fission} = 50 \times 0.8 = 40 \text{ neutrons},
\]

and 40 fission events on the average will yield, 40 fissions \(\times 2.5\) neutrons per fission = 100 second-generation neutrons.

In this simplified example, the prompt neutrons have exactly reproduced themselves, and since we are neglecting delayed neutrons from the present discussion, this leads us to the definition of the multiplication factor and state of criticality.

\[
k = \text{multiplication factor}
\]

\[
= \frac{\text{number of fission neutrons in current generation}}{\text{number of fission neutrons in the previous generation}}.
\]

For this example (and recall that delayed neutrons have been omitted from the discussion), the multiplication factor is

\[
k = \frac{100}{100} = 1.0 \text{ (critical)}
\]

Additionally, if

\[
k < 1, \text{ the system is said to be subcritical, and if}
\]

\[
k > 1, \text{ the system is said to supercritical.}
\]

With this simple system that is exactly critical, let us imagine that the average probabilities that characterize the system are suddenly changed to

\[
\text{Leakage probability} = 0.4, \\
\text{Absorption probability} = 0.6, \\
\text{Total "loss" probability} = 1.0.
\]

This sort of change could occur due to the addition of more material to that already present or merely rearranging the existing material (such as bringing pieces together) or due to a change in any other material near the uranium piece(s).
Now let us calculate the state of criticality of this system.

Leak out = 100 x 0.4 = 40 neutrons
Absorbed = 100 x 0.6 = 60 neutrons

As before, of those 60 that are absorbed by $^{235}$U nuclei there results

Capture = 60 x 0.2 = 12 neutrons,
Fission = 60 x 0.8 = 48 neutrons,

and on the average, 48 fission events will yield 48 fissions x 2.5 neutrons per fission = 120 second-generation neutrons and

$$k = 120 / 100 = 1.2 \text{ (supercritical)}.$$ 

Thus we have made a physical change to our system that resulted in the multiplication factor going from 1.0 to 1.2, i.e., our system has changed from exactly critical to supercritical. The consequence of this is that whereas before the neutron level in our system was just maintaining itself, now with each generation the neutron population (and fission rate) is increasing by a factor of 1.2. The detailed implications of this $k = 1.2$ on the actual rate of rise in the neutron population will be examined in Section V. Suffice it to say here that the fission rate will rise in much less than 1 second to a level such that overheating will occur, causing the fission rate to reduce itself, but only after a substantial number of fissions have occurred — accompanied by large (and possibly fatal) neutron and gamma-ray exposures to personnel in the immediate vicinity. Let us turn now to a second idealized system.

B. SOLID METAL — REFLECTED

For this example imagine that a sphere of $^{235}$U was undergoing various mechanical tests in a generally unreflected geometry (i.e., on a bench). Then, due to a procedural mistake the sphere was inadvertently enclosed in a thick shell of some heavy-atom material (iron, lead, tungsten, etc.). The reason for specifying a heavy-atom reflecting material is so that neutron slowing down via scattering can be neglected.

Assume that in its unreflected state that the average probabilities characterizing the sphere are:

Leakage probability $= 0.6$
Absorption probability $= 0.4.$

The multiplication factor in this state is then,

$$k = 1.0 \times 0.4 \times 0.8 \times 2.5 = 0.8 \text{ (subcritical)}.$$ 

Now, as a rule of thumb, a good reflecting material which completely enclosed a system can make as much as a factor of 2 change in the critical mass, which is defined as "that amount of material that will just sustain a chain reaction ($k = \text{Fundamentals}$
1.0) for the stated conditions." For compact geometries, a factor of two change in the fissile mass corresponds roughly to a multiplication factor change of 25%. Thus, assume in the reflected state our probabilities are changed to

Leakage probability = 0.5
Absorption probability = 0.5

The multiplication factor has then changed to

\[ k = 1.0 \times 0.5 \times 0.8 \times 2.5 = 1.0 \text{ (critical)} \]

Here we see that a system which was initially quite subcritical in its normal state, \( k = 0.8 \), became critical because of a postulated operational error. As a factor of two change in the mass of material required for critical is about the most that can be achieved in going from bare to well-reflected, for any system, operations are generally designed and planned such that for normal operating conditions \( k < 0.5 \). Then, in the event of an inadvertent reflection, such as a result of water flooding, the state of criticality, although it may increase by as much as 10 or 20%, will still be well below unity; that is, the system will be subcritical.

The two idealized systems we have just covered are often described as fast systems, the adjective referring to the velocity (~1.3 x 10^7 m/s) of the neutrons that cause the majority of the fissions.

The next two systems to be discussed are often characterized as thermal systems since the velocity of the neutrons causing fission is about 2,000 m/s, which is the velocity of molecular motion at room temperature.

C. SOLUTION — BARE

Although we often associate the word liquid with the definition of a solution, for our purposes we take the more general interpretation, which includes mixtures of solids and possibly gases. As we mentioned previously, the constituents need not be intimately mixed in order that the system have the neutronic characteristics of a solution. All that is necessary is that a neutron will typically scatter many times with diluent atoms for every interaction with a fissile atom. Examples are:

- plutonium nitrate (100 g/l Pu), H : Pu ~ 250 : 1,
- uranium + beryllium mixture; Be : U ~ 100 : 1, and
- 0.075-mm-thick uranium foils interspersed between 12.7-mm-thick Lucite plates.

The discussion that follows is restricted to solutions in which the diluent atoms have low atomic weights, i.e., the light atoms. This category generally includes atoms up to and including carbon (A = 12). The distinguishing feature of these solutions is that fast neutrons may lose appreciable amounts of energy when scattering off the diluent atoms. Since there are many more diluent atoms than fissile atoms in a solution, there is a high likelihood that a fast neutron (~1 MeV) will scatter many times with the diluent atoms and thereby lose energy until the neutron finally attains an energy roughly equal to that of the atoms and molecules in the system. For a system at 20°C, this is 0.025 eV (2,000 m/s).

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This neutron which has been moderated (thermalized) will now move about in the system until it either leaks out or becomes absorbed by one of the diluent nuclei or by a fissile nucleus. Although this is also exactly what fast neutrons do in a metal (unmoderated) system, there is a very important difference.

The relative cross sections of the nuclides — in particular the fissile nuclides — change dramatically with the energy of the neutron. Recall the figures depicting this dependence on the energy of the neutron (Figs. 2, 3, and 4). While the probability of a scatter event in $^235\text{U}$ has stayed relatively constant over the entire energy range ($10 \text{ MeV} \rightarrow 0.01 \text{ eV}$), the absorption cross section is ~100 times greater for thermal neutrons than for fast neutrons. Thus, a thermal neutron is much more likely to be absorbed during any one interaction with a $^235\text{U}$ nucleus than is a fast neutron. Put another way, the fast neutron is much more likely to scatter a few or perhaps many times and eventually leak out of the system than a thermal neutron, which will likely not scatter but be absorbed.

To illustrate the dramatic effect the thermalization of neutrons can have, consider the following, which compares the minimum critical $^235\text{U}$ mass for bare spheres of uranium metal and solutions of uranium and water.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^235\text{U}$ Mass, kg</td>
<td>48.7</td>
</tr>
</tbody>
</table>

These numbers show a factor of 30 difference in the critical masses of these two systems. The uranium used in the calculations that yielded these results is standard Oralloy or U(93), that is, 93.2 wt% $^235\text{U}$, ~5.8 wt% $^238\text{U}$, and ~1 wt% $^{244}\text{Pu}$.

If one were to perform calculations with uranium that was 100 wt% $^235\text{U}$ then these values would be reduced slightly. Conversely, as the $^{235}\text{U}$ fraction of the uranium is reduced, the critical mass increases rapidly. As a final example of an idealized system, consider fissile material reflected by a low-atomic-mass material.

D. METALS OR SOLUTIONS REFLECTED BY MATERIALS OF LOW ATOMIC MASS ($A \leq 12$)

This system introduces nothing new in the way of basic concepts or processes. The significance of considering this system is linked directly to criticality safety. As has been previously mentioned, the critical masses of bare systems are potentially as much as twice as large as the critical masses of well-reflected systems. Put another way, if a bare system has a multiplication factor of ~0.8 and it is inadvertently (accidentally) reflected, the increase in the multiplication factor may be sufficient for $k$ to exceed unity.

System changes that lead to undesired increases in the state of criticality are designed against, if they are recognized a priori and if considerations of the likelihood of occurrence and the cost and inconvenience associated with the design changes warrant it. A typical example of a consideration that is always given to bare systems is the possibility of flooding, i.e., reflection by water. This is because water is a good reflector, and it can completely surround the system in question easier than any solid material could. Events such as roof leaks, water pipe ruptures, and drain plugging can and do happen. On the other hand, reflection by some solid materials can lead to increases in the multiplication factor even greater than water reflection can, but this would nearly always require gross procedural and human factors errors in judgment and generally could not occur accidentally.
V. TIME BEHAVIOR OF FISSIONING SYSTEMS

During routine operations involving fissile materials (excluding reactors), the multiplication factor is held far below unity. If the multiplication factor is changed, then the rate of occurrence of fissions will also change. In analyzing this temporal behavior from a practical criticality safety standpoint, only prompt neutrons need be considered. However, to provide a more thorough groundwork, especially for the experiments to be conducted during this course, let us examine the importance of delayed neutrons in controlling the fission rate (i.e., power level) in systems that are intentionally brought almost to or slightly in excess of a critical state \((k = 1.0)\).

Consider the possible range of \(k\) for uranium and plutonium systems, as indicated in Figure 7. The upper limit on \(k\) is only approximate and can never be achieved in reality. It is of no practical consequence to criticality safety.

\[
\begin{array}{c|c|c}
\text{Critical} & \leftrightarrow \text{Subcritical} & \leftrightarrow \text{Supercritical} \\
\hline
0.0 & 1.0 & \sim 2.0
\end{array}
\]

Figure 7. Multiplication factor, \(k\).

To show that delayed neutrons need not be considered, in general, for criticality safety purposes, we may separate the multiplication factor into components,

\[
k = (1 - \beta)k + \beta k
\]

\[
= k_p + k_d
\]

where \(k_p\) is the prompt multiplication factor = \((1 - \beta)k\) and \(k_d\) is the delayed multiplication factor = \(\beta k\).

Recall that the delayed neutron fraction, \(\beta\), is only 0.007 for \(^{235}\text{U}\) or 0.003 for \(^{239}\text{Pu}\), thus \(k_p = (1 - \beta)k = k\), which clearly shows that if the system is accidentally made supercritical, \(k > 1\), then in all likelihood, a super-prompt critical state, \(k_p > 1\), will also be reached.

Let us emphasize this point with two examples:

Case 1: \(k = 1.1\), or, the multiplication factor exceeds that for critical by 10\%. Now, \(k_p = (1 - 0.007)(1.1) = 1.092\), and the system is supercritical on prompt neutrons alone.

Case 2: \(k = 1.01\), or the multiplication factor exceeds that for critical by only 1\%! Now, \(k_p = (1 - 0.007)(1.01) = 1.003\). Note that even for a system that is only 1% supercritical, the system is still supercritical on prompt neutrons alone.

Now let us turn to the time dependence of the prompt neutron population during a criticality accident \((k_p > 1)\).

It can be shown that the rate of change of the prompt neutrons in a system is given by

\[
n(t) = n_0 e^{\lambda t}
\]  

(1)
for an abrupt (step) change in $k$, where

$n_0 = \text{neutron level before the change in } k,$
$k'_n = \text{prompt multiplication factor after the change in } k,$
$l' = \text{average lifetime of prompt neutrons in the system},$
$t = \text{time, referenced to } t = 0 \text{ at the time of the change in } k, \text{ and}$
e = \text{base of natural logarithms} = 2.718 \ldots .

For unmoderated (fast) systems, the prompt neutron lifetime is in the range

$$10^3 < l < 10^5 \text{ seconds},$$

and for well moderated systems,

$$10^4 < l < 10^3 \text{ seconds}.$$

Systems that are only weakly moderated, e.g., $5 < H : U < 50$, would have average prompt neutron lifetimes between these bounds.

Although the prompt neutron lifetime is as much as 100,000 times longer in a thermal system than in a fast system, the important point is that the lifetime is short by comparison to human reaction times for all fissioning systems! Some examples will make the significance of this clearer.

Consider an abrupt change in $k$ from any subcritical state to a $k'_n$ of 1.1. According to Eq. (1) the prompt neutron population will increase as

$$n(t) = n_0 e^{0.1 - t}.$$

For the two extremes, $l = 10^3$ and $l = 10^4$ s, how much will the original neutron level have increased in only 0.1 second, in 0.2 seconds, and 1.0 second?

For $l = 10^3$

$$n(0.1) = n_0 e^{10} = 22,000 \ n_0,$$

$$n(0.2) = n_0 e^{20} = 485,000,000 \ n_0.$$

For this slow system, the neutron population (and thus the fission rate and the radiation (neutron and gamma) level in the vicinity of the system) has increased nearly a billion-fold in only two-tenths of a second. And, at

$$n(1.0) = n_0 e^{100} = 3 \times 10^{43} \ n_0.$$

This value could never be reached because overheating or other natural mechanisms would reduce the multiplication factor below prompt critical, but only after a large release of radiation (in much less than one second).

For $l = 10^4$, 

$$n(0.1) = n_0 e^{1,000,000}$$

$$n(0.2) = n_0 e^{2,000,000}$$

and,

$$n(1.0) = n_0 e^{100,000,000}$$

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How would this situation have been modified if the hypothetical accident had led to a state of criticality only slightly supercritical, say \( k = 1.017 \)? Since \( k_p = (1 - \beta)k \), let us assume the system is uranium bearing, for which \( \beta = 0.007 \); then \( k_p = 1.01 \).

Now, in one second the neutron population will rise to:

For \( l = 10^8 \), \( n(1.0) = n_0 e^{10} = 22,000 \ n_0 \).

For \( l = 10^4 \), \( n(1.0) = n_0 e^{1000} \).

Thus even for states of criticality only slightly supercritical and even for very thermal systems with relatively long prompt neutron lifetimes, the fission rate and neutron population will increase on a time scale that will result in the excursion terminating itself before human reactions have a chance to influence the outcome. These nuclear excursions will result in little or no mechanical damage to the fissioning system in almost all cases; however, the radiation exposure to nearby personnel can be, and in a few instances has been, lethal.

INFLUENCE OF DELAYED NEUTRONS

Before we consider the importance of those relatively few delayed neutrons, let us introduce some nomenclature. We have previously defined the point, \( k = 1 \), as critical. This point is also known as delayed critical, implying that the system is critical with the inclusion of delayed neutrons. When \( k = 1 + \beta \), then \( k_p = 1 \) and this point is known as prompt critical, implying that the system is critical on prompt neutrons alone. Finally, when one operates systems (e.g., reactors) in the vicinity of \( k = 1 \), then fine reactivity control is required, and the unit of reactivity most common for expressing small changes in the state of criticality is the dollar unit, defined by \( 1 \$ = \beta \). Note that the dollar is different for uranium and plutonium systems (0.007 vs. 0.003), but in all cases, it is the reactivity difference between delayed critical and prompt critical. The nomenclature is illustrated in Figure 8. A further subdivision of the reactivity scale is sometimes used for small reactivity changes, that is, the cent, and as for the monetary system, 100 cents = 1 dollar, or 1 cent = 0.01 $.

\[
\begin{align*}
\text{delayed} & \quad \text{critical} \\
\text{prompt} & \quad \text{critical} \\
1.0 & \quad \beta \\
\end{align*}
\]

\[\Delta k = \beta = 1 \text{ dollar} \rightarrow 1 + \beta\]

Figure 8. Delayed and prompt multiplication factors.

Now, during routine reactor operations, the state of criticality is brought to slightly supercritical, temporarily, when power-level increases are desired. For example, \( k \) is changed from 1.0 to 1.001 (note that \( k_p \) is still less than unity). At this slightly supercritical state, the neutron population will increase but on a time scale dominated by the delayed neutrons and not by prompt neutrons. That is, the increase will occur on a second or minute time scale instead of on a millisecond or microsecond time scale. This change is sufficiently slow that either automatic or manual control of the neutron level or fission rate is easily accomplished.
Consider the realistic example of \( k \) being changed from 1.0 to 1.001 for a uranium-fueled reactor (\( \beta = 0.007 \)). The neutron level would increase by a factor of 2.718 (\( e \)) in about 86 seconds. One would characterize the state of criticality by stating that the system is 0.143 $ or 14.3 cents above critical and is on an 86-second period, the period being the time required for the system power level or neutron level to increase by a factor of \( e \). After the desired power level has been attained, then the control mechanism(s) would be reset such that \( k \) would again equal unity and the power would remain constant thereafter.

It bears reiterating that this reactivity span between delayed and prompt critical (\( \beta = \Delta k \)), very small in absolute units, is more than sufficient for the control of reactors, as will be demonstrated during the course. On the other hand, as \( \beta \) is so small on an absolute basis compared to possible accidental changes in the state of criticality (\( \Delta k \sim 0.2 \)), it is of almost no consequence to criticality safety.

VI. FACTORS INFLUENCING CRITICALITY AND PRACTICAL EXAMPLES OF CRITICALITY CONTROL

In the first part of the course, many fundamental concepts were introduced and explained through the use of idealized systems. Those fundamental concepts will be related as practical criticality safety examples to storage and handling operations with fissile materials, particularly here at the Los Alamos National Laboratory. Additionally, the ten factors listed below are highlighted with examples. In combination with administrative controls, they provide the criticality control for all process operations.

- mass
- density
- shape
- volume
- concentration
- moderation
- reflection
- poisons
- enrichment
- interaction

A. MINIMUM CRITICAL MASSES AND SIZES

In this section, critical data and critical masses and sizes derived from experimental measurements are provided and discussed.

Let us examine and explain the critical mass curve for \( ^{235}U \) as shown in Figure 9. Here the critical \( ^{235}U \) mass of a spherical U(93) system is plotted as a function
of the $^{235}$U density; the diluent is water, which is assumed to be uniformly distributed in the system for U(93) densities at less than full density (17.5-kg $^{235}$U/l or the equivalent 18.7-kg U(93)/l). Curves for water-reflected and thin-steel-reflected (essentially bare) systems are drawn. Consider the lower of the two curves in the following discussion.

Starting from the fully dense, water-reflected system at 22 kg/l and 17.5 k: the critical $^{235}$U mass increases slightly as water is added uniformly to the system. The addition of water molecules initially has the overriding effect of pushing the uranium atoms farther apart, thereby enhancing neutron leakage. The effects of neutron moderation, i.e., thermalization (or slowing down), and absorption by the hydrogen nuclei, are relatively unimportant at such low H : U ratios. Proceeding to slightly lower $^{235}$U densities, the curve reaches a maximum at about 23 kg. At this point, neutron moderation has offset the leakage effect.

As the $^{235}$U is further diluted with water, the moderation effect continues to dominate until the critical mass reaches a minimum of about 800 g at a $^{235}$U concentration of approximately 50 g/l. Note that up to this point even though the critical mass has been decreasing, the system volume has been increasing. Thus, on a relative scale, the system leakage has been decreasing.

At this minimum, the system has a volume of

$$800 \text{ g} + 50 \text{ g/l} = 16 \text{ liters}.$$  

This corresponds to a sphere ~31-cm in diameter, exclusive of the reflector. Increases in the water content of the system at this point cause the critical mass to rise sharply. What is happening is that the system is "over moderated," that is, neutrons are readily slowed down to thermal energies by the high H : U ratio but the absorption by hydrogen nuclei is now becoming excessive. Put another way, the uranium atoms are becoming so spread out and dilute that the neutrons are no longer interacting sufficiently with them before being absorbed by the hydrogen nuclei. Finally, if the $^{235}$U density falls below about 11 g/l then the system could be made infinitely large and still not be able to attain $k = 1$.

From the above discussion, if one would locate 50 g/l on Figure 10 and go up until the water-reflected curve is intersected, the corresponding critical volume at this point would be about 16 liters. This is in agreement with the previous determination of the critical volume using mass and concentration.

The above discussion for the uranium data (Figs. 9 and 10) applies equally to the plutonium data (Figs. 11 and 12). Note that for plutonium, its initial rise in the mass required for critical (as dilution with water commences) is much more pronounced than for highly enriched uranium; the critical plutonium mass at an H/Pu of 5 is about twice the critical mass of the metal at full density. Also, the effect of the $^{240}$Pu isotope and some nitrates is very pronounced in solution systems, as indicated. This is due to the large absorption cross section of $^{240}$Pu for slow neutrons. This effect is much smaller for highly enriched uranium since the $^{235}$U absorption cross section is much smaller than that of $^{240}$Pu.
Figure 9. Critical masses of homogenous water-moderated U(93.2) spheres. Solution data appear unless indicated otherwise. (From LA-10880-MS, Figure 10).
Figure 10. Critical volumes of homogenous water-moderated U(93.2) spheres. Solution data appear unless indicated otherwise. (From LA-10860-MS, Figure 11).
Figure 11. Critical masses of homogeneous water-moderated $^{239}$Pu spheres. The points suggesting an intermediate curve apply to water-reflected Pu(NO$_3$)$_4$ solutions with 1 N HNO$_3$ and 3.1% $^{241}$Pu content of the plutonium. (From LA-10860-MS, Figure 31).
Figure 12. Critical volumes of homogeneous water-moderated $^{239}$Pu spheres. The points suggesting an intermediate curve apply to water-reflected Pu(NO$_3$)$_4$ solutions with 1 M HNO$_3$ and 3.1% $^{240}$Pu content of the plutonium. (From LA-10860-MS, Figure 32).
1. MINIMUM CRITICAL MASSES OF COMMON MATERIALS

The minimum critical masses of bare- and water-reflected spheres of common fissioning materials for both solid metal and solution (water-base) systems are as follows:

<table>
<thead>
<tr>
<th>Material</th>
<th>Metal* (kg)</th>
<th>Solution* (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>bare</td>
<td>reflected</td>
</tr>
<tr>
<td>Pu** (alpha phase)</td>
<td>10.2</td>
<td>~5.8</td>
</tr>
<tr>
<td>Pu (delta phase)</td>
<td>15.6</td>
<td>~8</td>
</tr>
<tr>
<td>U(93) (oralloy)</td>
<td>50</td>
<td>~25</td>
</tr>
<tr>
<td>$^{233}$U</td>
<td>~16.1</td>
<td>~8</td>
</tr>
<tr>
<td>$^{238}$Pu</td>
<td>~8</td>
<td>~7</td>
</tr>
<tr>
<td>$^{239}$PuO$_2$</td>
<td>~21</td>
<td></td>
</tr>
<tr>
<td>$^{240}$Pu</td>
<td>~80</td>
<td></td>
</tr>
<tr>
<td>$^{241}$Am</td>
<td>100 - 200</td>
<td></td>
</tr>
<tr>
<td>$^{243}$Am</td>
<td>150 - 200</td>
<td></td>
</tr>
</tbody>
</table>

* Solutions are idealized metal-water mixtures; reflector is thick water, i.e., ~10-cm.
** Pu is nominal weapons grade: 95% $^{239}$Pu + 5% $^{240}$Pu.

Departures from spherical geometry will, for all practical purposes, always decrease the state of criticality, i.e., reduce $k$. This is because a sphere has the minimum surface-area-to-volume ratio of any geometry, and as the ratio increases, so does neutron leakage. For example, a critical, water-reflected, alpha-phase plutonium sphere is about the size of a baseball. If this same amount of material were formed into a cylinder 1-cm in diameter, it would be 3.82-m long. This 5.5-kg cylindrical system would be far subcritical ($k < 0.1$) because the surface area (for neutron leakage) is about 30 times that of the same mass (and volume) sphere.

The important point to be made here is that much more material than the critical masses given in this table can be and sometimes is stored, processed, or handled in "high leakage" geometries for reasons of economy and practicality. Material stored in extended geometries should never be transferred to more compact containers unless the operation has been thoroughly investigated in advance.
2. MINIMUM CRITICAL SIZES OF CYLINDERS AND SLABS

In reality, systems are always of finite extent; however, for all practical purposes, the 1-cm-diameter x 3.82-m-long cylinder of \( \text{alpha-}\text{phase} \) plutonium described previously would be an infinite cylinder. In this context, infinite implies that essentially all of the neutron leakage is from the curved surface and essentially zero from the ends of the cylinder. For example, the surface area (neutron leakage area) ratio for this cylinder is

\[
\frac{\text{Area curved surface}}{\text{Area both ends}} = \frac{\pi(1 \times 382)}{\pi(0.5)^2} = 764.
\]

Thus, if the neutron population within the cylinder were distributed uniformly over its volume, then for every neutron leaking from the ends of the cylinder about 764 neutrons would leak from the curved surface.

Minimum diameters and thicknesses for infinite, critical cylinders and slabs are as follows.

<table>
<thead>
<tr>
<th>Material</th>
<th>Infinite Cylinder</th>
<th>Infinite Slab</th>
</tr>
</thead>
<tbody>
<tr>
<td>U(93) metal</td>
<td>7.5 (11.5)</td>
<td>1.3 (5.5)</td>
</tr>
<tr>
<td>(^{239}\text{Pu}) alpha metal</td>
<td>4.6 (6.0)</td>
<td>0.8 (2.7)</td>
</tr>
<tr>
<td>U(93) solution</td>
<td>14.2 (21.5)</td>
<td>5.0 (12.5)</td>
</tr>
<tr>
<td>(^{239}\text{Pu}) solution</td>
<td>13.0 (21.0)</td>
<td>5.0 (12.0)</td>
</tr>
</tbody>
</table>

*Thick water reflected and unreflected (bare) dimensions.
Figure 13. Estimated critical diameters of infinitely long cylinders of homogenous water-moderated U(93.2) spheres. Solution data appear unless indicated otherwise. (From LA-10860-MS, Figure 12).
Figure 14. Estimated critical diameters of infinitely long cylinders of homogeneous water-moderated $^{239}$Pu. The points suggesting an intermediate curve apply to water-reflected $\text{Pu(NO}_3\text{)}_4$ solutions with 1 N HNO$_3$ and 3.1% $^{239}$Pu content of the plutonium. (From LA-10860-MS, Figure 33).
Figure 15. Estimated critical thicknesses of slabs, infinite in other dimensions, of homogeneous water-moderated U(93.2). Solution data appear unless indicated otherwise. Unreflected infinite slabs are fictitious. (From LA-10860-MS, Figure 13).
Figure 16. Estimated critical thicknesses of slabs, infinite in other dimensions, of homogeneous water.

\[ H / 339 \text{Pu} \] for a-Phase Plutonium-Water Mixtures

\[ H / 339 \text{Pu} \] for Idealized Solutions

\[ H \] vs. \[ \text{Density of } 239 \text{Pu} \] (kg/L)

\[ \text{Infinite Slab Thickness} \ (\text{cm}) \]
3. INFLUENCE OF DENSITY ON CRITICALITY

The brief exposition given in this section is largely taken from reference LA-3612, which should be consulted for additional information regarding density effects. In particular, we will limit the discussion to bare, homogenous systems undergoing uniform density changes. For these stipulations, the influence of system density on critical mass is described by perhaps the only law in criticality physics that is simultaneously exact, simple, and useful. This law states "In a critical system, if the densities are increased everywhere to \( x \) times their initial value and all the linear dimensions are reduced to \( 1/x \) times their initial value, the system will remain critical."

Thus, to maintain \( k = 1.0 \) (critical) in a homogenous sphere, the critical radius must be inversely proportional to the density, or:

\[
r_c \propto 1 / \text{density}.
\]

Since the critical mass of a system may be written as the product of volume and density, we can obtain the following relationships between the critical mass and density.

For finite geometries (such as spheres, cubes, and cylinders)

\[
m_c \propto 1 / (\text{density})^2.
\]

For one-dimensional geometries, that is, thin slabs, very long cylinders, and spheres, the following critical mass / density relationships apply: slab — the critical mass per unit area of the slab is proportional to a constant; cylinders — the critical mass per unit length is proportional to one over the density; and, spheres (in fact, any three-dimensional body) — the critical mass is proportional to one over the density squared.

This density law is entirely general and applies to any mixture of materials in any geometrical shape and reflected in any manner, provided only that the entire system undergoes the same, uniform density change.

A few examples of high-leakage storage containers in use at LANL and elsewhere will be given in the section on handling and storage. First, let us consider one other practical means of storing or processing substantial quantities of fissile material in a critically safe manner.

4. USE OF NEUTRON ABSORBERS (POISONS) FOR CRITICALITY CONTROL

Without resorting to a high-leakage geometry, it is sometimes practical to maintain a low state of criticality during an operation or for hypothetical upset protection by the use of nonfissioniing materials, called poisons, which have very high neutron absorption cross sections. Neutron poisons are most effective for absorbing thermal neutrons; the most common of these are boron, cadmium, and lithium.

Simply, there are no materials that are extremely good absorbers of fast neutrons. By comparison, the absorption cross sections of \(^{235}\text{U}, ^{238}\text{Pu}\), boron, cadmium, lithium, hydrogen, and beryllium at 2,000 m/s (0.025 eV) are as follows.
ABSORPTION CROSS SECTIONS FOR THERMAL NEUTRONS
(in barns)

<table>
<thead>
<tr>
<th></th>
<th>235U</th>
<th>239Pu</th>
<th>B</th>
<th>Cd</th>
<th>Li</th>
<th>H</th>
<th>Be</th>
</tr>
</thead>
<tbody>
<tr>
<td>685</td>
<td>1020</td>
<td>764</td>
<td>2520</td>
<td>71</td>
<td>0.33</td>
<td>0.0098</td>
<td></td>
</tr>
</tbody>
</table>

From this tabulation it is evident that the neutron poisons boron, cadmium, and lithium can compete heavily for the available neutrons. On the other hand, hydrogen and beryllium, which are good moderators, do not compete with fissile isotopes unless the atom ratio of moderating atom density to fissile atom density is very large.

For example, consider a bare, thermal 235U-H2O system which is characterized by the average probabilities:

Leakage probability = 0.75

and

Absorption probability = 0.25.

Neglecting absorption in the water and assuming a capture to fission ratio of 1 : 4, the state of criticality would be

\[ k = 0.25 \times 0.8 \times 2.5 = 0.5. \]

To reduce the state of criticality to a lesser value for routine operations, say \( \sim 0.2 \), one could add, for example, boron to the solution. If it were added in the proportion two boron atoms per atom of 235U, and assuming the absorption cross sections were equal, then the new multiplication factor would be

\[ k = 0.25 \times 0.33 \times 0.8 \times 2.5 = 0.17, \]

where the 0.33 factor is the relative absorption rate in 235U divided by the total absorption rate.

As a second example of the potential use of neutron poisons, consider a bare fissile system for which it is desired to provide added criticality safety margin in the unlikely event of a flooding accident. Now, a water reflector will return predominantly thermal neutrons to the system; thus, if the bare system were tightly enclosed in a thin (e.g., \( \sim 1 \) mm) cadmium sheet, then less than 1% of the thermal neutrons would be returned in such a flooding accident. This shows how cadmium could be used to partially isolate the system from the consequences of a flooding accident.

B. PRACTICAL FISSION MATERIAL HANDLING AND STORAGE

The variety of fissile species throughout LANL and their diverse chemical and physical forms probably encompass that found anywhere. Thus, a look at some of the ways by which criticality is controlled in the handling and storage of fissile
materials at LANL will likely be recognized as very similar to controls in effect elsewhere.

Methods of criticality control discussed in this section include limiting volumes and dimensions of containers, limiting masses, and the use of internal neutron absorbers or poisons.

1. FIVE-LITER DISSOLUTION POTS

In the aqueous recovery section of the Los Alamos plutonium facility, the use of 5-liter pots for the dissolution of various plutonium compounds has been standard practice for over 20 years. These vessels are essentially spherical and are wrapped in a heating mantle over their lower portions.

From Figure 12, it is apparent that the minimum critical volumes for bare and thick-water-reflected spheres of plutonium solutions are about 12- and 6-liters, respectively. Also it is obvious that the normal operating conditions for the 5-liter pots is nearly bare (unreflected). Now, while full water reflection may seem incredible, even if this were to occur, the pot would remain slightly subcritical because of its constrained volume.

Thus, due to the relatively high neutron leakage afforded by the diameter of the 5-liter pots, they will remain subcritical at any credible solution concentration, even coincident with extremely unlikely reflection conditions.

Note, however, that while a rich (few hundred grams per liter) solution is essentially ever-safe in a 5-liter pot, if diluted in a larger vessel, criticality could be achieved with that same mass of plutonium.

2. CYLINDRICAL STORAGE PROCESS VESSELS AND STORAGE TANKS

Common to handling and storing of larger volumes of solutions of both plutonium and uranium are the use of cylindrical vessels of 6 inches (15 cm) in diameter. The cylinder lengths will vary depending on capacity requirements since there are about 18 l/m of 6 in. pipe. Once again, the relative ease with which neutrons can leak out of this vessel results in practical, large volume solution storage and handling under conditions whereby subcriticality is controlled by geometry, regardless of solution concentration or vessel length.

Obviously, the 6-in.-diameter vessel is a favorable geometry design regardless of its length, but only in isolation. 6 in.-, or even 5 in.- or less, diameter tanks can be made critical depending on solution concentration, array size, and tank spacing. However, emptying the contents of a 1-meter-long column (capacity 18 l) into a more compact vessel could lead to a critical system with the same total mass of plutonium or uranium.

3. STORAGE IN SLAB TANKS

The use of thin, flat-faced containers for solution storage has increased at LANL in the few past years. One group has designed, fabricated, and installed one of about 70 l capacity. As it is only 8-cm thick, it is conveniently and unobtrusively mounted above and away from other activities and equipment.

Its location precludes substantial accidental reflection on the broad faces. Also, many transverse through-bolts in conjunction with a pressure relief diaphragm provide confidence that hypothetical overpressurizations will not buckle or bow out a side wall of the tank, which would likely lead to a less-favorable, less-leaky (neutron-wise) geometry and possibly a criticality accident.
While specific, three-dimensional neutronics calculations were performed in the criticality assessment of this slab tank, guidance in this regard is also provided by Figures 15 and 16.

4. VAULT STORAGE OF FISSION MATERIAL

While there are numerous fissile material storage vaults throughout LANL, one of the largest and the one with the most diverse contents is in the basement of the plutonium facility. Here, there are several storage rooms on both sides of a lengthy corridor with plutonium and uranium metals, oxides, compounds, etc., stored in bottles and cans ranging up to large shipping containers.

For each stored unit, criticality safety is ensured by restricting the container volumes or mass of solid material or, frequently, both. An example is metal or oxide storage in (at most) few-liter cans. Large shipping containers always have the active material packaged in inner containers of limited volume.

With the location of many, often diverse fissile units in one room and many adjoining rooms, there is an added concern, namely that neutronic interaction among the units be controlled. That is, although each individual unit may be small and thus "leaky" as far as neutrons are concerned, if neutrons leaving one unit have a high likelihood of striking and causing fissions in a neighboring container, then it is possible that the entire array or assemblage of units may be capable of becoming critical even though none of the individual units can. This may be likened to fuel rods in a reactor where one or even many are subcritical by themselves, but together they form a critical assembly.

For this reason, not only are maximum floor, shelf, or cubicle loadings prescribed as criticality limits, but also spacing units as far apart as practical is encouraged.
A.5.14.5

Process Criticality Accident Likelihoods, Consequences and Emergency Planning

by

T. McLaughlin
Process criticality accident likelihoods, consequences and emergency planning

T. P. McLaughlin*

Evaluation of criticality accident risks in the processing of significant quantities of fissile materials is both complex and subjective, largely due to the lack of accident statistics. Thus, complying with national and international standards and regulations which require an evaluation of the net benefit of a criticality accident alarm system, is also subjective. A review of guidance found in the literature on potential accident magnitudes is presented for different material forms and arrangements. Reasoned arguments are also presented concerning accident prevention and accident likelihoods for these material forms and arrangements.

General guidance for emergency planning for facilities and operations involving significant quantities of fissile materials is contained in various regulations and consensus standards. In particular, international standard ISO 7753 Nuclear Energy — Performance and Testing Requirements for Criticality Detection and Alarm Systems requires that the net benefit of a criticality accident alarm system be evaluated. This mandate considers only a risk/risk evaluation, with no guidance provided as to cost/risk or cost/benefit considerations.

As risk is a combination of likelihood and consequence, both aspects must be considered, yet each is extremely difficult to quantify in most process situations. Concerning likelihoods, it is noted that only eight process accidents have been reported in the forty-five years that minimum critical quantities of fissile material have been available. All eight of these have involved solutions and only one occurred in a volume greater than 200 litres. Clearly these meagre accident statistics only highlight the obvious — criticality accidents with fissile solutions are very unlikely and ones involving non-solution forms are even more unlikely.

Probabilistic risk assessment (PRA) has been recognized as a possible avenue to determine likelihoods, but it has recognized drawbacks, notably in ‘hands on’ operations where failure rate data are very uncertain. Alternatively, it is argued that the large sums that would be spent (an estimate for the Los Alamos Plutonium Facility is a few million dollars) could be better used on control measures such as more criticality staff on the process floor. A recent ‘test’ PRA on only one of hundreds of operations in the Los Alamos facility cost about US$20 000, exclusive of the value of the time that operating personnel and criticality staff spent working with the PRA contractor.

The Author finds it noteworthy, in regard to the application of PRA, that in one of the eight accidents (Windscale), experts were unable to ascertain the accident mechanism even after it was determined in which vessel the accident had occurred.

The consequences of criticality accidents are a function of several factors: whether or not the operation is ‘hands on’ or in a shielded facility; the magnitude of the excursion; and emergency actions. The latter two will be discussed in detail in the remainder of this Paper, where it is also argued that with reasonable controls on operations, accidents with metals and dry compounds should be made so unlikely as to be considered incredible.

Magnitudes of criticality accidents are the subject of much controversy and misunderstanding. For example, the 1986 Los Alamos report, A Guide to Radiological Accident Considerations for Siting and Design of DOE nonreactor Nuclear Facilities contains a brief section on criticality accidents. In this section a table is presented of fission yields from accidents with different material forms. This table was reproduced from Woodcock and is included here as Table 1. The Nuclear Regulatory Commission also issues guidance on the magnitude of criticality accidents. It is noted in these NRC documents that predicting fission yields in heterogeneous and non-solution systems such as those described in Table 1 ‘results in a broad range of possible yields’ and ‘methods for estimating possible fission yields are less reliable’. The NRC also recommends that credible accidents be assessed for potential magnitude on an individual case basis.

In the body of this Paper, each of the material forms indicated in Table 1, the appropriateness of the fission yield values and, particularly for non-solution systems, reasons why effort might be better spent in controlling the accident likelihood at a vanishingly low level than in attempting to quantify its likelihood and consequences, are discussed.

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*Los Alamos National Laboratory, New Mexico, USA.

Solutions

Significantly, although not surprisingly, all eight of the reported process criticality accidents have involved material in solution as opposed to dry materials or mixtures of metal/powders and water. Reasons are numerous, including

(a) solutions have much smaller critical masses than dry materials and, indeed, all eight of the process accidents, while not in optimum geometries or concentrations, occurred with much less than minimum critical masses for unmoderated materials

(b) dry powders and accumulations of small metal pieces such as cutting chips from a machining operation, which (if immersed) may have small critical masses similar to solution values, have additional lines of defence which should be formidable — they are usually processed in moderation-controlled environments and/or in small vessels of favourable geometry

(c) loss of configuration control, that is, the controls which prevent fissile material from accidentally achieving a more reactive state than operating procedures provide, has lead to all eight accidents. Simply put, material moved or was moved from favourable geometry vessels to unfavourable geometry vessels due to combinations of design oversight, operator error, and equipment failures. Clearly, similar inadvertent movement of dry materials is much less likely, as should be the inadvertent loss of moderation control if it had been identified as a major line of defence in accident prevention.

A recent analysis for a design basis solution criticality accident at the Oak Ridge Y-12 Plant exemplifies the benefits of a situation specific review

(a) one has a reasonably firm basis for emergency planning

(b) other simplified methods, such as that offered by Tuck, may not be appropriate for potential upset conditions that are considered credible

(c) single values such as those offered by the NRC guides or by Woodcock (Table 1), provide no insight into what may actually lead to an accident situation and may be either significantly under- or over-conservative for emergency planning purposes.

The Y-12 analysis used CRAC solution excursion data to provide confidence in the upper limit of the first spike fission yield of a solution criticality accident. This approach may be applied even more readily to plutonium solution systems where one is confident that there is not significant wait-time associated with the initiation of the first persistent fission chain after the prompt critical state is reached. The potential for subsequent fission bursts and for eventual quasi-steady state solution boiling near the delayed critical point is also recognized. Whereas it may be difficult to assess the likelihood of permanent shut-down after the first fission spike when performing analyses for safety documentation, more importantly the case may be made that subsequent fission bursts and even significant additional fissions beyond the first burst are not a serious threat.

The CRAC data demonstrate that even with the continual introduction of fissile solution into a system which has just undergone a fission burst, subsequent spikes are delayed by several seconds or more. Any additional bursts are likely to be reduced in intensity by a factor of 5 or 10 from that of the initial burst. Power and energy histories for one of the (typical) CRAC excursions is shown in Fig. 1. This illustrates both the time delay and lower magnitude associated with subsequent bursts. These two observations have important implications on emergency planning

(a) The time delay of several seconds between bursts provides anyone in the immediate vicinity of the
initial burst with ample time to remove themselves by the time of the second burst. This is a major justification for a criticality accident alarm system for those not immediately threatened by exposure to direct radiation from the first burst, a combination of evacuation routes and (expected) reduced yields of subsequent spikes should assure that no life-threatening dose is received during facility evacuation. Once personnel are sufficiently distant such that direct doses are not a concern (and this should be verified at any muster location) then one can monitor for fission product radiation levels and move personnel as appropriate to prevent further exposures. It is noteworthy that fission product doses have not led to life-threatening exposures even though yields in some of the eight accidents exceeded the initial burst yield by more than two orders of magnitude.

In summary, one can conclude with reasonable confidence that if prompt evacuation proceeds via appropriate routes then significant direct doses should be limited largely to those resulting from the initial burst. If the reaction is not shut down after the first burst then area monitoring should enable the prevention of significant exposures from persistent, low-level direct doses or from fission product radiation.

Liquid/Powder

The scenario which led to the $3 \times 10^{20}$ value in Woodcock's report (Table 1) is one whereby autocatalytic phenomena are acting. In particular, he describes a situation in which dry powder becomes flooded, goes prompt critical as an equivalent very rich solution, and then the mixing and dilution which accompany the excursion introduces additional reactivity, as one is sliding down the critical mass versus concentration curve. Woodcock acknowledges that there are competing feedback effects, the positive one already postulated and the known negative effects of thermal expansion and microbubble formation. Finally, he states that 'this estimate is rather a shot in the dark.'

Stratton also alludes to the possibility of positive feedback as rich solution becomes diluted. However, he states that 'it is difficult to imagine an explosive reaction.' Clearly, then, he does not give credence to the $3 \times 10^{20}$ value, as in a few hundred litres or less this would lead to an extraordinary explosion.

Perhaps the Woodriver Junction criticality accident came as close to matching Woodcock's scenario as any experimental evidence existing. Here 11 l of 240g $^{235}$U/l solution was poured into a large vessel containing about 4 l of sodium carbonate reagent. A fission burst occurred near the end of the pouring process which had about $10^{17}$ fissions, a specific yield of about $5 \times 10^{12}$ fissions/l. This specific yield is within the range of the CRAC data-specific yields and thus does not show a discernible autocatalytic yield augmentation as the fission solution diluted in the sodium carbonate solution.

If process-specific reviews by criticality specialists ever reveal any scenarios leading to unacceptable consequences then controls must be exercised that reduce the likelihood to a vanishingly small value, that is, an acceptable risk level.

**Liquid/Metal pieces**

Woodcock does not include any discussion of the bases for the fission yields of $3 \times 10^{18}$ and $1 \times 10^{19}$ in his report. It should be noted, however, that he is not referring to the 'system of small pieces of fission metal' indicated in Table 1, but instead to 'the yields for metals or solids in water refer to one or a small number of pieces.' This situation should be easily controllable and indeed may be incredible in most operations. It would be extremely rare that a water-flooded and/or reflected critical mass would be assembled as a single, dry unit. Were this necessary, additional precautions to preclude the possibility of flooding/reflection would be taken. For a few large pieces, one would provide spacing controls to assure generous safety margins. Solid material in storage would generally be in containers such that the container volume provides approximately one litre per kilogram of stored material. This assures that no accumulation of a small number of pieces, dry or in any admixture of water, will pose any credible criticality concerns.

**Solid uranium and solid plutonium**

Criticality accidents with solid metal systems (including alloys) should be readily controlled at a likelihood of occurrence that is vanishingly small. It is almost inconceivable that masses approaching the bare critical sphere values would be handled in any compact form, either as a single unit or as an accumulation of pieces, as in a burst reactor configuration. Only rarely are there operational requirements which necessitate working with more than the water-reflected spherical critical mass which was addressed in the previous section.

However, the criticality safety specialist has long recognized the potential for extreme consequences were an unmoderated metal criticality accident to occur. As Table 1 illustrates, the possible magnitudes are greater for uranium than for plutonium (all else being the same) due to the statistical nature of fission chain initiation in the presence of a weak source. A manifestation of this recognition of potentially large fission yields with uranium metal is the large casting facility at the Y-12 plant. This is a shielded facility with a built-in neutron source to minimize both yields and consequences of extremely unlikely accidents.

It should be emphasized that in spite of the shielding, it is the effort put into accident prevention and yield mitigation that is most important. If the consequences are unacceptable then the accident likelihood must not be credible.
Large storage arrays

Normal operations involving storage of fissile materials should be in compliance with appropriate federal requirements and consensus standards such as DOE Order 5480.5 and ANS-8.7. The storage arrays may be expected to have sufficient margins of subcriticality to compensate for credible normal and abnormal contingencies. A typical arrangement should be expected to result in a maximum neutron multiplication factor not exceeding 0.9 for all evaluated credible contingencies. It is further required that no single mishap, misoperation, or violation of procedure will lead to nuclear criticality.

The additional mass necessary to achieve prompt criticality with a single unit is between 1% and 3% of its critical mass, depending on whether the material is plutonium or uranium. The same can be said of an array at critical. However, the relation between the reactivity change to a unit in the array and the array reactivity is such that the 1-3% change in mass must be uniform throughout the array, i.e., to increase the array reactivity by an amount $\Delta k$, each unit in the array must be increased by this same $\Delta k$.

An equivalent reactivity addition to the array may be also effected by increasing the number of storage units or by reducing the volume of the storage container or of the storage cell volume in the array. In either of these cases, there is a dependence on the neutronic coupling between the units of the array. At critical, low-mass units will be strongly coupled, whereas large-mass units will be weakly coupled, a condition that also subsists in the sub-critical state.

For example, to change the $k_{\text{eff}}$ (for uranium units) from the critical state to a value of 1.01 would require a uniform change in excess of 3% in the mass of the units in the array, or a 5-7% uniform reduction in the volume of the array, or a 7-13% increase in the number of units in the array. The mass increment required is independent of the neutronic coupling and the ranges given for the volume and number of units correspond to progressing from strong to weak neutron coupling. These values are about the minimum to produce the prompt critical state for enriched uranium.

An accident during operation in a facility can, however, be expected to be initiated from the sub-critical state. If the sequence of events leading to delayed criticality in a storage array were to begin at a nominal $k_{\text{eff}}$ of 0.9, then the required changes become a uniform mass augmentation of 37%, a uniform array volume reduction ranging from 44 to 53%, and an increase ranging from 262 to 377% in the number of units.

The implications of these results are that the accidental achievement of the critical state throughout a storage array due to successive violations of administrative controls has a very low probability of occurrence and prompt criticality is impossible, given the time required to effect the necessary changes.

The achievement of the critical or prompt-critical state in a single storage location would have to be considered or interpreted as array criticality. However, the contribution to the fission yield of the event by the array reactivity contribution among the units of an array is a function of the margin of sub-criticality of the units. An increase in the reactivity of a single unit in an array by an amount $\Delta k$, leads to a reactivity increase of about $\Delta k/N$ to the array, where $N$ is the total number of units in the storage array. This is typically a value of magnitude about that of the uncertainty associated with the array $k_{\text{eff}}$. The total yield may even be less than would occur were the overloading of mass accomplished outside a storage area. As the neutron background is higher than normal in storage areas there is the likelihood of an earlier than usual initiation of the fission chain.

For extreme upset conditions, such as vault flooding or material collecting on the floor during an earthquake, simple common-sense storage practices and a case-specific analysis should lead to the conclusion that either the critical state cannot credibly be reached or, if the upset condition is so severe that criticality cannot be precluded, then consequences of the criticality accident are minor compared to the total accident consequences. Under no circumstances can an accidental scenario be envisioned which would incorporate the simultaneity, speed, and neutron source requirements which would lead to anything approaching the ‘3 x 10^22 fissions’ and ‘serious explosion’ that Woodcock proposes.

A fundamental storage practice for unmoderated fissile materials should be a maximum effective density, i.e., the fissile mass divided by the outer container volume, which does not exceed about 1.0 kg/litre. For such a simple storage practice it can be readily shown that even relatively large, compact accumulations of containers (such as are often postulated to be associated with earthquakes) remain subcritical.

Summary

Whereas most regulatory guidance and, indeed, common sense, dictates that criticality accident risks be evaluated, both the likelihood and the consequence components of this risk are very difficult to quantify. However, this risk evaluation is necessary input into decisions relating to criticality accident emergency planning, including alarm systems.

Several points relating to these likelihood and consequence issues are argued in this paper:

(a) a case-specific analysis should be performed rather than adopting simplistic fission yield values such as presented in Table 1
(b) fissile material processes and storage involving dry materials should, in general, be much more readily controlled than those involving solutions
(c) efforts expended on emergency planning for criticality accidents postulated to occur with dry materials might be better spent on reducing acciden likelihoods by providing more effective design ar
oversight of process operations and improved operator and supervisor knowledge and awareness for large-scale fission solution processing. Accident likelihoods, although not readily quantified, will generally not be able to be reduced to the ‘incredible’ level. That is, it is generally agreed that for such operations emergency planning is cost and risk effective. However, the CRAC data coupled with site-specific evaluations provide sufficient information to enable emergency planning to be based on realistic fission yield estimates.

In summary, accident experience, CRAC data, and case specific evaluations, coupled with appropriate emergency planning should provide confidence that criticality accidents are local events with insignificant off-site consequences. Postulated accidents with large fission yields, such as those indicated in Table 1, must be controlled so that likelihoods are so remote as to be considered incredible and thus the risks are acceptable.

References
A.5.14.6

Criticality Safety for the Nuclear Material Storage Facility TA-55, PF-41

by

J.A. Schlesser
Los Alamos
NATIONAL LABORATORY
memorandum
Health and Safety Division
HS-6, Nuclear Criticality Safety

SUBJECT: CRITICALITY SAFETY FOR THE NUCLEAR MATERIAL STORAGE FACILITY - TA-55, PF-41


SUMMARY

We have performed several analyses to determine the state of criticality for various fissile material storage array configurations in the nuclear material storage facility. The array specifications were provided to us by Paul Smith of Merrick and Company. We have determined that there are generous criticality safety margins for the proposed 8 x 83 x 5 storage array in each bay. Details of the analyses and results are presented below.

Due to the large fixed costs associated with fissile material storage facilities, e. g., construction, safeguarding, accountability, etc., and the possible economic advantages of storing more fissile material in the same volume, let us elaborate briefly on the criticality safety margins. Should non-criticality safety considerations not prohibit items from being stored on smaller center-to-center spacings, then a doubling of the number of units beyond that represented by an 8 x 83 x 5 array in each bay (6,640 units for both bays) could be easily accommodated from a criticality safety standpoint. Further, with the innovative use of strong neutron absorbers and constraints on the average density of the fissile material in each can, then a factor of three, or even four, increase in the vault capacity is likely achievable.

The referenced memo provides the results of additional parameter surveys performed for the same facility under a broader spectrum of storage conditions.

CALCULATIONAL MODELS AND ASSUMPTIONS

There will be identical storage arrays fitted into each of the two bays of TA-55, PF-41. The following information was the basis for the computer model developed. Each array will have the approximate dimensions of 13 feet wide by 127 feet long by 10 feet tall (see Figure 1). The array will consist of square carbon steel shrouds of 18 inch sides with a length of approximately 10 feet. Each shroud will have a 14-inch diameter cavity essentially the full length of the shroud (See Figure 2). The size of the shroud determines the spacing in the array, i. e., the stored units will have an 18-inch center-to-center spacing since there will be no free space.
between the shrouds.

In addition, the storage bay was modeled with the ceiling at a height of 20 feet. The walls, ceiling, and floor were modeled as ordinary concrete, 18-inches thick. A gap of 0.3 inches was modeled between the fissile array and the concrete walls in the x (8) direction, and -15 inches in the y (83) direction. Carbon steel (-3 inches) was modeled at the bottom of the array just above the concrete floor. The wall between the bays was modeled also as ordinary concrete but 12 inches thick.

Each storage container was modeled as being a 5-inch diameter Schedule 40 stainless steel pipe with end caps (also stainless steel) of 0.75-inch thickness with a total height of approximately 12 inches (See Figure 3). The secondary container was modeled as a 14-inch diameter Schedule 5 stainless steel pipe with end caps of Schedule 5 (0.188") thickness. The calculational model incorporated minor modeling approximations, such as, the secondary container being modeled as a right circular cylinder versus the design with curved end caps. These approximations were made in a manner that resulted in neutronic conservatism.

The fissile material used in the calculations was taken to be 4,500 g of alpha-phase plutonium with 95 wt% $^{239}$Pu and 5 wt% $^{240}$Pu at a density of 19.86 g/cc. The fissile material was initially modeled as a right circular cylinder with a diameter of 5 inches and a height of ~0.7 inches (See Figure 3). The other variations of the fissile material consisted of the same diameter but varying heights which model variations in the density of the fissile material (See Fig. 3A). In all cases, a constant mass of 4,500 g was maintained. These variations simulate fissile material pieces which might be placed in the inner container but do not occupy the same volume as a full density (19.86 g/cc) single piece. For example, miscellaneous size and shape pieces from broken buttons and shells will generally pack in a can at less than one-half of full density. Also, a constant, uniform density is an excellent neutronic representation of full density pieces with void space between them. Similarly, a low density metal model is a good approximation to an oxide powder. Thus, this variation from a full density disc to a very low density medium spans the range of expected, actual storage conditions, which are as yet unspecified.

Credit was not taken for the actual presence of boron, as a neutron poison, in the walls separating the two bays. Atom densities for the material(s) used are presented in Table 1.

For additional conservatism and consistency with previous analyses, six-unit-high arrays were modeled and calculated, although the planned array is only five-units high.

CALCULATIONAL METHOD

The results reported in this analysis were performed with KENO V.a, a Monte Carlo criticality code and utilized Hansen-Roach 16-energy-group cross sections. Each case was executed for 30,000 neutron histories, which resulted in a statistical uncertainty of less than 0.006 in the multiplication factor for any case.
RESULTS

The results of the several calculations performed are reported in Table 2 and plotted in Figure 4. It can be seen from Table 2 and Figure 4 that the highest multiplication factor results when the plutonium is at its maximum density and, therefore, its smallest volume. Conversely, expected storage conditions, whether as several, small pieces of metal in each can or as a loose oxide, would be consistent with a much lower average fissile density and thus afford larger safety margins for the same total vault inventory, or an increase in vault inventory (reduced can spacing) with still generous safety margins.

Results of the several performed calculations will be maintained in HS-6 Files and are available for review.

CONCLUSIONS

For the ~7,968 unit capacity of the arrays (8 x 83 x 6) which occupy the two storage bays, there are generous criticality safety margins. The number of units (7,968) represents a heat loading of ~79 kw based on a nominal 2.5 w/kg fissile.

However, due to the very high degree of subcriticality for the calculated (6-high) arrays, it would be possible to store at least twice as many units with still generous safety margins, and with innovative use of strong neutron absorbers such as boron, it could well be achievable to fit three or even four times as much fissile material into this vault before true criticality limits were approached.

If there are questions regarding this analysis or criticality safety of the facility, please do not hesitate to call on us.

CC: P. T. Cunningham, CM-NM, MS F628
     W. T. Wood, NMT-DO, MS K524
     C. H. Smith, NMT-8, MS E583
     R. S. Sharp, WX-11
     W. McNeese, E583
     W. Merriman, E583
     P. Smith, Merrick and Company.
     HS-6 Files
Table 1.

Fissile Material Atom Densities

<table>
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<tr>
<th>Material</th>
<th>Density</th>
<th>Element or Isotope</th>
<th>Weight Percent</th>
<th>Atom Density, atoms / barn-cm</th>
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<tr>
<td>Plutonium</td>
<td>19.86</td>
<td>$^{239}$Pu</td>
<td>95</td>
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<td>$^{240}$Pu</td>
<td>5</td>
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<td>Stainless Steel (Keno mix = 200)</td>
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<td></td>
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<td>Si</td>
<td>33.7</td>
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Table 2.

Multiplication Factors for Storage Array
Two 8 x 83 x 6 Arrays (7,968 units)

<table>
<thead>
<tr>
<th>Density of Fissile Material in Inner Container, g/cc</th>
<th>Array Multiplication Factor $k_{\text{eff}} + 3\sigma$</th>
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<tbody>
<tr>
<td>19.86</td>
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</tr>
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<td>2.23</td>
<td>0.54</td>
</tr>
</tbody>
</table>
Figure 1. Illustration of Array in TA-55, PF-41 Rows
Vertical Array has 6 storage containers, one of which is depicted in Figure 3.

Figure 2. Storage Shroud, as Modeled
Figure 3. Single Storage Container Modeling Details
Figure 3A. Single Storage Container
Additional Modeling Details
Figure 4. Multiplication Factors for 8 by 83 by 6 (x, y, z) Arrays

Values are for units of constant mass (4,500 grams)
A.5.15.1

Review of the Rocky Flats Fire

by

R.E. Felt
DEPARTMENT OF ENERGY
PLUTONIUM ES&H VULNERABILITY ASSESSMENT

ASSESSMENT TEAM TRAINING

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REVIEW OF THE ROCKY FLATS FIRE

Rowland E. Felt
Fire Triangle

Fuel

Air (Oxidizer)

Heat (Temperature)
BURNING PLUTONIUM

- Ignition temperature – 560°C
- Melting temperature – 650°C
- Rate of combustion – ~240 g/hr or 4 g/min (massive metal)
- Oxygen requirement – 32 g/hr or 0.53 g/min
- Air equivalent – 3.76 ft³/hr or 0.063 ft³/min
PLUTONIUM METAL FIRES

- How do they start?
- How high are the flames?
- How long do they burn?
- How do you extinguish?
THE DOW CHEMICAL COMPANY
ROCKY FLATS PLANT
OF THE
U.S. ATOMIC ENERGY COMMISSION
# COMPARISON OF BURNING PROPERTIES OF HOOD MATERIALS

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature of Softening °C</th>
<th>Temp. of Initial Decomposition °C</th>
<th>Temp. of Ignition of Decomposition Vapor °C**</th>
<th>Self-sustained Ignition Temperature °C*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benelex 401 (Formally Benelex 70)¹</td>
<td>–</td>
<td>200–300</td>
<td>345</td>
<td>445 Charred 510 Char burning</td>
</tr>
<tr>
<td>Plexiglas – G²</td>
<td>170–200</td>
<td>300–325</td>
<td>338</td>
<td>Evaporated without ignition at 520°</td>
</tr>
<tr>
<td>Plexiglas SE-3 (flame retardant)</td>
<td>170–200</td>
<td>300–325</td>
<td>390</td>
<td>Evaporated without ignition at 550°</td>
</tr>
<tr>
<td>Neo–Sol Rubber Gloves³</td>
<td>–</td>
<td>200–250</td>
<td>325</td>
<td>325</td>
</tr>
</tbody>
</table>


**Temperature at which ignition of solid materials is sustained without external temperature source.

¹ Trademark of Masonite Corp
² Trademark of Rohm & Haas
³ Trademark of Charleston Rubber Co.
Is Benelex 401 Combustible?

Conclusion

Combustible, but it will not sustain combustion.
Fire Ignition Mechanism

Burning Plutonium Briquette

Combustion Gasses

Stainless Steel Can

Ventilation

Wood Fiber - Plastic Composite Material: Benelex - 401

CHAR Zone

600°C
FIRE FIGHTING DECISION

Fire is beyond CO₂ and dry chemicals

Only fire fighting option is water

Use Water
- Possible criticality
- Risk of life

Let it Burn
- Obey company policies
- Potential collapse of building

Consequences
- Loss of job
- Fire is out of control
- Protect the environment

- Contamination of environment
- Job security
- Firefighter protection
FACILITIES

- Fire-sensing elements -- use and condition?
- As-built drawings
- Plutonium storage requirements
- Off-shift coverage
- Adequacy of ventilation system
ADMINISTRATIVE

- Authority of firemen to make decisions
- Firemen's entry into building
- Restrictions placed on firemen
- Operating procedures
- Safety budgeting
- Responsibilities of safety personnel
- Offsite emergency response plans
- Training of firemen
- Criticality limits — reasonable?
- Priority of production over safety
FIRE SAFETY

- Flammable materials — in and out of gloveboxes
- Housekeeping — periodic cleanups
- Hazard evaluations
- Adequacy of fire fighting equipment
- Communication between sites
- Material Safety tests
- Credible accident analyses
- Safety records — incentive systems
FINDINGS

- Fire was not set intentionally
- Plastic windows were primary fuel
- Ventilation system provided air flow to spread fire
- One percent of 600 tons of Benelex 401 burned
- Conveyor system without physical barriers provided path for the fire to spread
- Storage of plutonium briquettes in open can provided ignition source
- Benelex 401 cabinet in glovebox 134-24 was source of fuel for initial fire
- Storage cabinets nullified heat sensing systems
CONCLUSIONS

- Improved standard of fire protection needed in plutonium facilities
- More information needed on plutonium ignition and burning
- Glovebox system needed:
  - Fire detectors
  - Automatic suppression systems or oxygen-deficient atmosphere
  - Fire isolation mechanism
  - Safe containment of burning plutonium
  - Automatic sprinkler systems in operating areas
ACTIONS TAKEN

- Findings and recommendations applied to new construction
- Review of all existing facilities
- Improve fire protection in all facilities
- Organizational re-evaluation of fire safety responsibilities
- R&D program on burning plutonium, radiation shielding materials, and effect of water on burning plutonium
DESIGN CHANGES -- BUILDING 707

- Conveyor fire doors
- Hood fire doors
- Fire walls to ceiling
- Compartmentillation of working area
- Fire rated door between working areas
- Adequate space between hoods
- Overhead sprinkler system
- Centralized fire alarm system
- Raised, sloping floor at down stairwells
- Elimination of conveyor underpasses
- Additional fire protection (sprinklers) in filter plenums
- Heat detectors in hood exhaust
- Water drains in all hoods
- Catch basin for fire fighting water
- Smaller window area in hoods
- Glass windows where possible
- Shields on inner hood gaskets
- Elimination of most Benelex shielding
- Fire retardant paint on remaining Benelex
- Shadow shielding technique rather than direct contact
- Additional plutonium storage
RECOMMENDATIONS CONCERNING
PLUTONIUM HANDLING

- The amount of combustible material in the immediate area of plutonium metal should be held to a minimum.
- Plutonium metal should never be stored in contact with flammable material.
- Plutonium metal in all forms should always be stored in metal containers with lids.
- Noncombustible physical barriers should be provided to limit the maximum quantity of plutonium that can conceivably be involved in a single fire, to a quantity which constitutes a reasonable risk.
- Partitioned zones should be established to prevent the spread of contamination should an accident occur. These zones would also provide effective fire walls to contain the spread of fires.
- Automatic fire or heat detection devices should be provided in glovebox facilities where plutonium metal is handled.
- Consideration should be given to possible changes in plutonium geometry in case of fire. Gloveboxes and equipment should be designed to avoid plutonium conditions which could constitute a nuclear criticality risk.
- Where warranted by real or potential exposure hazards or value of the plutonium metal involved, provisions for automatic fire protection by argon gas flooding or fixed piping of dry extinguishants should be considered.
- Plutonium metal should only be stored and handled in an area in which external fire hazards have been reduced as much as possible.
A.5.15.2

Additional Readings on Plutonium Fires and Accidents
FIRE--ROCKY FLATS PLANT--MAY 11, 1969

On May 11, 1969, a major fire occurred at the Rocky Flats (Colorado) Plant of the Atomic Energy Commission (AEC). The Rocky Flats Plant, which produces plutonium parts for nuclear weapons, is located approximately 21 miles northwest of Denver, between Golden and Boulder. The facility is operated for the AEC by The Dow Chemical Company under a contract administered by the Rocky Flats Area Office of the AEC's Albuquerque Operations Office.

The fire occurred in Building 776-777 which is used for manufacturing plutonium parts. This building is a complex facility which has been rearranged and modified repeatedly over the years to meet changing production requirements and schedules. The equipment in Building 776-777 includes various types of machinery operated in "glovebox" systems.

The gloveboxes are under a slight negative pressure with respect to the air in the room around them. Although they are fairly well sealed, air enters the gloveboxes from the room in which they are housed and exits through ducts to filtered systems on the roof. This provides a means for working safely with plutonium while separating the operator from this potentially hazardous radioactive material. Gloveboxes have porches which are sealed by rubber gloves which workers use to perform operations in the boxes. The gloveboxes used in related system operations are connected by conveyor lines. In turn, the systems are interconnected by other conveyor lines, by which plutonium is transferred from one operation to another. The conveyor lines connecting the gloveboxes are long enclosed tunnels lined with plastic windows. In some areas, thick pieces of either plastic or cellulosic laminate material (made from wood chips) have been placed on the inside or outside of the gloveboxes and conveyor lines as radiation shielding.

The first indication of a fire was an alarm received in the plant's fire station at 2:27 p.m. on May 11 from the heat-sensing system which monitors temperatures at various locations in the glovebox systems in Building 776-777. (The first statement by AEC concerning the fire was issued at about (over)
The fire originated within the North Line, moved rapidly through the North-South Overhead Conveyor Line, and subsequently spread through one of the interconnecting conveyors and into the Center Line. (See figure 1.) Some plutonium contained in these lines burned, and as the glovebox windows burned out, plutonium oxide was released into the room. (Note: When plutonium metal burns, it converts to the oxide form from which it can again be converted to metal without significant loss of material.) Because of the extensive plutonium contamination and smoke, all personnel entering the area during the fire were required to use self-contained breathing air systems which severely limited both access to, and time in, the fire area. There were no lost-time injuries from the fire or the firefighting, although one firefighter inhaled some plutonium, most of which was quickly eliminated following treatment. (This was reported in AEC's second public statement issued at 10:30 a.m., May 12.)

A small portion of the 600 tons of radiation shielding material surrounding the gloveboxes and conveyor lines was ignited during the fire. The heroic efforts of the well-trained firefighters successfully stopped the spread of fire to the shielding material.

The damage to Building 776-777 and its equipment was extensive. In addition to the actual fire and smoke damage, the building was heavily contaminated internally with plutonium. Substantial parts of the utility systems within the building were severely damaged. Some of the interconnected buildings sustained minor interior contamination. The fire did not breach the building roof, but slight exterior contamination was measured on the roof of Building 776 and an adjoining building, apparently due to a minor failure of a filter. Plutonium also was tracked out of Building 776 by the firefighters and was detectable on the ground around the building. There is no evidence that plutonium was carried beyond the plant boundaries. (See public announcement of May 13.) The present estimate of the financial loss

(continued)
for the damage to buildings and equipment, including cost of decontamination, is $45,000,000. The estimate does not include the cost of the plutonium recovery. The value of the plutonium which will not be economically recoverable will be small.

The available evidence indicates that the fire originated on the lower shelf of the storage cabinet in Glovebox 134-24 (see figure 2) in the North Line. Plutonium briquettes (discs three inches in diameter and one inch thick of either pressed scrap metal or lath turnings) and some loose scrap metal were stored in uncovered cans in the storage cabinet. The exact cause of ignition is unknown; however, plutonium in the form of chips or lath turnings is a pyrophoric material. The heat from the burning plutonium metal evidently caused the storage cabinet, which was constructed mostly of cellulosic laminate material and plastic, to char and generate flammable gases which could have been ignited by burning plutonium. The heat of the burning gases could ignite other briquettes and initiate a slow burning of the storage cabinet materials, particularly in the cracks between the joined sections of the cellulosic materials.

The smoke in the exhaust system of the North Line gradually clogged the filters. Flames erupted on the outer surfaces of the cabinet and spread to the combustible gloves and plastic windows on Glovebox 134-24. Up to this time, the fire was still undetected by the few people who were in the building that day because the smoke, flames, and heat were contained within the glovebox system. Since the heat detectors were located outside and under Glovebox 134-24 and were insulated by the floor of the storage cabinet, they were incapable of sensing the fire. (Similar detectors elsewhere in the glovebox system subsequently did function, and the alarm was sounded.)

Once the plastic windows of Glovebox 134-24 were breached, the inrushing air fanned the fire and caused it to spread into the North Conveyor Line and the gloveboxes east of Glovebox 134-24.

The airflow in the North Conveyor Line normally goes from east to west. However, because of the clogged filters, the airflow in the Line reversed and followed the second ventilation system which is part of the North-South Overhead Conveyor Line and the Center Line. When the fire reached the North-South Line, it turned south because of two factors, a closed metal door in the North Line and the direction of the airflow. On reaching the Center Line, the fire again went east because of the airflow.

Findings

1. With the evidence now available, the AEC has no basis for concluding that the fire was set intentionally.
2. The plastic windows contributed heavily to the spread of the fire and the extent of the loss. These windows, a major structural part of the containment system, provided a fuel surface on the inside of the glovebox-conveyor systems. Continued operation of the glovebox ventilation systems provided a supply of air to support the combustion. Under these conditions, burning of the windows and plutonium would have resulted essentially in the same loss as was experienced even if no other combustible materials had been present.

3. Less than one percent of the total of almost 600 tons of combustible radiation shielding was consumed in the fire.

4. The long interconnected conveyor system without physical barriers provided a path for the fire to spread. The closed metal door in the North Line demonstrated the effectiveness of even a simple firebreak in the Line.

5. The storage of plutonium briquettes in cans without lids provided potential ignition sources.

6. Without the plastic and cellulosic laminate cabinet in Glovebox 134-24, it is unlikely that a plutonium briquette burning in an open metal container would have ignited the plastic windows.

7. The addition of the storage cabinet, which nullified the heat-sensing system in Glovebox 134-24, prevented an earlier warning of fire.

Conclusions

1. Facilities such as Building 776-777 require a higher standard of fire protection than previously provided.

2. More needs to be known about the spontaneous ignition and burning properties of plutonium.

3. For plutonium operations involving interconnecting glovebox systems, the following should be considered:
   a. Means for detecting fire within the system,
   b. means for automatic suppression of fire within the system (an alternative is to use an oxygen-deficient atmosphere),
   c. means of isolating fire to small areas within the system, and
   d. a design providing for safe containment of burning plutonium.

-6-

(continued)
4. In view of the successful use of water in combating the fire, automatic sprinklers should be provided in the operating area of Building 776-777. However, further research is necessary before one can assume that sprinklers should be provided in all plutonium operating areas.

**Action Taken by AEC Subsequent to the Rocky Flats Fire**

1. The findings and recommendations are being applied by the Commission in the construction of new facilities at Rocky Flats. Concurrently, a review is being made of all existing facilities at the plant.

2. The AEC has directed its field offices and contractors to reexamine major fire risks and to improve fire protection throughout AEC facilities.

3. The AEC has initiated an in-depth survey of all major weapons manufacturing plants by two consultant companies (Factory Insurance Association and Factory Mutual Research Corporation.)

4. A reevaluation is being made of the organizational arrangements of the operating contractors for assuring fire safety both in facility design and operating practices.

5. The AEC will carry out a research and development program to provide more precise data on burning of plutonium and of radiation shielding materials and on the effect of water on burning plutonium.

**Status Report on Current Plant Situation**

1. Recovery and cleanup efforts in Building 776-777 have been remarkably effective and will be important in offsetting the effect of the fire on production schedules. Contractor management and employees have worked with great ingenuity and perseverance to clean up and decontaminate major portions of the building and to restore production capability there.

2. Decontamination, cleanup, and installation of equipment in the fire-damaged building have made possible the resumption of developmental production, even though not yet full scale. This is a significant step toward getting plant operations back fully on stream. About 80 percent of the 211,000 square foot structure has now been decontaminated.
3. More than 99 percent of the plutonium that was in the building before the fire has been retrieved. Eventually, the AEC expects to reuse essentially all of this plutonium. The balance is combined with other fire debris and will be handled routinely as is other waste material.

Division of Operational Safety
U. S. Atomic Energy Commission
Washington, D. C. 20545
PLUTONIUM FIRES

During conduct of routine plutonium operations in a ventilated hood, a plutonium chip (created during a roughing cut) spontaneously ignited, fell into and caused ignition of a pile of plutonium chips in an adjacent container. The operator applied carbon tetrachloride in an attempt to extinguish the fire. A violent reaction ensued accompanied by rapid combustion of the metal. The heat and generated gases raised the pressure within the hood from below to above atmospheric pressure, thus forcing some of the fumes into the room. Clean-up of contamination due to plutonium oxides resulting form the fire will cost an estimated $8,000. The intensity of the fire was sufficient to melt the bottom of the metal container holding the chips.

Reports of similar incidents are recorded at other locations. These recent incidents are considered of significance, not because of any new fire protection information gained, but rather because they suggest the possible need for re-education of employees regarding plutonium fire hazards.

Aside from possible loss of the high-value material involved, plutonium fires are of concern because of the following considerations:

1. Critical Mass

When the quantity of metallic plutonium involved in a fire exceeds “always safe” quantities, a self-sustaining nuclear reaction may result from changes in metal configuration (e.g., melting, settling of oxides, etc.) and/or as a consequence of neutron-moderating effects of materials applied to the fire (e.g., water). Critical mass hazards are obviously of no concern during a fire where the quantity of metal handled is smaller than “always safe” amounts.

2. Personnel Hazards

The extreme toxicity of plutonium oxides that may be generated and dispersed during a plutonium fire tends to complicate fire control and extinguishment measures.
3. Decontamination

The expense in time, money, and manpower necessary to decontaminate an area in which a plutonium fire has occurred is extremely large when compared to clean-up expenses following a small fire in other metals. Because of this aspect, a fire involving amounts as small as gram quantities of plutonium may require sizable decontamination expenditures. The high hazards and loss potentialities which may be expected to accompany a plutonium fire suggest the need for commensurate fire prevention and control planning at all locations where plutonium fire problems may be encountered.

PLUTONIUM FIRE EXTINGUISHMENT AND CONTROL

Comparatively little is known regarding plutonium fire extinguishing methods that are reliable in all cases. Much is known, however, of fire extinguishing measures that should not be used. It is known, for example that the rate of plutonium combustion may be markedly increased and, under some conditions, explosions may occur following application of water, foam, soda-acid, carbon tetrachloride, or dry chemical (sodium bicarbonate) “extinguishants.” The application of CO₂ cannot be relied upon to extinguish plutonium fires and its use may significantly increase dispersal of plutonium oxides over the immediate area.

Met-L-X (sodium chloride), G-1 (graphite), sand, solomite, and magnesium oxide, ALL IN THE FORM OF DRY POWDER OR GRANULAR MATERIAL, have been used, or have been suggested for use, as “safe” plutonium fire extinguishants. These materials cannot be relied upon in all cases to extinguish plutonium fires. Their application can, however, serve the valuable purpose of confirming the highly toxic oxides created during the fire as well as providing sufficient thermal insulation to expedite handling of the burning metal.

The techniques and materials used in handling plutonium fires may be expected to vary with the amount, form, and location of the metal at the time of the fire. The conditions most frequently encountered are those in which “always safe” quantities of plutonium are handled in sealed hoods operated under negative pressure. In such cases, an attempt should be made to isolate the burning metal (if this can be rapidly done) and to cover the burning metal with one of the dry materials mentioned in the preceding paragraph. The extinguishant-covered burning metal should then be placed in a metal container which has previously been partially filled with extinguishant, and more extinguishant added, if necessary, before fitting a loose metal cover on the container.

Plutonium fires generally take place without visible flame and are characterized by comparatively slow combustion accompanied by local emission of intense heat and brilliant white light. While the latter aspect may be partially masked by an oxide coating over the burning metal surface, the heat is often sufficient to cause melting of stainless steel, etc. There are some indications
that the melting of steel in contact with burning plutonium may be at least partially due to formation of eutectic alloys having a lower melting point and higher pyrophoricity than plutonium. When burning plutonium metal is placed in a metal container, care should be taken to ensure that the container is filled with sufficient extinguishant to prevent direct contact of the plutonium with the metal sides of the container. While an appropriate lining (e.g., graphite) may be used to prevent direct plutonium contact with the metal container, use of extinguishant within the container is still desirable for the dual purpose of providing thermal insulation and for reducing contamination spread by confining oxides generated during plutonium combustion.

The fire control procedure outlined above may or may not result in extinguishment of plutonium fires. If extinguishment occurs, the metal may spontaneously re-ignite when subsequently exposed to air. If extinguishment does not take place, the plutonium may continue to burn under the extinguishant as long as a day or more before complete conversion to the oxide.

PLUTONIUM FIRE PREVENTION

The Argonne National Laboratory has recently undertaken a detailed research project which will attempt to determine reasons for the observed wide differences in pyrophoricity of metallic plutonium and certain other heavy metals. Circumstantial evidence suggests that such vagaries are probably intimately associated with water-metal reactions occurring either during or after formation. Control of moisture in preparation and subsequent handling of the metal, therefore, appears to be a basic factor in minimizing the possibility of plutonium fires.

Experience has definitely established that spontaneous, self-sustaining plutonium fires can (under conditions not fully understood) take place in air in massive forms of the metal, but are more likely to occur where finely divided metal is involved. The extent to which probability of fire is influenced by the type of coolant used is not known. During “dry” plutonium operations, plutonium chips may spontaneously ignite due, at least in part, to the heat generated during chip creation. To avoid possible spread of fire, the amount of chips in the immediate vicinity of operations should be kept at a minimum. Combustible material likewise should be kept out of the vicinity. If is probable that the incidence of fires during operations may be minimized if conducted in dry air or dry inert gas. If any lubricants are used during operations, they should be as free of moisture as practicable.

If plutonium chips are to be stored for a period exceeding 24 hours prior to recovery operations, the probability of spontaneous fires may be reduced by briquetting the chips in an inert atmosphere (argon or helium) followed by initial exposure; and preferably storage, in dry air.

Storage, handling, and shipment of plutonium metal in quantities larger than “always safe” amounts involve appraisal of critical mass, security, and cost factors, discussion of which is beyond the scope of this paper. While each
problem of this type requires individual evaluation from a fire standpoint, a few precautions deserve mention:

1. The amount of combustible material in the immediate area of plutonium metal should be held to a minimum.

2. Means should be provided for prompt and proper notification in the event of fire. Consideration of automatic detection devices and periodic inspections is involved.

3. Noncombustible physical barriers should be provided to limit the maximum quantity of plutonium, that can conceivably be involved in a single fire, to a quantity which, if lost, is acceptable to management as a known calculated risk.

4. In providing the physical barriers above, consideration should be given to the possible changes in metal geometry from fire, accumulations of plutonium oxides, and the effect of various fire extinguishants which might be used.

5. Responsible personnel should receive continual training in approved fire prevention and fire fighting techniques. Facilities necessary for conducting such operations safely should be provided and periodically checked.

6. Where warranted by real or potential exposure hazards or value of the plutonium metal involved, provision of automatic fire protection by inert gas flooding or fixed piping for dry extinguishants should be studied.

SUMMARY

Until such time as further information becomes available from research into the causative factors of pyrophoricity of metallic plutonium, preventing and controlling plutonium fires must be determined by past experience coupled with use of educated judgment. The high value, the toxicity, security and critical mass considerations, combined with the unknowns in plutonium pyrophoricity and the fact that no effective means for extinguishing plutonium fires are known, combine to urge considerable caution in the handling of this metal. The following general guides for plutonium fire protection appear warranted:

1. Limit the maximum quantity of plutonium metal kept in any one area to an amount which, if lost by fire, constitutes a reasonable known risk.

2. In a plutonium fire, isolate the burning metal rapidly, e.g., by covering with extinguishant and placing in a covered metal container, to minimize dispersal of plutonium oxide contamination.

3. Plutonium metal should only be stored and handled in an area in which external fire hazards have been reduced as must as possible.

4. Expect to have a fire.
PLUTONIUM CHIP FIRE

The incident described below is quoted from the Report of Investigation (with minor modifications to eliminate security aspects) to illustrate the need for extreme care in combating fires involving fissionable materials:

"A small fire occurred in the fabrication line, resulting in contamination being spread throughout the production area. The sequence of events are as follows: Plutonium chips had been processed into a briquette, placed into an 8" diameter, 6" deep, stainless steel container, and moved down the fabrication line conveyor to an analytical balance for weighing.

"The analytical balance is enclosed in a dry box connected to the fabrication line but separated by a sliding door. This door is used for entry and exit of material and to prevent air turbulence during weighing, at which time the box becomes a dead-air dry box although still at a static pressure approximately 1" of H2O negative to the area in which the operator is located. The chemical operator had inserted his hands into the glove of the dry box, opened the sliding door, removed the material from the stainless steel container, placed it on the balance, closed the door, and had nearly completed weighing the briquette. At this time he noticed the briquette had started to smoke and burn. In attempting to remove the briquette from the balance pan, it was spilled on the floor of the dry box. Burning material

Appendix J-1
ignited a glove in the dry box. The operator immediately secured a CO₂ extinguisher and attempted to extinguish the burning glove. In so doing, CO₂ pressure was expelled into the dry box, causing contamination to be forced out into the area as the operator overlooked opening the sliding door leading to the fabrication line. Several extinguishers were used to control the burning, with little success. At this time responsible supervision arrived on the scene and immediately opened the sliding door. The burning material was then scooped up, put back into the stainless steel container in the fabrication line and left to burn under control. The glove port was taped up with masking tape thus again confining the material within a controlled area.

"The fire did no damage to the balance or other equipment within the enclosures. However, contamination was widespread in the immediate area with counts of 27,000 per minute or above. The analytical laboratories, maintenance shops and development areas on the same floor were not contaminated. The clothes of 44 personnel were contaminated to some degree and skin contamination was evident on 16 personnel. All were decontaminated within one hour, with the exception of 3 people who were sent to Medical for further scrubbing. These 3 men were returned to the job within 3 hours after reduction of count to within tolerance limits by the Medical Department. Urine samples were negative on all but 2 employees, one of whom had 15% of tolerance and the other 24% of tolerance. Sampling is being continued on these 2 men.

"Contamination to employees was mainly by inhalation and absorption by body contact. Nose counts showed less than 250 counts per minute. Loss of fissionable material was very minor, amounting to approximately 5 grams. The cost of decontamination of the area amounted to $9500. This includes maintenance labor, production labor, miscellaneous material and supplies, protective clothing and cleaning materials and waste disposal.

"The exact cause of the fire is undetermined to date; however, the briquette is believed to have ignited spontaneously from friction caused by relief of stresses.
from the briquetting operation. Research is in process to see if the cause of this spontaneous ignition can be determined. Briquetting of this material has been discontinued until the research is completed. All employees in the production department have been reindctrinated in the proper method of fighting or handling metal chip fires."
A small amount of metallic plutonium spontaneously ignited within a dry box in a so-called "fireproof" building which was relatively free of combustible material. The story behind the $300,000 or more property damage ultimately suffered from this incident tangibly illustrates many fire protection aspects of broad applicability wherever radioactive materials are handled.

Metallic plutonium presents three major hazards: (1) It can spontaneously ignite in certain forms; (2) as a fissionable metal, plutonium must be handled with special care to avoid accidental criticality incidents; (3) plutonium and its products of combustion are toxic to such a degree that extreme care is necessary to avoid ingestion, inhalation, or skin contact. All of these hazards were involved in the incident described below.

At 13:13 p.m., watchmen discovered a fire which appeared to consist of plutonium within a dry box, plastic parts of the box itself, and rubber gloves (normally used to avoid skin contact during handling of plutonium). Knowing that plutonium was handled and stored in the area, firefighting was delayed until personnel could put on protective clothing and evaluate the hazards involved. Portable carbon dioxide extinguishers, ranging up to 177-pound units, were emptied on the fire without effect. Although there was considerable uncertainty concerning the criticality hazards involved, water spray finally was applied to the fire and proved effective for its control.
The dry box fire discussed above had two serious consequences: (1) It allowed escape and dissemination of considerable plutonium contamination throughout the immediate area; (2) it also burned through the combustible CWS filter at the dry box permitting flames and some unburned combustible gases to pass through ventilating ductwork to the large main bank of filters which were of a combustible type. Combating fire in the main filter bank was impeded both by radiological hazards to personnel and by difficulties in selecting methods for extinguishing the fire without simultaneously destroying the integrity of the filters.

On two occasions during the fire, minor explosions were experienced from as yet unexplained causes, but are suspected to have occurred in the explosive gas generated by plastic heated in the fire. About 13 hours after its inception, the last remnants of the blaze were extinguished. Virtually all of the units in the large filter bank were destroyed.

Contents

Plutonium Hazards and Dry Box Design

A peculiarity of this incident was the abnormally large extent to which the entire chain of events was influenced by hazards associated with a relatively small amount of metallic plutonium. The chain started with spontaneous ignition of the metal - an unusual but far from unprecedented experience - which produced intense but localized heat during relatively slow combustion. This heat was of itself of little significance beyond the important fact that it served to ignite adjacent flammable materials (primarily the plastic used in portions of dry box construction). A combination of concern over the relatively high toxicity of fumes created by plutonium combustion, and the need for carefully evaluating criticality risks that might be encountered, resulted in a significant delay in selecting and initiating use of combative measures after the initial fire was detected. To reduce possible personal exposure to toxic plutonium fumes, the ventilating fan controls were switched to the high-speed position. This action, however, together with fire destruction of the flammable filter in the dry box exhaust, allowed fire spread to the main bank of combustible filters which, in turn, were damaged by
fire and permitted escape of some plutonium contamination to the surrounding external area. Nullification, due to fire; of the dry box ability to confine plutonium hazards permitted spread of toxic plutonium combustion products within the building.

When these facts are viewed in retrospect, it appears (by hindsight) irrational that facilities were ever designed in such a manner as to permit hazards from a relatively insignificant amount of material to so strongly influence the chain of events which led to a major loss. The incident strongly reflects the general need for a more comprehensive program for detecting and evaluating fire risks both in design and operating phases, with particular emphasis on evaluating the inordinate degree to which fire risks are influenced by even small quantities of radioactive materials and, conversely, the abnormally large extent to which radioactive material hazards are increased during even a small fire. The same facts suggest the desirability of approaching design of dry boxes used for radioisotope handling by applying the same "containment" philosophy applied to reactors, namely, to design facilities to withstand and to contain all radiological hazards in the event of the worst credible incident. The separation of facilities is also suggested for reduction of the total risk.

Ventilation and Filters

Ventilation for dry boxes used in handling radioactive materials may serve several purposes. One of the most important is to prevent accidental escape of radioactive materials into external areas by operating the ventilating system so as to maintain a negative pressure within the enclosure. Expansion of hot gases generated by a fire within a dry box tends to increase internal pressure at a rate ranging from insignificant to explosive, dependent on the materials involved and the conditions under which combustion occurs. If the rate of pressure rise due to fire exceeds capacities of the dry box ventilating system, air pressure within the dry box may exceed that of external surroundings, thereby increasing risk of external dispersal of contamination.

Dry box ventilating systems are normally equipped with a filter intended to remove radioactive contamination. Until fairly recently, the only available satisfactory filters were of a combustible type. Such filters may affect fire risks in
several ways. Particulate combustion products created by incineration tend to clog filters, thereby reducing air flow and decreasing dry box ventilation efficiency during a period in which increased ventilation efficiency is needed. Destruction of the filter by fire may permit spread of flames and contamination outside the dry box, which occurred in this instance. Finally, some types of paper filters may spontaneously ignite following prolonged exposure to certain chemical fumes (such as nitric or perchloric acids). In some cases, devices such as fire screens, automatic dampers or automatic sprinklers may have considerable value in preventing fire spread through the dry box ventilating system.

Many installations handling radioactive materials utilize a large bank of secondary filters to "back up" the much smaller filters provided on individual dry boxes. The difficulties in combating fires involving large banks of secondary filters were well illustrated by the incident outlined in SERIOUS ACCIDENTS Issue No. 83, dated July 27, 1955. Comparable problems were encountered during the incident described above. Such filters present several difficult fire problems. If ventilation is left on during a fire to remove smoke and contamination-spread hazards within the building, risk of increased fire damage to the secondary filters (and their immediate surroundings) must be accepted, plus the risk of dispersing radioactive particulates through destroyed filters out the stack to be dispersed over an area that may exceed confines of the plant. Water, one of the few known effective extinguishing agents for large filter fires, has serious drawbacks in that water damage promotes filter failure which, in turn, prevents filters from serving their intended purpose, that of removing radioactive particulate matter. Hazards attending the use of large banks of combustible filters may to a degree be reduced by providing fire barriers between filters, by minimizing maximum allowable size of secondary filter banks, and possibly by provision of automatic sprinkler protection. Provision of noncombustible filters affords the cheapest and most effective currently-known answer to the large filter fire problem on existent facilities. (Specifications for fire resistive filters are available in the AEC Headquarters Safety and Fire Protection Branch.)
Firefighting and Fire Detection

Whether justified or not, the realistic fact must be faced that fires involving radiological risks commonly result in considerable delay in initiating manual firefighting activities. Because of this, increased usage of automatic fire detection and control devices is certainly justified to a degree far exceeding the justifiable practice commonly used for identical risks in which radiation hazards are absent. It is quite probable that the provisions of one or two automatic sprinklers within the dry box involved in this fire would have permitted earlier fire detection, much earlier establishment of fire control, and limited fire and contamination damage to immediate surroundings. The provision of automatic sprinklers admittedly may introduce new risks of contamination spread in water run-off and, in the case of fissionable materials, the danger of inducing an accidental criticality incident. The incident provides tangible evidence to support the belief that failure to provide automatic fire detection and control measures for radiological risks will in general result in a level of personal injury and property damage risks exceeding that which would exist if automatic fire detection and control devices were used. It is certain that any evaluation of fire hazards, including radiological risks, must seriously include due allowance for the far lower rapidity and efficiency of manual firefighting operations that may rationally be expected to be conducted where radiological risks are involved.

Design Simplicity

Experience in explosives manufacture affords a surprising number of analogies to guide users of radioactive material in efforts to minimize decontamination expenses. Explosive manufacturers commonly limit the maximum possible risk at any single location by limiting both the amount of material handled and the maximum number of people permitted at one location. Explosives handling areas are kept as free as possible of noxious materials and facilities. Exposed surfaces are minimized, and particular care given during design to minimize the time and expense required for conduct of cleaning these surfaces of contamination. Extreme care is, of course, given to avoidance of fire risks. While few radioactive materials will involve any explosion risk, the extreme
importance of minimizing radioactive decontamination expense in
the event of fires suggests that radioactive material users may well profit by the hazard limitation and housekeeping
techniques that have been found effective and economically justifiable in the explosives manufacturing field.

Conclusions and Consequences

Following the incident described above, added weight has been given to the AEC-sponsored plutonium fire hazard research
program, a proposal for establishing engineering design
criteria for dry box construction to ensure incorporation
of adequate fire protection has been submitted, and considera-
tion is currently being given to the potential benefits to be
derived by holding a meeting of all major AEC contractors
concerned with plutonium risks to expedite maximum interchange
of available information on plutonium hazards and means for
their control. The program for replacing combustible filters
with filters of a noncombustible type has been accelerated.
Increased provisions of automatic fire detection and control
devices on radiological risks are expected.

Perhaps the most important general conclusion that may be
drawn from review of the incident is the need for increased
attention to evaluation of fire risks involving radiological
and/or criticality hazards.
BURNING PLUTONIUM CHIPS EXPLODE IN CARBON TETRACHLORIDE DEGREASING BATH

One step of a degreasing operation being conducted within a glovebox involved dipping a perforated bottomed stainless steel can, filled with metallic plutonium chips, into a carbon tetrachloride bath. The container was then hung on a hook where the excess solvent was permitted to drain or evaporate while the operator left to obtain more chips. On his return, about five minutes later, he found the previously cleaned chips were on fire. This fact of itself was unusual but not unprecedented and a standard procedure existed for handling such contingencies. In implementing this procedure (which involved placing the chips on the glovebox floor, covering the container top and allowing the chips to burn out), the rubber-gloved hand of the operator slipped, allowing the burning chips to fall into the carbon tetrachloride bath. An explosion, accompanied by a shock wave, immediately followed.

The explosion ruptured the glovebox (see accompanying illustration). Flying fragments injured the operator's left hand to a degree causing ultimate loss of the left thumb and index finger. Damage to equipment ($3,679), loss of product parts ($2,279), decontamination ($42,723), costs to recover 900 grams of plutonium dispersed through the glovebox line ($3,078), and plutonium losses ($4,600), comprise the elements making up the $56,359 direct loss suffered from the incident.

The investigating committee report included the following recommendations:

1. Hinged spring loaded lids should be provided on the solvent dip tanks to insure that the tanks are not inadvertently left open.

2. The sump next to the drainboard should be covered so that chips cannot fall into the solvent well.

3. Prior to opening the lid of the first dip tank, operators shall check to assure that no evidence of fire exists in the chips to be cleaned.

(over)
4. Laboratory investigations should be conducted to determine relative rates of reactions between burning plutonium (and uranium metal) and organic solvents and oils. The objectives should be to determine the safety of present metal chip operations and to recommend safer systems.

5. Laboratory investigations should be conducted (and information from other AEC sites correlated) to define the conditions which cause the spontaneous ignition of plutonium metal chips.

Division of Operational Safety
U. S. Atomic Energy Commission
Washington, D. C. 20545

To: Blod T. Rossie
From: W. H. Harkness
Subject: Emergency Ex. 10312

The first touch response to the alarm was correct through the tunnel with the fire.

A list of these were reviewed which led to a widespread communication, including the medical staff.

(see pictures on pages 3 and 4)
Metallic plutonium lathe operations, conducted within a glovebox, utilized a circulating oil coolant system, details of which are given in exhibit I. During normal operation, a small portion of the oil splashed or dripped to the base of the glovebox where it was impounded by a drip pan (not shown in the sketch) having a pipe connection to a valve in the "box drain" line. This valve was normally kept in a "cracked-open" position so that during operation, drip pan oil accumulation was removed continuously.

Components of the box drain line, shown in exhibit II, were arranged to permit flow of oil through a screen in the drip pan, through the side outlet of a piping "T" connection, and through the previously mentioned valve, to the suction side of the coolant oil recirculating pump.

The incident occurred during attempts to unclog the "box drain" line. (Two maintenance men, a supervisor, and a health physicist were present during the entire operation; all were wearing respirators.) When initial attempts to clear the line (e.g., by flushing with carbon tetrachloride) proved unsuccessful, the decision was made to try to clear the line by rodding the pipes and connections located beneath the glovebox. To control anticipated contamination, a 3'x4'x2'-high paper and plastic "pen" was constructed around the drain piping. Paper towels, a bottle of decontamination solution, and a plastic pan (to catch the anticipated flow of oil when the drain was opened) were placed on the floor of the "pen". The pipe cap was removed and a welding rod was used to probe inside the drainpipe in an attempt to dislodge any obstruction. It was noted that this probing produced a few sparks when the rod contacted a metallic object in the drainpipe. Subsequently, a center punch was inserted into the drainpipe in an attempt to remove forcefully the obstruction. The hole in the "pen" through which the center punch was inserted was sealed around the punch using tape. The first light blow on the center punch caused a spark at the location of the obstruction. The second blow produced a large amount of sparking accompanied by a football-sized ball of fire that narrowly missed the employee's face. The plastic and paper pen ignited and the copper drain line in the vicinity of the "T" turned a cherry-red color from intense heat within the pipe. The fire, which lasted about one minute, was controlled, using a portable extinguisher.

(over)
EXHIBIT I

INCIDENT TOOK PLACE DURING WORK ON THIS SECTION. SEE EXHIBIT II FOR DETAILS.
PIPE CONNECTION TO GLOVEBOX DRIP PAN

COOLANT PUMP INLET

DRIP LINE VALVE

PIPE CAP
Contamination generated by the fire spread throughout the building and through 25,000 square feet of an adjoining building. Cleanup costs account for most of the $17,000 loss resulting from the incident. Air samples, taken 100' to the north, 190' to the northwest, 125' to the west, and 60' to the south of the fire, were highly contaminated. The general pattern and extent of airborne contamination levels, relative to surface contamination levels (which were not excessively high in the building areas involved), provide evidence of small particle sizes (0.12 micron measured count median diameter and 0.32 measured mass median diameter).

All persons leaving the building after the fire were requested to take a shower. Fifteen employees within the general area of the fire received inhalation exposures resulting in depositions of 0.008 to 0.17 microcurie in the lung.

Incident Cause

Investigators believe that the incident was induced by friction. Prior experience (see SERIOUS ACCIDENTS Issue #246) had demonstrated that burning plutonium chips can react explosively with carbon tetrachloride. Analyses of residues in the drain line confirm that a plutonium-carbon tetrachloride reaction occurred within the pipe. The ball of fire is attributed to ignition of hydrocarbon oil vaporized during metal combustion.

Lessons Learned from the Incident

This incident again attests that a relatively minor fire in radioactive materials can lead to sizable property damage by initiating airborne spread of contamination and that the extent of spread is governed by drafts existing during and immediately after the fire. Property damage and loss limitation by appropriate pre- and post-emergency control of ventilation is a matter warranting careful individual study on all facilities handling radioactive materials subject to spread during a fire.

The probability of incident occurrence during maintenance could have been reduced by use of an inert gas atmosphere at the exposed ends of the vent line and by substitution for carbon tetrachloride of a flushing fluid having lower potential for reactivity with plutonium.

The incident also raised questions as to the adequacy of procedures and equipment for promptly warning employees in the event of real or threatened exposure to airborne radioactivity.

(continued)
The hazard of carbon tetrachloride-metallic plutonium reactions was pointed out in SERIOUS ACCIDENTS Issue #246, March 12, 1965, and the potential would be suspected from information in SERIOUS ACCIDENTS Issues #47, June 12, 1953, and #23, May 1, 1952. Further publicity to prevent potential carbon tetrachloride reactions with reactive metals would appear justified. The facility that suffered the incident has discontinued use of traps of the type mentioned above and has initiated a study of all piping systems having a potential for collecting metallic plutonium.

Division of Operational Safety
U.S. Atomic Energy Commission
Washington, D.C. 20545
FIRE DURING GLOVEBOX CLEANUP LEADS TO $23,000 DAMAGE
VIA CONTAMINATION SPREAD

One of the required steps in preparing a plutonium glovebox line for disposal involved stripping the paint to ensure recovery of plutonium. The normal process for doing this involved application of a nonflammable paint remover (sodium hydroxide, methylene chloride), followed by a layer of a "cocoon" paint remover containing 50% acetone) to help loosen the paint and to reduce contamination spread during subsequent paint-stripping operations. Containers of the "cocoon" agent were adequately labeled to call attention to fire and vapor explosion hazards.

The work permit stated that the operation would be conducted in an inert atmosphere and it was assumed by some persons that a nonflammable paint remover would be used. The paint-stripping work was initiated with the knowledge that other operations, conducted in the same line, utilized a muffle furnace. The guillotine door separating these two operations was left slightly open. The adequacy of ventilation within the glovebox was known to be marginal at best.

The day preceding the accident, paint was partially stripped from the glovebox using the nonflammable paint remover. The box was then painted with "cocoon" slips because the muffle furnace was off on that day, these activities were conducted without incident.

The day of the accident, work was initiated by stripping the "cocoon" that had been painted on the previous day. The airlock to the glovebox exterior is opened, the "cocoon"-removed and the stripped material placed in the airlock. The airlock was then reopened and three quarts of the "cocoon", in an open-top container, was introduced and subsequently used for painting the top and upper half surfaces of the glovebox. The empty container was then placed in the airlock and the painter left to get more "cocoon". He returned to the airlock and was in the process of introducing three quarts of "cocoon" when he was hit by a flame which came suddenly out of the airlock. He dropped the container and left the area with burns on both forearms and on his forehead. Others in the area saw fire travel from the muffle furnace, out of the airlock and extend in a wall of flame to the ceiling. They immediately vacated the area and called the fire department. Firemen rapidly extinguished the external fire with portable CO₂ extinguishers but fire continued to burn in the airlock. This fire was ultimately controlled by introducing solid CO₂.

(over)
Ductwork for a booster exhaust system was in the process of being modified at the time of the incident. With reference to the drawing shown, it should be noted that a ventilating duct extended from room 180 D (the room in which the incident occurred) to a paint shop on the floor above. The greatest amount of contamination probably spread through duct "A" into the plenum where ducts "B" and "C" had some of it back into the paint shop through the spaces left for yet-to-be installed valves. The magnitude of the contamination spread over the floors of the building is indicated by the $23,000 cost for cleanup.

All employees at the scene of the accident were wearing respirators. None received significant internal radiation exposures. While the skin of twelve employees was contaminated, decontamination was readily obtained in all but one case, where continued treatment over several days was required.

Lessons learned from the above incident are largely apparent. The use of flammable fluids implies need for effective hazard control procedures.

The proper use of a work permit could, of itself, have served to prevent the accident. Elimination of a fire hazard through use of nonflammable substitute is indicated where these are available. The potentials for contamination spread clearly increase with increasing size and complexity of building ventilation systems. The major lessons learned from this incident are not new—but their emphasis at other locations having similar risks.

Division of Operational Safety
U. S. Atomic Energy Commission
Washington, D. C. 20545
Ventilation Ducts – An Underrated Fire Hazard

May 11, 1989, marked the 20th anniversary of the Rocky Flats (Colorado) fire. This fire, which occurred in Building 776-777 of the facility, spread very rapidly through the overhead conveyor lines and one of the interconnecting conveyors into the center line. Damage to Building 776-777 and its equipment was extensive. Not only was there fire and smoke damage, there was also severe damage to substantial portions of utility systems within the building and internal plutonium contamination.

Although the exact cause of the fire was not determined, evidence indicated that the long, uninterrupted glove box lines in Building 776-777 created a wind-tunnel effect. In addition, the interconnected conveyor system, which had no physical barriers, provided a path for the fire to spread rapidly over a long distance. The plastic windows that were a major structural part of the containment system created an additional fuel source in the glove box containment system; continuous operation of the glove box ventilation system provided a constant supply of air to support combustion. Thus, the 1969 fire at Rocky Flats moved very rapidly over a long distance and caused extensive damage to the facility.

Duct fires also have the potential to cause extensive damage, since these fires can easily spread very quickly to other rooms or floors. On April 5, 1989, for example, there was a fire in an exhaust duct for a grinding operation in Building 444 at Rocky Flats. Like the long, uninterrupted glove box lines that contributed to rapid spreading of the 1969 Rocky Flats fire, the long, uninterrupted duct enclosures in Building 444 allowed the fire to spread very quickly.

Common Duct Fire Elements—Inadequate Inspection, Cleaning, Monitoring, and Control

The duct fires described above are only two of a significant number that have occurred over the past 10 years. All of these fires had two elements in common: (1) lack of an adequate duct inspection and cleaning program; and (2) lack of adequate monitoring and control of “hot work” activities, such as cutting, welding, and grinding.

In a duct fire at the Martin Marietta facility in Oak Ridge on April 19, 1989, oil residue was ignited by a piece of hot oxide that entered the exhaust duct. Although periodic cleaning had been recommended following a similar incident at the facility in 1979, the exhaust system obviously had not been cleaned. The buildup of oil and oxide residue found in the exhaust system ductwork apparently had accumulated over a period of years.

DOE 5380.4 designates National Fire Protection Association (NFPA) standards as the “prescribed standards” for fire protection programs at DOE facilities. Two of these standards, NFPA 90A (Standard for the Installation of Air Conditioning and Ventilation Systems) and NFPA 91 (Standard for the Installation of Blower and Exhaust Systems), contain valuable guidance for inspecting, cleaning, and maintaining these systems. Adherence to these NFPA standards and the use of an aggressive “hot-work” permit system that required both a walk-down of an affected area and a dedicated fire watch could have prevented all of the duct fires reviewed.

High-Risk Operations

In general, the duct fires reviewed could be attributed to one of four types of operations — torch welding or cutting on plenums; welding, cutting, or grinding in the vicinity of ducts; grinding sparks igniting loaded filter bags; or uranium machining.

Torch Welding or Cutting on Plenums — Several duct fires occurred during welding or cutting operations. These operations typically involved the modification or demolition of ducts without considering or accounting for any combustible materials inside them. Fires resulted from the combustion of such overlooked materials as paper
trash (e.g., paper towels) and organic fibers (e.g., lint, hair) or from oils that had condensed on the interior duct walls. There was no indication that a viable inspection or cleaning program for duct interiors had been implemented in any of the cases reviewed.

Welding, Cutting, or Grinding in the Vicinity of Ducts — Duct fires were also started due to welding, cutting, or grinding on or near plenums. In these cases, the fires involved the exterior of the ducts rather than the interior. The most significant fires in this category were caused by combustion of either duct insulation itself or the highly combustible facing that is found on the insulation of many ducts. Apparently these combustible finishes were not identified as combustible materials or were not recognized as such during preplanning activities.

Grinding Sparks Igniting Loaded Filter Bags — In some of the fires reviewed, combustible materials were ignited during otherwise routine grinding operations. In one case, a fire occurred because the ventilation system was loaded with sawdust from a belt sander used exclusively for sanding wood. In this case, as in all the cases reviewed in this category, there was no effective duct/filter cleaning program at the facility.

Uranium Machining — Numerous duct fires occurred during uranium machining operations. Typically, sparks were ingested into the exhaust duct, where they ignited uranium dust or fines that had collected inside the duct. In some of these cases, rubberized, flexible sections of duct were also ignited. The lack of a vigorous duct cleaning program also contributed to these fires.

**Recommendations**

Taking actions such as those recommended below will help prevent ventilation duct fires.

1. Site preventive maintenance programs should provide for inspection and cleaning of ventilation and exhaust ducts. The following areas are of particular concern:
   - Areas where combustible liquids (e.g., lubricants or cutting oils, solvents, etc.) are used. These materials condense on interior duct surfaces and present a highly combustible interior finish. Lint, hair, and similar items build up on oily surfaces. Preventive maintenance is particularly important for ducts serving equipment where oil is used — in cutting operations, for example. However, it is important to note that even water-based cutting/cooling fluids can present a fire hazard. These fluids can condense on the interior duct surfaces, leaving an oil or ester coating when the water evaporates.
   - Areas where Class "A" combustible materials or fibers may be entrained in the ventilation/exhaust system. Laundry and computer operations, for example, are problem areas for the entrainment of Class "A" combustibles.

2. To the extent possible, combustible materials should not be used in the construction and insulation of ducts. Combustible materials used in these activities include such seemingly minor components as rubberized, flexible sections of ducts and the paper/foil surface on some insulation.

3. Preplanning activities should be required prior to cutting, welding, grinding, and other "hot work." These activities include both a review of the work to be accomplished and an inspection of the actual work area by a qualified person. Consideration should be given to conductive transmission of heat to combustible materials or surfaces and to contact with flame, slag, or sparks. Fire watches should be used at appropriate locations, and "first-aid" fire fighting equipment should be provided. (In one of the incidents reviewed, a fire watch was in effect when the fire began; however, no fire extinguisher was available to extinguish the fire when it was in the incipient stage.)

4. Sprinkler protection should be installed inside ducts that convey flammable or combustible materials or in ducts where these materials may accumulate. If the general area is already protected by automatic sprinklers, it is often relatively simple to extend protection to the inside of the duct. (In some of the cases reviewed, sprinkler protection inside the duct prevented a large fire loss.)

In addition to the recommendations listed above, NFPA 90A and NFPA 91 contain important and helpful guidance for addressing ventilation duct fires. In high-risk areas, for example, these standards recommend the installation of an access door in ducts to facilitate inspection and cleaning. Using these standards as a basis for developing necessary procedures and programs will also aid in the prevention of ventilation duct fires.

**Conclusion**

In the 20 years since the fire in Building 776-777 at Rocky Flats, fire protection programs have been enhanced at all DOE facilities based on the recommendations of the Factory Insurance Association and Factory Mutual Research Corporation. However, in the past 10 years, duct ventilation fires have resulted in significant losses, and most of these fires had the potential to cause a much larger loss. More importantly, all of these fires could have been prevented if the appropriate NFPA standards and the recommendations listed above had been implemented at the facilities where these fires occurred.
A.5.16
Ion Exchange Resins and Minor Events
by
T. Muscatello
DEPARTMENT OF ENERGY
PLUTONIUM ES&H VULNERABILITY ASSESSMENT

ASSESSMENT TEAM TRAINING

April 19–21, 1994
Colorado Springs, Colorado

ION EXCHANGE RESINS AND MINOR EVENTS

Tony Muscatello
INTRODUCTION

- Several explosions and fires in nuclear facilities from ion exchange resins
- Numerous leaks and spills of stored plutonium solutions in DOE facilities
- Other contamination including incidents from plutonium storage and handling
- Nitric acid–related incidents
ION EXCHANGE RESINS
STRUCTURE

Strong Base
Anion Exchangers

Strong Acid
Cation Exchangers
ION EXCHANGE RESIN
HAZARDS

Strong–base anion exchangers

- Combined oxidizer and fuel (in nitrate form)
- Subject to radiolytic degradation from plutonium
  - lowers ignition temperature
- Lower ignition temperature when loaded with Pu(NO₃)₆²⁻
  - < 100°C

Strong acid cation exchangers

- Generally more stable than anion exchangers
- Still subject to radiolytic degradation
  - less sensitive than anion exchangers
- Organic material provides fuel for fire or explosion
# ION EXCHANGE RESINS
## ACCIDENT SUMMARY

<table>
<thead>
<tr>
<th>No.</th>
<th>Date</th>
<th>Resin Type</th>
<th>[HNO₃]</th>
<th>Metal Ion</th>
<th>Temperature</th>
<th>Result</th>
<th>Country or Site</th>
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<td>6/62</td>
<td>Anion(SB)</td>
<td>7N (36%)</td>
<td>Pu</td>
<td>77°F</td>
<td>Rupture</td>
<td>France</td>
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<td>7/63</td>
<td>Anion(SB)</td>
<td>8N (40%)</td>
<td>Pu</td>
<td>77°F</td>
<td>Rupture, Fire, Charring</td>
<td>RFP</td>
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<td>11/63</td>
<td>Anion(SB)</td>
<td>7N (36%)</td>
<td>Pu</td>
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<td>Fire</td>
<td>Hanford</td>
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<td>4</td>
<td>10/64</td>
<td>Anion(SB)</td>
<td>&gt;13N (60%)</td>
<td>Np</td>
<td>95°F</td>
<td>Explosion</td>
<td>SRP</td>
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<td>5</td>
<td>7/65</td>
<td>Anion(WB)</td>
<td>2N (10%)</td>
<td>Fe&amp;Cr²</td>
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<td>BNL</td>
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<tr>
<td>6</td>
<td>1/67</td>
<td>Anion(SB)</td>
<td>0.5N (3%)</td>
<td>²⁴⁴Cm</td>
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<td>7</td>
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<td>²³⁸Pu</td>
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<td>Explosion</td>
<td>Russia</td>
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1  WB = weak base, SB = strong base, SBP = strong base polyvinylpyridine
2  Suspected to be present
## ION EXCHANGE RESINS
### ACCIDENT CONSEQUENCES

<table>
<thead>
<tr>
<th>No.</th>
<th>Worker</th>
<th>Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pu injection, cuts</td>
<td>Minimal</td>
</tr>
<tr>
<td>2</td>
<td>No injuries</td>
<td>Glovebox gloves and plexiglass windows destroyed by fire</td>
</tr>
<tr>
<td>3</td>
<td>No injuries</td>
<td>Redox canyon shutdown for 6 weeks for fire damage repair</td>
</tr>
<tr>
<td>4</td>
<td>No injuries</td>
<td>Hot canyon crane contaminated</td>
</tr>
<tr>
<td>5</td>
<td>Acid burns</td>
<td>Acid cleanup</td>
</tr>
<tr>
<td>6</td>
<td>No injuries</td>
<td>Small column destroyed, hot cell equipment damage</td>
</tr>
<tr>
<td>7</td>
<td>No injuries</td>
<td>Minor contamination</td>
</tr>
<tr>
<td>8</td>
<td>Internal Am deposition, cuts, and acid burns; 8 others slightly contaminated</td>
<td>Glovebox damaged, column destroyed, room still contaminated</td>
</tr>
<tr>
<td>9</td>
<td>Minor contamination</td>
<td>Column destroyed, hot cell damaged</td>
</tr>
<tr>
<td>Factor</td>
<td>Reason</td>
<td></td>
</tr>
<tr>
<td>------------------------------</td>
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<td>Nitrate resin form</td>
<td>Oxidizing group</td>
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<td>High nitric acid concentration</td>
<td>High concentration $\text{NO}_3^-$</td>
<td></td>
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<tr>
<td>High temperature</td>
<td>Increases rate of oxidation</td>
<td></td>
</tr>
<tr>
<td>Plutonium loading</td>
<td>High concentration of $\text{NO}_3^-$</td>
<td></td>
</tr>
<tr>
<td>High crosslinking</td>
<td>Groups held close together</td>
<td></td>
</tr>
<tr>
<td>High radiation exposure</td>
<td>Resin degraded</td>
<td></td>
</tr>
<tr>
<td>Large resin volume</td>
<td>Low thermal conductivity</td>
<td></td>
</tr>
</tbody>
</table>
ION EXCHANGE RESINS
PRECAUTIONARY MEASURES

- Keep resins wet—in use and in storage
- Avoid contact with concentrated nitric acid
- Do not expose resin to sources of heat (without sufficient cooling)
- Provide pressure relief equipment—valves and rupture disks
- Do not leave resins loaded with large amounts of radioactive materials for long periods of time
PLUTONIUM SOLUTION LEAKS AND SPILLS

- Large volume of plutonium solutions in storage
  - 80,000 gallons at SRS
  - 28,000 L at RFP
  - 7,000 L at Hanford PFP

- Plutonium solutions are not chemically stable
  - Generate H₂ gas from radiolysis
  - Acidity is gradually destroyed by radiolysis
  - Potential for precipitation

- Tanks and pipe system eventually corrode and leak

- Mitigating factor – plutonium solutions do not create airborne contamination until they dry out

- "Infinity rooms" at RFP
OTHER CONTAMINATION INCIDENTS

- ORPS recorded 320 plutonium related contamination occurrences (1990 – 1993)
- Two hundred and thirty-three were personnel contamination
- Twenty-one involved internal uptake
- Examples to be presented by Martz and Haschke
NITRIC ACID – RELATED INCIDENTS

- Corrosive and oxidizing substance
- For example, SRS report summarized (1952 – 1991)
  - Uncontrolled chemical reactions: 61 events
  - Inadequate rate of addition control: 14 events
  - Inadequate concentration control: 8 events
  - Inadequate temperature control: 18 events
  - Spontaneous combustion: 9 events
  - Personnel injuries: 104 events
  - Miscellaneous reactions: 13 events
SUMMARY

- Relatively low consequence events have had a very high frequency of occurrence

- Facility workers are frequently directly affected
  - By the event itself
  - By subsequent clean-up and repair operations
A.5.17

Assessment Methodology and Question Set

by

T. Muscatello
DEPARTMENT OF ENERGY
PLUTONIUM ES&H VULNERABILITY ASSESSMENT

ASSESSMENT TEAM TRAINING

April 19–21, 1994
Colorado Springs, Colorado

ASSESSMENT
METHODOLOGY AND QUESTION SET

Tony Muscatello
ES&H VULNERABILITY ASSESSMENT METHODOLOGY

- Based on barrier analysis
  - Material at risk
  - Barriers used to protect material at risk
  - Adverse conditions/events which challenge barriers
  - Compensatory measures
  - Consequences to worker, environment, public
ES&H VULNERABILITY ASSESSMENT METHODOLOGY (Cont.)

- Site Assessment Team to perform site and facility specific vulnerability assessment
- Site assessment team has detailed experience and expertise
- Working Group Assessment Team will verify and validate Site Assessment Team data and assist in finalizing vulnerability profile
Figure A-1
ES&H Vulnerability Assessment Approach

Identification of ES&H Vulnerabilities
- Environment
- Worker
- Public
QUESTION SET

Question 1 - Facility

Provide summary description of the facility including description of processes, (simplified process/material flow diagrams)

Information

- Facility landlord
- Program sponsor
- Facility age/design life
- Design mission/interim mission/current use
- ES&H experiences
- ES&H documentation
- Plutonium aggregation areas
- Important design features
- Design uncertainties
- Facility location (relative to site boundary)
QUESTION SET

Question 2 – Holdings

Summarize plutonium holdings. Identify packaging (include the maximum age of package) and major plutonium isotope. Retain classified inventory data on site.

- Disassembled weapons components in DOE custody
- Metal
- Oxide
- Scrap/residues
- Solutions
- Reactor fuel (not already reviewed in Spent Fuel Study)
- Sealed sources
- TRU waste (co-located with plutonium)
- Holdup
- High level liquid waste (co-located with plutonium)
- Cumulative inventory difference
- Other
QUESTION SET

Question 3 – Physical Barriers

Characterize facility physical barriers for

- Worker protection
- Environment and public protection

Complete a separate table for each material aggregation
QUESTION SET

Question 4 – Adverse Conditions

Indicate actual or potential adverse conditions that are applicable to the material/packaging/barriers/facility combinations described in Questions 1, 2, and 3

- In-facility
- Material
QUESTION SET

Question 4 – Adverse Conditions (continued)

In-Facility Guideline Examples:

- Inadvertent transfers – use of administrative vs. engineered controls, lack of facility knowledge
- Aging – nearing or exceeding facility, equipment, or barrier design life (e.g., plastic ~ 1 yr.)
- Organic/nitric acid reaction – mixing of concentrated nitric acid with organic materials
- Equipment failure – common cause versus single event
- Change in mission – time of standby or limitations of standby
QUESTION SET

Question 4 – Adverse Conditions (continued)

In-Facility Guideline Examples (continued):

- Other co-located hazards – not controlled adequately, storage of potentially explosive materials without controls

- Corrosion – not monitored or considered, unexpected sources (e.g., $^{238}\text{PuO}_2$ powder on rubber gloves), rusting (>5%) containers, leaking plutonium solution tanks or bottles

- Inadequate configuration knowledge – lack of or inadequate documentation, training, as-built, or P&IDs

- Combustible loading – exceeding combustible material limit or lack of combustible material loading limit program, fire department inhibited by security measures
QUESTION SET

Question 4 – Adverse Conditions (continued)

In-Facility Guideline Examples (continued):

- Inadequate seals – poor or degraded seals on gloveboxes, packages, ducts, HEPA filters (e.g., filter bypass)

- Potential water sources – in areas where water is excluded (e.g., vaults) or evidence of water (water stains or deposits)

- Inadequate drains – clogged or absent where needed, material holdup, uncertain discharge point

- Inadequacy of design basis (e.g., seismic, fire, wind, etc.) – exceeding analyzed material at risk, outdated analytical basis
QUESTION SET

Question 4 – Adverse Conditions (continued)

In–Facility Guideline Examples (continued):

- Inadequate preventive and corrective maintenance – large number (hundreds) of backlog work orders, especially on safety systems or mission–related items

- Administrative controls – large number (dozens) of backlog UOR corrective actions or any old (>1yr) UOR corrective actions, restrictions on material access prevent or delay safety–related activities

- Other–specify – other credible adverse conditions
QUESTION SET

Question 4 – Adverse Conditions (continued)

Material Guideline Examples:

- Pressurization – bulging cans or drums, gas generating materials in unvented cans or drums

- Pyrophoricity – exposure of plutonium metal to hydrogen or moist atmospheres (including inert), >200g accumulations of unstabilized oxides, mixing of pyrophoric materials (>3 wt%) and combustibles, storage of <0.05 mm plutonium metal particles

- Radioactivity – high radiation materials requiring inspection or handling that will exceed 500 mRem/yr or approach 5 Rem/yr limits (e.g., materials requiring frequent repackaging) to workers

- Chemical reactivity – chemically reactive plutonium materials in storage not adequately analyzed, acids stored in plastic bottles >5 yrs
Material Guideline Examples (continued):

- **Americium buildup** – radiation or heat hazards not adequately addressed (e.g., materials in vaults may exceed heat limits)

- **Hydrogen buildup** – storage of hydrogen-generating materials in unvented containers, exceeding lower flammability limit (4% $\text{H}_2$)

- **Radiolysis** – exposure of plastic packaging to alpha radiation, storage of high-concentration plutonium solutions (>90g/L) at low acidity (<1N) for more than 5 yrs; (leads to precipitation)

- **Volume expansion** – exposure of plutonium metal to oxygen or other chemical reactant in containers not sufficient to hold resulting material (up to 4-fold expansion)
QUESTION SET

Question 4 – Adverse Conditions (continued)

Material Guideline Examples (continued):

- Oxidation – non-hermetically sealed plutonium metal containers (e.g., canning imperfections), >2% weight change
- Corroding containers
- Other-specify – any other material-related adverse conditions
QUESTION SET

Question 5 – Events

Identify those historical, current, or potential events which have resulted or may result from adverse conditions identified in Question 4

- In-facility
- Material
- External
- Natural phenomena
QUESTION SET

Question 6 - Compensatory Measures

Describe how compensatory measures at the facility prevent and/or mitigate the adverse conditions and events identified in Questions 4 and 5.

- Preventive
- Mitigative

Describe administrative controls as well as hardware design adequacy, maintenance availability, operability and reliability for prescriptive and mitigative systems/measures.
Examples of Preventive Administrative Controls:

- Surveillance and Testing - Procedures in place to assure operability of systems, including return to service after maintenance; surveillances up to date

- Human Performance Management - Organization, staffing, resources, and communications adequate to deal with process hazards

- Personnel Reliability - Programs in place for drug and alcohol abuse prevention, control of overtime, mitigation of staff turnover, and other fitness for duty issues
QUESTION SET

Question 6 - Compensatory Measures (Continued)

Examples of Preventive Administrative Controls:

- **Housekeeping** - Physical conditions of work places adequate for protection of workers, materials and facilities, and conduct conducive to safety culture

- **Facility Knowledge** - Program in place to compensate for loss of knowledge base and skills of retiring personnel

- **Safety Culture** - Attitudes and skills of personnel are positive even if the face of changing missions and priorities
QUESTION SET

Question 7 - Consequences

For each event identified in Question 5, accounting for compensatory measures described in Question 6, identify potential consequences to the workers, environment, or public

- Direct injury
- Exposure
- Contamination
- Environmental Release (ground, water and air)

General guidelines - don’t consider consequences requiring more than 3 independent events; however, consider common cause(s)
QUESTION SET

Question 8 – Overall Site Summary

Based on the Site Assessment Team report, provide an overall assessment of the site ES&H vulnerabilities

- A description of the site's most important ES&H concerns
- A description of which plutonium activities pose the highest risk
- A discussion of current planned actions to minimize worker exposure, reduce environmental risks, and protect the public
- Provide any noteworthy programs or practices related to plutonium storage, handling, process, and/or shipping
DOCUMENT RESULTS

- If a vulnerability exists complete a Vulnerability Assessment Form (VAF)

- Both Site Assessment Teams and Working Group Assessment Teams will capture ES&H Vulnerabilities on the VAF
ASSESSMENT PROTOCOL

Working Group Assessment Team, Site Assessment Team, and DOE Operations Office staff should interact by way of candid verbal communications.

Both teams need to understand vulnerabilities concerning plutonium operations and storage.

Vulnerability information will serve as a baseline for plutonium disposition study.
WALKDOWN FOCUS

- Facility condition
- Postings and limits
- Rad protection
- Monitoring, control, alarm conditions
- Process equipment conditions
- Facility equipment conditions
- Material and packaging verification
TABLE TOP DISCUSSION TOPICS

- Uncertainties about material and packaging
- Uncertainties about barriers
- Adverse conditions and events
- Operational history and experience
- Compensatory measures
OPERATIONAL HISTORY

- **Purpose**
  - Tool for Working Group and Site Assessment Teams
  - Topic for Working Group Assessment Team training (Site Team Leaders included)
OPERATIONAL HISTORY
(Continued)

- Computerized database
  - Search of ORPS and SPMS
  - Search site accident history files
  - Identify events relevant to Plutonium ES&H concerns
  - Sort events by site/facility

- Reference collection
  - Recent assessments
  - Search DIALOG and OSTI databases
A.5.18

Safeguards and Security Assessment for Plutonium Vulnerabilities

by

B. Smith
DEPARTMENT OF ENERGY
PLUTONIUM ES&H VULNERABILITY ASSESSMENT

ASSESSMENT TEAM TRAINING

April 19–21, 1994
Colorado Springs, Colorado

SAFEGUARDS AND SECURITY ASSESSMENT
FOR PLUTONIUM VULNERABILITIES

Brian Smith
SCOPE

- Sources of data on plutonium
- Interface assessment
- Data collection
- Findings
SOURCES OF DATA ON PLUTONIUM

- Material control and accountability records
- Criticality safety
- Waste management
- Cleanup plans
- ALARA studies
- Maintenance records
INTERFACE ASSESSMENT

- Personnel access
- Ease of movement
  - Personnel
    - Routine
    - Emergencies
  - Materials
- ALARA
- DOE orders
- Planning and coordination
- Security training
DATA COLLECTION

- Interviews
- Observations
- Topics of discussion
OBSERVATIONS

- Ingress/egress
- Material movements
- Process operations
- Physical inventory
- Measurements
INTERVIEWS

- Security
- Material control and accountability
- Health physics
- Maintenance
- Operations
- Waste management
FINDINGS

- Access control
- Health and safety
- Emergencies
TOPICS OF DISCUSSION AND OBSERVATION

- Security procedures
  - Area access authorization
  - Access control
  - Material handling authorizations
  - Surveillance procedures
  - Lock downs
- Security hardware and vital area configuration
- Material control and accountability procedures
- Work rules
- Security maintenance
- Provisions during emergencies
- Health physics
- Safety analysis
- Safeguards and security
- Waste management
- Administrative support
A.5.19

Database Training

by

J. Levin
DEPARTMENT OF ENERGY
PLUTONIUM ES&H VULNERABILITY ASSESSMENT

TEAM TRAINING

April 19-21, 1994
Colorado Springs, Colorado

DATABASE TRAINING

JACK LEVIN
DATABASE TRAINING

- Historical occurrences database
- Question set response data entry process
- Plutonium ES&H vulnerability assessment database
HISTORICAL OCCURRENCES DATABASE

- Contents
  - "Plutonium" related records from:
    - Rocky Flats (RFP) Occurrences, 1952–1988, 1,111 records
    - Historical Incidents Database (HID) Project, 25 records

- Characterized by information data elements (Assessment Plan, Figure A-3)

- Searchable by
  - Site
  - Facility
  - Type of:
    - Material
    - Adverse conditions
    - Consequences
    - Barrier
    - Event

Intent is to provide perspective on historical events both at individual sites and across the complex for SAT and WGAT
## HISTORICAL OCCURRENCES DATABASE

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<thead>
<tr>
<th>SITE</th>
<th>NUMBER OF RECORDS</th>
</tr>
</thead>
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<td></td>
<td>ORPS</td>
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<tr>
<td>Los Alamos National Lab.</td>
<td>61</td>
</tr>
<tr>
<td>EG&amp;G Mound Applied Tech.</td>
<td></td>
</tr>
<tr>
<td>PANTEX, Mason &amp; Hanger</td>
<td>5</td>
</tr>
<tr>
<td>Argonne Nat'l Lab – East</td>
<td>8</td>
</tr>
<tr>
<td>New Brunswick Lab</td>
<td>6</td>
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<tr>
<td>Westinghouse Savannah River Co.</td>
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<td>Westinghouse Hanford Def. Ops.</td>
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<tr>
<td>Battelle Memorial Inst. – PNL</td>
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<td>EG&amp;G Idaho – INEL</td>
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<tr>
<td>Brookhaven Nat'l Lab</td>
<td></td>
</tr>
<tr>
<td>Nevada Test Site</td>
<td></td>
</tr>
</tbody>
</table>
HISTORICAL OCCURRENCES DATABASE

STRUCTURE

- Name of Facility/Organization
- Facility code
- Building
- Report number
- Date of occurrence
- Subject or title
- Description
HISTORICAL OCCURRENCES DATABASE

Minimum system requirements

- IBM compatible/MS–DOS 3.3+
- 80386 CPU
- 4 Mb RAM
- 3 Mb hard drive free space
- MS–Windows 3.1

Database, application, FoxPro–Windows run–time module will be provided on 3.5", 1.44 Mb diskette
HISTORICAL OCCURRENCES DATABASE

- Demonstration
  - Set search criteria
  - Display summary hit list result
  - Display historical occurrences description result
QUESTION SET RESPONSE DATA ENTRY

- Enter response in WordPerfect 5.1 question set template
- Limit narrative to 1–2 pages per question and include references
- Insert rows in tables as necessary
- Prepare one question set for each site–facility–function
QUESTION SET RESPONSE

- Walk-through of sample question set data entry
QUESTION SET RESPONSE

QUESTION 1 – FACILITY

- Enter site, facility, function in space provided
- Enter facility landlord, program sponsor, in space provided
- Enter facility age and design life (in years) in space provided
- Insert narrative responses immediately after each question, including sequential reference number
- Enter applicable references, including appropriate number
QUESTION SET RESPONSE

QUESTION 2 – HOLDINGS

- Enter DOE material manager in space provided
- Enter principal plutonium isotope, package types (Table A-1), and maximum age for each package or barrier type
  - Next cell = tab
  - Previous cell = shift tab
- Insert additional rows as necessary
  - Alt-F7, Ins, 1
QUESTION SET RESPONSE

QUESTION 2A – CLASSIFIED HOLDINGS

- Classified information
- Maintain in secure setting, remains at site
- DO NOT ENTER classified information in electronic question set responses
QUESTION SET RESPONSE

QUESTION 3 – PHYSICAL BARRIERS

- Duplicate template for each material aggregation
- Enter material aggregation in space provided
- Enter barrier type (Assessment Plan, Table A–2) for each barrier in space provided
- Edit WB–17 "Other" or EB–12 "Other" as necessary. Add types if necessary.
QUESTION SET RESPONSE

QUESTION 4 – ADVERSE CONDITIONS

- Replace □ with X as appropriate
- Insert description on line below applicable adverse condition
QUESTION SET RESPONSE

QUESTION 5 – POTENTIAL EVENTS

- Replace □ with X as appropriate
- Insert description/reference on line below applicable potential event
QUESTION SET RESPONSE

QUESTION 6 – COMPENSATORY MEASURES

- Replace □ with X as appropriate
- Insert description, uncertainties, concerns on line immediately below applicable compensatory measure
QUESTION SET RESPONSE

QUESTION 7 – CONSEQUENCES

- Enter Events identified in Question 5

- Insert additional rows as necessary
  - Alt–F7, Ins, 1

- Enter Y or N as appropriate
  - Next cell = tab
  - Previous cell = shift–tab

- Enter event name and explanation for each "N"
QUESTION SET RESPONSE

QUESTION 8 – OVERALL SITE SUMMARY

- Insert narrative responses immediately after each question
ES&H VULNERABILITY ASSESSMENT FORM

- Duplicate template for each vulnerability
- Enter vulnerability number in space provided
  Site – Facility – Function – Sequential number
- Enter narrative response in spaces provided, table will expand as text is entered
- Block 9 – enter applicable adverse condition and vulnerability event/concern. Replace __ with X for applicable potential consequences.
- Enter names of team member, team leader
DRAFT SITE REPORT

- Print draft question set responses and vulnerability assessment forms
- WGAT review and validation
- Revise as necessary
- Print final question set responses and vulnerability assessment forms
- Return hard copy and electronic files to working group
A.5.20

Team Dynamics

by

B. Parker
Assessment Team Training
April 19 - 21, 1994

Team Dynamics

Presented by:
Bryan Parker

Operations & Training
Technology Applications (OTTA)
Idaho National Engineering Laboratory
EG&G Idaho, Inc.
TEAM SKILLS-TEAM DYNAMICS

PURPOSES

Purpose of the Assessment Project

- **Prepare** a comprehensive assessment of the environmental, safety and health (ES&H) vulnerabilities arising from the Department's storage and handling of its current plutonium holdings.

- The assessment will **identify and prioritize ES&H vulnerabilities**, and serve as an information base for identifying interim corrective actions and options for the safe management of fissile materials.

- "**Confirm what we know and reveal what we don't know,**... for the safe management of fissile materials. *This effort is not a compliance audit or a fault-finding exercise. It is to gather data.*"

Assessment Team Training Purpose

At the conclusion of the training, team members will be able to:

- Work in teams to conduct facility assessments in an effective manner.

- Write findings consistent with the information needs of the DOE.

- Gain a clear understanding of the purpose of the study, how the study will be conducted, what their roles and responsibilities are, and the knowledge and techniques for gathering needed information.
Lesson Purposes

- Bring groups of individuals to a common understanding of the essential elements necessary for effective work teams.

- Begin or continue the team development process helping move the Assessment Team membership toward becoming a functional work team at the appropriate level.

IMPORTANT DEFINITIONS

Team-work

Teamwork is *based* on great individual execution of assigned responsibilities, not compromise and cooperation. The minute an offensive tackle looks back to try to cover up for a quarterback who can’t take the snap, he is compromising his effectiveness as a tackle and usually winds up on his back watching the quarterback get sacked. Only when everyone excels at an assigned task do we have true teamwork. (Chuck Conradt, Author, “The Game of Work”)

Teamwork is the effective utilization of the varied skills and experiences of each individual to create a better way, it is creativity, applied with innovation and exercised with determination. A successful team effort is not a mysterious event that just “happens” because fate brought the right group of people together. It rarely works that way. Real teamwork happens as the result of a deliberate and well thought-out plan, sound leadership toward a clear vision, specific goals, and a definite strategy to get people working well together. (Brendan Reddy, Professor, University of Cincinnati)
GROUPS VERSUS TEAMS

Groups

Members group together for administrative purposes only. Individuals work independently, sometimes at cross purposes with others.

Members tend to focus on themselves because they are not sufficiently involved in planning the unit's objectives. They approach their job simply as a "hired hand".

Members are told what to do rather than being asked what the best approach would be.

Members distrust the motives of colleagues because they do not understand all roles on the team. Expressions of opinion or disagreement are considered non-supportive.

Members are so cautious about what they say that real understanding is not possible. Game playing may occur and communications traps are set to catch the unwary.

Members may receive good training but are limited in applying it to the job by the supervisor or group members.

Members find themselves in conflict situations which they do not know how to resolve. Their supervisor may put off intervention until serious damage is done.

Members may or may not participate in decisions affecting the team. Conformity often appears more important than positive results.
Teams

Members recognize their interdependence and understand both personal and team goals are only accomplished by mutual support. No "turf" or "NIH."

Members feel a sense of ownership for their jobs and unit because they are committed to goals they helped establish.

Members contribute to the organization's success by applying their talent and knowledge to team objectives.

Members work in a climate of trust and are encouraged to openly express ideas, disagreements and feelings.

Members practice open and honest communication. They make an effort to understand each other's point of view.

Members are encouraged to develop skills and apply what they learn. They receive the support of the team.

Members recognize conflict is a normal aspect of human interaction but they view such situations as an opportunity for new ideas and creativity. They work to resolve conflict.

Members participate in decisions but understand the leader must make a final ruling whenever the team cannot decide. Positive results, not conformity are the goal.

Dangerous Misunderstandings About Teams & Teamwork

1. Calling a work unit a team in the belief that "team language" alone will change the way work is done.

2. Initially "sharing" leadership short-cuts development.

3. Teams can develop on their own, without real support from within/without (i.e., training, resources, & time).

4. There is no need for a clear vision or expectations.

5. Setting up teams is an isolated act.
6. Teams are not results oriented until they mature.

7. Traditional managers & supervisors can't coach or facilitate teams.

8. Teamwork means lots of meetings.

9. Teamwork works in any setting, any time.

10. Teamwork is easy to do and implement.

How much of a team do we really need to be?

<table>
<thead>
<tr>
<th>High Performance Team</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highly Functional/Competent Team</td>
</tr>
<tr>
<td>Competent/Contributing Team</td>
</tr>
<tr>
<td>Informal Unit/Group/Team</td>
</tr>
<tr>
<td>Group of Individuals</td>
</tr>
<tr>
<td>Individual Contributors</td>
</tr>
</tbody>
</table>
Highly interdependent and interactive team which must maintain their team “processes” at a high level to achieve true effectiveness and move toward their decided upon common mission. There is a major effect on productivity and overall success (team and organizational) without on-going attention to appropriate high performance team practices and behaviors.

Interdependent and interactive team which needs to be well above average in team effectiveness. Team members pay extra attention to group processes. This functional team, not individuals, makes a significant contribution to productivity and overall success (team and organizational).

Team makes a competent/important contribution to overall success (team and organizational). Team member interdependence and routine interactions means that contributions could not exclusively come from individuals. Team members are aware of and attend to group processes.

Some kind of loose organization exists but does not make an indispensable contribution to productivity or overall success (team and organizational). Some routine interaction is necessary to achieve the decided upon goal. Some attention is paid to group process.

A grouping of individuals which makes little vital contribution as a formal unit. Has working practices which do not necessarily require a decided upon group process. The individuals share very little routine interaction.

Not really a team at all (more like individuals who interact occasionally). Individuals contribute just as well to the end result without routine interaction or collaboration.
SEVEN CHARACTERISTICS OF HIGH PERFORMING TEAMS

One Team members share a common vision & purpose

Prepare a comprehensive assessment of the environmental, safety and health (ES&H) vulnerabilities arising from the Department's storage and handling of its current plutonium holdings.

- Purpose must be clear, understood, and accepted
- Challenging goals must be mutually agreed upon
- Individuals do not abandon their own personal goals (goals align with team vision, purpose, and goals)

Two Team members are empowered

Empowerment

The process of engaging others in accomplishing an organization's goals by developing them for and providing them with their own responsibility and authority. To empower is to take seriously, to give energy to. (Tom Peters, Author)

- Empowerment is encouraged by four elements
  --listening
  --trust
  --clarification
  --balance
- Power is within the team to make decisions
• Responsibilities are shared

• Team processes enable members to do their jobs easily

Three-Positive relationships and communications exist

Team-ness

The feeling of true teamwork. It's about excellence. It's no excuses, no stars, no names! It's owning. It's much bigger than the sum of the parts. True teamness happens when everyone is committed to the cause, paddling in the same direction. You know you are there when the feeling is right. (Bryan Parker)

• Trust must be mutual with all members

• Stars & excuses are not allowed

• Situation, issue, or behavior, are the focus; don't personalize conflict

• Conflict and differences are respected

• "Teamness"-the feeling of teamwork is encouraged

• Listening remains the forgotten element of communication

• "Clustering" enhances the team's communication always and all ways
THE "CLUSTER"

A cluster is an informal meeting that can be called by any member of a specific work team. The purpose of the cluster is to encourage cooperation, openness, and better communication with team members. Most often, the cluster is held as a “stand up gathering” to encourage “quick hitting” communications. It can be held just about anywhere. If the cluster turns into a formal sit-down, agenda-driven meeting it is less effective. Clusters should not turn into formal staff meetings or forums for tangential topic discussion.

Team members need to understand that anyone, at any time can call a cluster. This is a simple form of empowerment leading to self-direction. However, some simple helps need to be followed or a team can soon get clustered to death!

Clustering should happen when:

1. salient/important information needs to be shared
2. critical information is needed to help complete a team-essential task
3. good news is available for sharing
4. solid information is available to stop speculation
5. needed to encourage “teamness”

Don’t cluster when:

1. the subject is trivial
2. a formal meeting would be better
3. there is poor preparation
4. you could communicate better in some other way
5. the information has negative interpersonal impact to any member of the team.
How is the cluster announced? Most often, there is less than 10 minutes notice. Because the cluster is intended to be short, informal, and cover only very essential information, everyone on the team is encouraged to "drop" what they are doing and gather at the designated cluster spot. A typical announcement may go something like this: "Cluster here (wherever here is) at 10:00--be there!" or "Five minute clarification cluster in my office in 5 minutes."

Who has the responsibility to announce a cluster? The announcement obviously begins with the team member who will be sharing, or needing information. After that, it is everyone's responsibility to "get the word out." This happens very quickly--quick phone calls, quick announcements over cubicle walls, or controlled yelling on the sidewalks! Someone may even be designated as the "clusterer," to walk through the work area/site ensuring everyone is aware of the impending cluster.

Often times, clusters do not require everyone's attendance. When only specific people are needed, this mini-cluster should be announced only to those people. If there is a question regarding who should be involved always move toward more participation not less.

If utilized appropriately, the cluster can encourage "teamness," promote openness, and improve intra-team and inter-team communications immensely. The cluster concept addresses the critical communication and collaboration dimensions needed to encourage true teamwork.

---Team members are flexible---

- Comfort zones-beware!
- Strengths are recognized and utilized
- Change is recognized and adapted to
- Roles are understood
"WHAT IS MY ROLE ON THE TEAM?"

**Task-oriented roles** help the team to perform its task(s).

1. **Initiating**: Helping the team get started
2. **Seeking information or opinions**: Requesting facts, asking for clarification.
3. **Giving information or opinions**: Offering useful information; expressing what one thinks or feels.
4. **Clarifying or elaborating**: Interpreting or reflecting ideas and suggestions.
5. **Summarizing**: Organizing ideas so the team will know what it has discussed.
6. **Checking for consensus**: Checking to see how much agreement exists.

**Maintenance-oriented roles** assist in helping teams work together on a continual basis without damaging egos.

1. **Actively Listening**: This involves acknowledging that the other person is understood.
2. **Encouraging**: Being friendly, warm, and responsive to others and their contributions.
3. **Gate-keeping**: Attempting to keep communication channels open; making it possible for others to contribute.
4. **Managing conflict/harmonizing**: Attempting to reconcile disagreements between opposing points of view so the group can continue to work.
Self-oriented roles do not serve the group's needs and are not functional. They block progress toward the task.

1. **Blocking**: Being negative, stubbornly resistant or disagreeable.

2. **Attacking**: Deflating the status of others; attacking values, acts, or feelings.

3. **Playing**: Displaying lack of involvement in a team's processes.

4. **Seeking recognition**: Boasting or reporting on personal achievements.

5. **Deserting**: Withdrawing in some way, is indifferent, silent, or aloof.

6. **Dominating**: Asserting power of superiority to manipulate the group.

7. **Shifting subjects**: Changes the subject continually. Goes off on tangents.

---

Five: There is a commitment to achieve optimal productivity

- Group process (the "how") is the key to success

- Commitment to deadlines and goal achievement (the "what") is essential
Decisions—decide beforehand how they will be made

Six—Team members are recognized and appreciated

- Recognition by team leader and members should be frequent and frank

Seven—Morale and team spirit are high

- Work environment should be fun and collaborative
- Team spirit is collaborative, positive, and sincere
- Trust, respect, and equality are needed
- Language is que to the state of the team; “we” not “I”

STAGES OF GROUP DEVELOPMENT

- Two key variables to watch during group/team development—competence and commitment
- Four predictable stages of group development:
  1. Orientation “Forming”—productivity is low, morale is relatively high
  2. Dissatisfaction “Storming”—productivity increases slowly, morale drops to lower level
  3. Resolution “Norming”—productivity increases, morale begins to improve
  4. Production “Performing”—productivity is high, the team is working optimally, morale is high
FUNDAMENTALS OF EFFECTIVE TEAMWORK

Why write an article on the participant's role in creating high performing teams? Most articles and books address only the leader's role. However, members play a critical part in helping their group achieve its goals. Too often members assume that the success of the group is primarily the responsibility of the designated group leader. Often, if the group fails to function productively, participants either withdraw and become passive or become angry and aggressive. In either case, they contribute little to the group's success. The truth is that when each member accepts and shares responsibility for the success of the group, powerful and exciting things begin to happen. This article is for those group members who want to know what they can do to help their group.

As a group member who wishes to inspire the development of a high performing team, you must take three essential steps.

Step One: Be clear about what you want to create. What does a high performing team look like? An ancient Chinese proverb says: "If you don't know where you're going, any path will take you there."

Step Two: Be clear about what the path looks like. Once you understand what the path looks like, you will be in a better position to recognize the signposts along the way.

Step Three: Develop and use the group skills needed to facilitate the journey.

This article is about these three steps: what a high performing team looks like (the seven characteristics of a high performing team); what the path looks like (how to diagnose the stage of group development); and, most importantly, what kinds of things you as a member can do to facilitate the journey.
PERFORM: CHARACTERISTICS OF A HIGH PERFORMING TEAM

What does a high performing team look like? It can best be described by seven characteristics depicted by the acronym PERFORM.

**Purpose.** Members of high performing teams share a sense of common purpose. They are clear about what is the team’s “work” and why it is important. They can describe a picture of what the team intends to achieve. They have developed mutually agreed upon and challenging goals that clearly relate to the team’s vision. Strategies for achieving goals are clear. Each member understands his/her role in realizing the vision.

**Empowerment.** Members are confident about the team’s ability to overcome obstacles and to realize its vision. A sense of mutual respect enables members to share responsibilities, help each other out, and take initiative to meet challenges. Policies, rules, and team processes enable members to do their jobs easily. Members have opportunities to grow and learn new skills. There is a sense of personal as well as collective power.

**Relationships and Communication.** The team is committed to open communication and group members feel they can state their opinions, thoughts, and feelings without fear. Listening is considered as important as speaking. Differences of opinion and perspective are valued and methods of managing conflict are understood. Through honest and caring feedback, members are aware of their strengths and weaknesses as team members. There is an atmosphere of trust and acceptance and a sense of community. Group cohesion is high.

**Flexibility.** Group members are flexible and perform different task and maintenance functions as needed. The responsibility for team development and leadership is shared. The strengths of each member are identified and used, and individual efforts are coordinated when necessary. The team is fluid and open to both opinions and feelings, hard work, and fun. Members recognize the inevitability and desirability of change and adapt to changing conditions.

**Optimal Productivity.** High performing teams produce significant results. There is a commitment to high standards and quality results. They get the job done, meet deadlines, and achieve goals. The team has developed effective decision-making and problem-solving methods that result in achieving optimum results and encourage participation and creativity. Members have developed strong skills in group process as well as task accomplishment.

**Recognition and Appreciation.** Individual and team accomplishments are frequently recognized by the team leader, as well as by team members, by celebrating milestones, accomplishments, and events. Team accomplishments are valued by the larger organization. Members feel highly regarded within the team and experience a sense of personal accomplishment in relation to their team and task contributions.

**Morale.** Members are enthusiastic about the work of the team, and each person feels pride in being a member of the team. Confident and committed, members are optimistic about the future. There is a sense of excitement about individual and team accomplishments as well as the way team members work together. Team spirit is high.
A team that is at the PERFORM stage is ideal; however, groups do not start at that stage. Instead, groups tend to move through a series of predictable stages in their development from a collection of individuals to a high-performing team. While each group is unique, all groups tend to share common stages and characteristics. Knowing and understanding these stages and characteristics helps to clarify the interactive process that occurs when several individuals meet.

The two key variables used to determine the group’s stage of development are level of Productivity and level of Morale. Productivity relates to how competent the group is in its level of knowledge and skills and its ability to complete tasks. Morale relates to the group’s commitment as measured by its motivation, confidence, and cohesion.

Stage 1: Orientation. During this stage, productivity is low and goals are unclear. Skills and knowledge as a team are undeveloped. Morale is relatively high since members are eager and have positive expectations for the group. Group members are dependent on the leader and have some anxiety about their individual roles and connection with the group.

Stage 2: Dissatisfaction. Productivity increases slowly as the group’s skills and knowledge start to develop. Morale, however, drops to a low point as initial hopes and expectations for the group are not easily met. It is the inevitable “after-the-honeymoon” effect. Feelings of frustration, competition and confusion are evident.

Stage 3: Resolution. Productivity continues to increase as group skills and knowledge further develop. Goals become clearer or have been redefined. Morale begins to improve as the group develops methods of working together. Negative feelings are resolved. Cohesion and positive feelings increase, and confidence as a group begins to develop.

Stage 4: Production. In this stage, the team has developed the skills and knowledge necessary to work well together and to produce desired results. All the PERFORM characteristics are evident. Members have positive feelings about each other and the accomplishments of the group. They are no longer solely dependent on the leader for direction and support; instead, each member assumes leadership roles as necessary. This stage is indicative of a high-performing team.

The productivity and morale curves depicted in the Stages of Group Development model (Figure 1) illustrate the growth that a group experiences during its life cycle. The amount of work accomplished steadily increases from low to high through the four stages. Morale, on the other hand, starts out high in Stage 1 (Orientation), and then takes a sudden dip in Stage 2 (Dissatisfaction) as the initial high expectations of group members are not met. If, in the Dissatisfaction stage, conflict is dealt with, interpersonal issues are resolved and tasks are redefined so they are more achievable, then morale begins to build again in Stage 3 (Resolution). Ultimately, both productivity and morale are high in Stage 4 (Production).

Figure 1: Stages of Group Development

Using this model to determine a group’s stage development requires that team members develop the skill of observing the group’s interaction. Each member’s ability to diagnose which stage the group is in is helpful to the group’s development.

It is easy to recognize a high-performing team. When all of the PERFORM characteristics are present and operating, the group is in Stage 4 (Production).

If the group is not in the Production stage, it is somewhat more difficult to determine which other stage the group is in. The stage can be pinpointed by specifically focusing on two of the PERFORM characteristics—Morale and Productivity. (See Figure 2.)

How high is group morale? Are group members satisfied? Morale and satisfaction tend to be higher in the Orientation stage as there is excitement associated with the new group and expectations are high. Morale then tends to dip in the Dissatisfaction stage as the “honeymoon” period wears off and the reality of the slow progress ahead becomes apparent. As progress is made, however, morale once again increases as the group becomes more productive in the Resolution stage. Thus, if morale is extremely low, the group is likely to be in Stage 2 (Dissatisfaction).

How productive is the group? Is the group getting the job done? Are effective decisions being made and appropriate actions taken? Group productivity tends to increase steadily; therefore, the amount of work getting done is an indicator of the development stage—the more work accomplished, the higher the stage of development. If little or no progress is being made by the group, it is likely to be in the Orientation stage; that is, the group may be energetic, but not much is being achieved. Thus, Stage 1 (Orientation) is characterized by low productivity and high morale.

If the group’s morale is improving, the group is likely to be in the Resolution stage. For example, the group has learned how to work together openly and how to make effective decisions. Although confidence is not strong, members feel increasingly good about working with one another. Thus, Stage 3 (Resolution) is characterized by high productivity and improving morale.

<table>
<thead>
<tr>
<th>IF</th>
<th>THEN</th>
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<tbody>
<tr>
<td>Productivity: Low - Moderate</td>
<td>Stage 2 — Dissatisfaction</td>
</tr>
<tr>
<td>Morale: Low</td>
<td></td>
</tr>
<tr>
<td>Productivity: High</td>
<td>Stage 4 — Production</td>
</tr>
<tr>
<td>Morale: High</td>
<td>A High-Performing Team!</td>
</tr>
</tbody>
</table>

Figure 2: Diagnosing the Stages of Group Development
HELPING THE TEAM DEVELOP

Once the group’s development stage has been diagnosed, it is each member’s responsibility to help the team develop. A group can be compared to a machine. It has a job to do, and it must function smoothly to complete the job efficiently. Behaviors that directly affect the group’s productivity in getting the job done are called Task Behaviors. Task behaviors provide direction for the group.

Those behaviors that are related to improving morale and the smooth operation of the group are called Maintenance Behaviors. Maintenance behaviors provide support for the group. Both types of behaviors are critical if the group is to develop fully. Ideally, task and maintenance behaviors are shared by all members.

Task Behaviors Focus on the Group’s Goals

Task behaviors focus on what the group is to accomplish. They are important in every stage; however, they need to be emphasized when productivity is low, when goals are unclear, and when knowledge and skills need to be developed. This is characteristic of Stage 1 (Orientation) and Stage 2 (Dissatisfaction). These behaviors are especially important when a group first begins to work together. Listed below are examples of task behaviors.

Clarifying and Elaborating includes interpreting suggestions, clarifying confusion, defining terms, restating messages, and building on ideas.

“...I see what you mean, John, and, in addition, we might be able to...”

Summarizing behavior involves synthesizing all of the relevant information and presenting it in an understandable way.

“To summarize what we’ve discussed...”

Consensus Testing entails checking with group members for agreement on a task-relevant decision or evaluating the decision a group has reached based on stated criteria.

“Does everyone agree, then, that our options are...”

Coordinating means managing and sequencing the flow of ideas or information.

“Let’s hear all the alternatives before we decide on the best course of action.”

It may be helpful to appoint one of the group members the role of monitoring task behaviors to keep the group focused on moving toward its goals, interjecting as necessary to keep the group on track.

“...It seems like we’re getting off track. We agreed to discuss this topic for 30 minutes. That time is up. Do we want to continue on this subject or move on to the next item on the agenda?”

Maintenance Behaviors Help the Group Function Smoothly

Maintenance behaviors are directed toward developing or maintaining group harmony and cohesiveness. They are most needed when morale is low in Stage 2 (Dissatisfaction) and when morale is improving in Stage 3 (Resolution). Listed on the next page are examples of maintenance behaviors.
Active Listening involves acknowledging that the other person is heard and understood through the use of verbal and nonverbal cues.

"If I understand you correctly, what you are saying is..."

Encouraging involves being friendly, warm, and responsive to having others participate in the group discussion.

"Gary, you've had some experience in this area. I'd really like to hear what you think."

Gatekeeping behaviors include monitoring the group communication, allowing less talkative members to contribute, and controlling the air time of more assertive members.

"Tom, your points are important. I think we should hear from some of the members who haven't commented yet."

Managing Conflict includes attempts to resolve or reconcile differences between group members.

"Since we all agree that the project needs to be completed before the end of the month, let's see if we can discover a creative way to include the best of both Larry and Michele's ideas."

Again, it may be helpful to assign a specific group member the role of monitoring maintenance behaviors in the group process. This person would write down his or her observations of how the group interacts and how frequently the maintenance behaviors are used, giving feedback to the group members.

"I observed that Bob withdrew from the discussion as soon as someone disagreed with him, and every time Cindy tried to speak, she was interrupted."

Applying Task and Maintenance Behaviors to Group Development

Diagnosing the group's stage of development is a prerequisite for determining what combination of task and maintenance behaviors are most needed for the group to function more effectively. For example, in Stage 1 (Orienta-

tion), when morale is high and productivity is low, task functions are most helpful. Goals and roles need to be defined and skills need to be developed.

In Stage 2 (Dissatisfaction), when both productivity and morale are low, a combination of task and maintenance behaviors provide the direction and support needed to move the group to the next stage. In Stage 3 (Resolution), when productivity is high and morale is low or developing, maintenance behaviors are required to build the group's confidence and cohesion. When the group is operating as a high-performing team in Stage 4 (Production), each person provides task and maintenance behaviors as necessary.

SUMMARY

To be an effective team member, each participant must understand the stages of group development and acquire the skills necessary to move the group from one stage to the next. It requires that each member be able to diagnose which stage the group is in, as well as to provide the direction and support needed to move the group to the next stage through the use of task and maintenance behaviors.

Productivity and morale are enhanced when group goals are clear and attainable, when interaction among members is trusting and open, and when the group is behaving cohesively as a unit. Developing the skills and knowledge of every team member is well worth the effort, considering the productivity potential and human satisfaction that can result from a high-performing team.
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Item No. 282
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Interviewing

by

D. Denier
Assessment Team Training
April 19 - 21, 1994

Interviewing

Presented by:
Don Denier

Operations & Training
Technology Applications (OTTA)

Idaho National Engineering Laboratory
EG&G Idaho, Inc.
INTERVIEWING

PURPOSE

Purpose of the Assessment:

- Prepare a comprehensive assessment of the environmental, safety, and health (ES&H) vulnerabilities,
- Identify and prioritize ES&H vulnerabilities,
- Serve as an information base for identifying interim corrective actions and options,
- Confirm what we know and reveal what we don’t know,

...regarding the safe management of fissile materials.

This effort is not a compliance audit or a fault-finding exercise. It is to gather data.

Purpose of this Training:

- Provide the members of each team with recommended METHODS of interviewing that will yield consistent and useable data
- Provide each team with a PROCESS for planning their assessments to ensure that the needed data is compiled and recorded effectively and efficiently

APPROACH

Work Backwards - Focus on the End Product

- ...then build a plan that will provide the information needed to complete the report.
End Product is the final report (Working Group Assessment Team and Site Assessment Team. Report Outlines, Assessment Plan, Attachment A4-1). This report will contain charts and graphs that illustrate data.

What does each team have in common?

- Same question set will be completed by the Site Assessment Team (Question Set, Assessment Plan, Attachment 2, A2-6).
- Same Information Data Elements will be used in reporting the data (Information Data Elements, Assessment Plan, Attachment A2-5, Figure A-3).
- Same team composition consisting of DOE leadership and technical, scientific, and engineering experts.
- Same vehicle for recording data (Vulnerability Assessment Form, Assessment Plan, Attachment 2, A2-7)

What are the variables?

- The plan for gathering information.
- The way questions are asked.
- The way information is recorded.
- The degree of follow-up on conflicting data.
- The assumptions and interpretations made based on available data and member expertise.

The methodology is a qualitative approach that relies on the experience and expertise of the Site Assessment Teams in making determinations regarding the likelihood of barrier
failures, relevant historical experience, and the frequency of adverse conditions/events. (Assessment Plan, Attachment 2-2)

The Working Group Assessment Teams will then use historic data, tabletop discussion topics, and the Question Set and Checklist to review and develop a more comprehensive understanding of the consequences and potential vulnerabilities resulting from current plutonium storage and handling operations.

This requires clear roles, responsibilities, data gathering, and report preparation PLAN!

... this training is designed to remove as much inconsistency as possible from the data gathering and reporting processes.

DEVELOP A PLAN

Consider both:

- The Team plan
- Your Individual Plan

Purpose of these plans:

- Organized approach
  - Use Team Manager’s Checklist (handout)
- Divides and assigns of responsibility
  - Team member roster listing disciplinary expertise.

Assessment Team Training

Page 3 of 12
- Examine the Question Set. Who owns what parts and what is the best way to assess?

- Organizes assessment activity
  - Build your team’s schedule
  - Review and catalog existing materials (What’s missing that we will need before we arrive on-site?)
  - List anticipated meetings and interviews to include dates, times, subjects, locations, and attendees.
  - Allow for follow-on meetings and interviews.
  - Make notes in your manual as thoughts come to mind.

- Enables a meaningful Final Report
  - Ensure the assessment and interview plan covers all of the material required for the final report.

- Provides milestones and a means to measure progress toward completion.
  - All teams meet Thursday at 4:00 to work on their assessment and interview plan.

BASIC MANAGEMENT - Plan what you do; Do what you plan; Record it!
METHODS OF ASSESSMENT

FOUR ELEMENTS (list examples)
- Document Review
- Tabletop Discussion
- Walkthrough/Walkaround/Walkdown
- Interview

All elements employ:
- Sampling
- Questioning
- Observation
- Data comparison
  - Confirm data
  - Examine inconsistencies
  - Identify voids
  ... and more interviews

DOCUMENT REVIEW (list examples and where they are obtained)
- Question Set
- ORPS/SPMS reports
- Program Reviews
- Site's "List of Issues"
- Previous audits/assessments
- Procedures
- ...and more...(what more?)
  - Record and correlate observations
  - List "next-steps" based on data
- Collaborate with team members
- Initiate follow-up

(Discussion - How is it done?)

TABLETOP DISCUSSION

A "group" interview designed to:
- Covers topics prescribed in the Assessment Plan, Attachment A2-28.
- Clarifies questions from document reviews
- Defines processes in general
- Identifies need for follow-up interviews

WALKTHROUGH/WALKAROUND/WALKDOWN

What are they and what are their purposes? (list examples of when each is appropriate)
- Covers topics prescribed in the Assessment Plan, Attachment A2-30

Walkthrough
- Upon entry to the facility
- Provides general overview of site, layout, facilities, and a representative picture of site activities.
- Cursory in nature

Walkaround
- Accompanied visits to specific areas
- Observe routine activities
- Provides understanding
  ...and provides opportunity for interview.
Walkdown

- To follow-up on perceived inconsistencies
- To verify perceived voids
- To observe specific processes or conditions
- To confirm data points
- Because your instincts say you should
  ...and as long as you are there, interview.

INTERVIEWS

Individual or small group discussions.

Remember the charter!

Purpose of the Assessment:

- Identify and prioritize ES&H vulnerabilities,
- Serve as an information base for identifying interim corrective actions and options,
- Confirm what we know and reveal what we don’t know,

... for the safe management of fissile materials.

This effort is not a compliance audit or a fault-finding exercise. It is to gather data.
THE INTERVIEW PROCESS

Professionalism - Individual and team
A process used for assessing DOE facility training programs can be applied to our teams:

- The team manager assumes responsibility for the conduct of all team members ensuring a high degree of professionalism.
- Team members shall agree to conduct themselves in a professional manner at all times.

Professional conduct includes:
  Confidentiality,
  Professionalism,
  Accountability,
  ... and more.

The Interview

- Plan the interview
  - Schedule time without distractions
  - Write out questions in advance and validate them with other team members

- Opening
  - Put the person at ease
  - State the purpose of the visit
  - Explain what information is needed
  - State how long the interview should last
  - Reinforce that their input is important
  - Explain how the information will be used
Questioning
- Begin with "open-ended" questions
- Use "appraisal questions" where needed
- Summarize with "closed questions;" "You said this - is that correct;" to confirm understanding
- Use "leading questions" carefully

Active Listening
- The MOST IMPORTANT part of the interview
- More physically exerting than speaking

Closing
- When information obtained is no longer meaningful
- If more than an hour has passed, summarize and break, or agree to return at another time.
- Use "closed questions" to summarize
- Friendly and brief
  ...thank the interviewee for their time, cooperation, and information.
- **Follow-up**
  - As soon as possible following the interview,
  - Reconstruct notes
  - Write conclusions on Vulnerability Assessment Forms
  - Develop follow-up questions
  - Hand-off follow-up questions to the appropriate team member
  - Update your plan

---

**ACTIVE LISTENING**

- **Listening involves**
  - Hearing the message
  - Processing what is heard
  - Verbally acknowledge understanding
  - Visually acknowledge understanding

- **Barriers to listening**
  - Preconceived expectations (pos/neg, simple/complex)
  - Planning your next response
  - Competing demands (distractions)
  - Extra mental time and space (difference between listening and talking speed)
  - Emotionally charged statements
  - Passive listening
- Detrimental Actions
  - Interrupting
  - Counseling
  - Speaking too fast
  - Failing to summarize
  - Jumping to conclusions
  - Finishing sentences of interviewee
  - Asking questions before the interviewee has completed response
  - Failing to transition between topics

- Skills of Active Listening
  - Empty the cup
  - Read between the lines (facts/feelings)
  - Extra mental time to take notes (CAUTION: don’t write too much)
  - Write follow-up questions
  - Separate "important" from "nice-to-know"
  - Show the interviewee that you hear the message (verbal/visual)

Interviewing Styles
- Friendly Chat
- Emotional
- Interrogation
- Standard
- Businesslike (the preferred style)
Interviewer Probes
- Clarifying
- Silence
- Expanding
- Repeating
- Confirming

Common Mistakes
- Talks too much
- Communicates desired response
- Fails to follow-up leads
- Interrupts interviewee
- Manages time poorly
- Writes too much
- Biased
- Forms premature conclusions

Questions

Role-Play an interview
TEAM MANAGER'S CHECKLIST

Facility ___________________ Visit Date(s) ___________________

I. PRE-VISIT PREPARATION

- Review prior studies and assessments (e.g. NMMSS, National Academy of Science, recent Field Office assessments, etc.).
- Review facility background material
- Review authorization basis documentation
- Review environmental evaluations
- Review recent vulnerability issues (ORPS, SPMS)
- Share facility information with other team members.
- Contact facility and schedule a Pre-Visit discussion with SAT leadership.
- Develop an agenda for the Pre-Visit discussion

II. PRE-VISIT DISCUSSION

- Review logistics including clearances, site specific training requirements, meeting rooms, clerical support, etc.
- Discuss control of classified material
- Discuss safety issues for material and facility inspections
- Assist facility in understanding and responding to question set.
- Gather materials on motels, restaurants, and maps of area.
III. VISIT PREPARATIONS

- Confirm team members participation

- Review facility Question Set, Vulnerability Assessment Forms, and distribute copies to team members.

- Promulgate memo giving team member assignments, area responsibilities, visit strategy, and general schedule of events

- Provide information to team members as requested

- Coordinate travel information including desired flight schedule, motel arrangements, car rental needs, and driving assignments.

- Submit clearance information for team

- Call SAT leader to verify needed resources
  - workroom
  - reproduction support
  - conference rooms
  - list of materials needed in workroom
  - security access

- Call SAT leader with proposed work schedule, and names of team members. Include:
  - entrance meeting time, participants, and content
  - projected walkthroughs and interviews
  - daily team meeting time, participants, purpose
  - daily management debrief meeting time, participants, purpose
  - summary meeting time, participants, purpose
  - exit meeting time, participants, purpose

- Schedule and plan team meeting in hotel to organize site visit and verify responsibilities
IV TEAM ON-SITE ACTIVITIES

Entrance Meeting

- Prepare entrance comments
- Coordinate agenda with SAT leader.
- Conduct entrance meeting

Daily Activities

- Conduct daily team meetings
- Post daily updates of team agenda
- Assess progress of team members in drafting comments for final report.
- Remind team members of their responsibilities for:
  - Protection of classified materials
  - Protection of personnel health and safety
  - Compliance to facility operating procedures

Last Day Activities

- Conduct summary meeting to resolve open issues
- Prepare agenda and conduct exit meeting (see Attachment 1 for sample agenda)

V. POST VISIT ACTIVITIES

- Complete draft report
- Send report to SAT and WGAT members for review
- Complete final report and submit to DOE-HQ
EXIT MEETING SAMPLE AGENDA

Attendees: DOE and M&O facility management, SAT and WGAT members, and stakeholders

1. Explain purpose of meeting

2. Introduce participants

3. Provide summary of activities

4. Summarize vulnerabilities

5. Explain status of WGAT report

6. Explain process of completing WGAT report

7. Identify additional information needed for report and schedule SAT review

8. Ask for and answer questions

9. Summarize key points of discussion express thanks
## ES&H Vulnerability Assessment Form

<table>
<thead>
<tr>
<th>Vulnerability #</th>
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</thead>
<tbody>
<tr>
<td><strong>Block #1:</strong> Title of Vulnerability. (&lt;20 words)</td>
<td></td>
</tr>
<tr>
<td><strong>Block #2:</strong> Executive Summary. (&lt;50 words) Concise description of the sequence of events leading to the vulnerability.</td>
<td></td>
</tr>
<tr>
<td><strong>Block #3:</strong> Describe the material, packaging, barrier and facility combinations that contribute to the vulnerability.</td>
<td></td>
</tr>
<tr>
<td><strong>Block #4:</strong> Describe adverse conditions, events, and related concerns that contribute to the vulnerability.</td>
<td></td>
</tr>
<tr>
<td><strong>Block #5:</strong> Describe the compensatory measures that reduce the severity of the vulnerability.</td>
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</tr>
<tr>
<td><strong>Block #6:</strong> Describe the likelihood of the event which causes this vulnerability and consequences which could result.</td>
<td></td>
</tr>
</tbody>
</table>
ES&H VULNERABILITY ASSESSMENT FORM

Block #7: Describe the timing of corrective actions (if any). Use the terms imminent (imminent ES&H issue), near-term (ES&H issue that may become an imminent hazard with further degradation), or longer term (ES&H issues which are being mitigated through barriers/compensatory measures).

Block #8: Additional comments, views, or plans by the site operations office and M&O Contractor to mitigate or minimize any potential vulnerability.

Block #9: Database Criteria. (Use identifiers from question set tables.)

List adverse conditions:
- 
- 

List potential events/concerns:
- 
- 

Potential Consequences.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Worker Safety and Health</th>
<th>Public Safety and Health</th>
</tr>
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<tbody>
<tr>
<td>Ground</td>
<td>Contamination</td>
<td>Contamination</td>
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<tr>
<td>Water</td>
<td>Exposure</td>
<td>Exposure</td>
</tr>
<tr>
<td>Air</td>
<td>Physical Injury</td>
<td>Physical Injury</td>
</tr>
</tbody>
</table>

Signature, Team Member

Signature, Team Leader

04/05/94 4:01pm
INTERVIEWING AND ACTIVE LISTENING

What exactly is the most important skill used during interviews?

Active listening may well be the most critical single element in the conduct of an effective interview.

The interviewer must practice well-developed listening skills if the other interviewing skills are to be effective. Active listening makes up 70 percent of a successful interview.

To define active listening and clarify its role in effective communication, we first have to define "communication." Communication can be defined as the process of sending and receiving messages. It is the process whereby two people converge on intended meaning through give and take, a mutual accommodation and effort.

Listening is a more physically exerting activity than speaking. During interviews, you must be prepared to apply a lot of effort to listen actively to the people you are interviewing.

The definition of active listening contains three components: hearing the message, processing what you heard, and showing you understand verbally (i.e., paraphrasing) and non-verbally (i.e., nodding).

The barriers to effective listening include five items: expectations (i.e., positive or negative, simple or complex), competing demands (i.e., distractions), extra mental time (i.e., difference between listening and talking speed), emotionally charged words (i.e., automatic response words such as inadequate or unqualified), and passive listening (i.e., focus on interviewee's message not ours).

The detrimental actions to effective listening include items such as interrupting, speaking too fast, failing to summarize, jumping to conclusions, finishing sentences of interviewee, asking questions before interviewee has completed response, and failing to transitions between topics.

The skills involved in active-listening include the following: reading between the lines (i.e., facts and feelings), using extra mental time to take notes, writing follow-up question, separating important from nice-to-know information, and showing interviewee you hear the message (i.e., feedback and nonverbal expressions).

Your attitude as an active listener projects that you are responsible to do most of the work during the interview, willing to spend the extra effort to listen, accommodate other's needs, and personally responsible for the accuracy of the message.
INTERVIEWING PROCESS

Interviewing is a form of oral communication involving two people. The team member (interviewer) and the facility person (interviewee) share information by asking and answering questions. Team member interviews should be directed, scheduled, and purposeful.

We can define each of the five steps of the interviewing process: planning, opening, questioning/listening, closing, and follow up.

Planning

PLANNING is the first step to ensuring an effective interview. The plan developed during the data collection lesson is expanded for interviewing. Planning includes the following:

- reviewing pertinent facility information and data collection guideline package questions;
- selecting appropriate facility personnel to be interviewed;
- developing a list of questions (i.e., interview guide);
- assembling necessary forms, references, and procedures;
- scheduling sufficient time in a distraction-free, comfortable environment.

Opening

The second step of interviewing is the opening. The opening orients the interviewee to the assessment process, the interviewer's purpose, the interviewer's background, and goals of the interview.

The opening establishes rapport and a comfortable discussion environment. General topics of interest to the interviewee (i.e., sports, hobbies, news, and schools) may be used to relax the interviewee and set a friendly tone. Be aware of open body language messages that signal that the interviewee is ready to begin the questioning.

Questioning/Listening

The interviewer's questioning steers the interview in a logical sequence. Questions should be clear, designed to cover important information, and focused on one issue at a time. Follow an interview guide to organize the questioning sequence. Listen carefully to discover the important facts.

Use various types of questions during the interview to control various types of interviewees (i.e., verbose or quiet).
Use open questions to solicit a great deal of information about a specific topic. Open questions are sometimes called primary or lead-in questions. Use them to introduce new topics issues within a topic. For example, "How do you determine the storage requirements for the various forms of plutonium?" is an open question that allows the interviewee a wide range of responses.

Open questions consume more time and elicit more information than closed questions.

Closed questions are used to solicit a small amount of information in a brief amount of time. Closed questions are usually secondary questions used to follow up primary open questions. The interviewer uses secondary questions when responses to primary questions seem incomplete, superficial, or vague. For example, "By journeyman, do you mean 2 or 3 years of facility-specific experience?" is a closed question that restricts the interviewee's response to a brief answer, while at the same time probing to find the interviewee's exact meaning.

The initial phase of the questioning will typically involve open questions and then move into closed questions. As appropriate, the interviewer summarizes the topic and then transitions into another one. As new criteria or issues are investigated, the cycle of open questions to closed questions continues until the interviewer concludes the session.

An interview should not last over one hour. If nonproductive, excuse yourself and leave. If interrupted extensively, reschedule.

Avoid leading questions that influence the answer by suggesting the response. For example, "You think you need more operators, don't you?" is a leading question.

You can get the same information by asking a neutral question such as, "What do you think about the number of operators involved in this process?"

The conversation should be active by using appropriate probes (i.e., silence or pauses; brief, neutral comments; or internal summaries of key points).

Follow-up or secondary questions should be asked when clarification is needed.

The interviewer should allow the interviewee to think about and answer each question without interruption. The interviewer should be listening more than taking. Avoid emphasizing methods and techniques used in your organization.

Take legible notes containing key phrases to ensure eye contact is maintained and time is conserved.
Closing

The closing should be definite and should occur when the information obtained ceases to be meaningful. If more than one hour passes, consider summarizing the interview and returning after a short break or at another time.

The closing is indicated by emphasizing closed questions that summarize the interviewee’s major points.

The closing should be friendly and brief. The interviewer should thank the interviewee for their time and cooperation.

Follow Up

As soon as possible after the interview, reconstruct notes, write conclusions drawn from the interview information on the Vulnerability Assessment, and/or develop follow-up questions needing additional research. The process for developing conclusions involves the following steps:

1. Review key phrases from interview notes.
2. Group related ideas together.
3. Review information or documentation referred to during the interview.
4. Write a complete sentence (i.e., conclusion) from each group of key phrases on clean page or in the appropriate section of the Vulnerability Assessment Form.
5. Write follow-up questions for remaining key phrases. Determine the best information source (i.e., interviewee, observation, or records review) for the follow-up activity.

Handoff important follow-up information or issues not related to assigned objectives to the appropriate team member.

When updating your plan, cross off resolved items and add new ones.

Conduct a self-critique of your interview to determine the effectiveness of your technique. Ask yourself these questions: Did you...

- Adapt to the interviewee’s communication style?
- Show interest in the person and topic under discussion?
- Avoid distracting or annoying behavior?
- Act courteously and professionally?
- Listen actively to interviewee’s message?

Modify your techniques as needed to improve your next interview.
FIVE INTERVIEWING STYLES

Interviewing styles vary almost as much as personalities. In general, there are five styles of interviewing.

The preferred style for interviewing is the businesslike approach. However, everyone has a natural style, and strong interviewers can flex their style to fit the interviewee.

Friendly Chat

The friendly chat is uncontrolled and nondirected. The amount of useful information obtained from using this style is minimal. The friendly chat is useful during the opening to relax tense or suspicious interviewees.

For example, Jane Pauley uses the friendly chat to disarm aggressive guests.

Emotional

The emotional style depends on the interviewer’s gut reactions or first impressions. This is a dangerous style to employ during an interview because conclusions are based on premature assumptions, not valid facts.

For example, a father interviewing his daughter's first date may question the young man in an emotional style to ensure his daughter's safety and well being. Consumer advocates such as Ralph Nader may invoke this style when questioning politicians or perceived corporate offenders.

Interrogation

The interrogation is a severely stressful style for the interviewee. Interrogations promote an autocratic relationship. The interview appears to be on an investigation or witch hunt similar to the cross examination of a witness.

For example, F. Lee Bailey may interrogate a client before accepting a case.

Standardization

The standardized approach treats the interviewee impersonally. A set of predetermined questions are asked in a standard order without benefit of exploration or follow-up into related areas. This style is stiff and limits the expression of the interviewee.

Host Pat Sajak on Wheel of Fortune uses a standardized set of questions to introduce his guests on the popular television show.
Businesslike - the Preferred Method

The businesslike style recognizes that the meeting is a social interaction with a purpose. Worthwhile information is exchanged and both parties benefit from the interview.

Savvy news reporters such as Ted Koppel use this style to get the most from their interviewee in the least amount of time.

Changing your style is an effective technique for managing a difficult (i.e., reluctant or hostile) interviewee. When the interviewee is nervous, a friendly chat is needed before moving into the businesslike style. If the interviewee is visibly upset or angry, a standardized approach may be used to bring the interview to a quick closing or break.

INTERVIEWER PROBES

Various probes are used to control and focus the interviewing session. Knowing when to use the probes facilitates the information gathering for the team member. Selecting the right probes provides positive feedback to the interviewee and requires active listening by the interviewer. Consider using the following probes for these specific situations.

Clarifying

Clarifying is an attempt to determine the meaning of the interviewee's response. For example, ask the question "Did you physically open the container, x-ray it or both?" to clarify the analysis process used for a particular program.

When inconsistencies in information are obtained, clarifying follow-up questions are used to sort out the misinformation.

Neutral Response

Neutral Response is an attempt to encourage more discussion without biasing the information with an assenting or dissenting comment.

For example, a nod or comment such as "Yes, I see," are neutral responses.

Silence

Silence is a powerful tool when seeking additional explanation. A simple, quiet pause accompanied by eye contact with the interview will solicit additional information from the interviewee.

This type of active listening demonstrates interest and understanding.
Expanding

Expanding statements are used to encourage the interviewee to elaborate on an issue or perspective.

For example, comments such as, "Tell me more" or "Is there any additional information I should know?" prompt the interviewee to continue with further explanation or details.

Repeating

Repeating a question shows persistence in getting an appropriate answer from the interviewee. This technique is used when interviewees are verbose or avoiding the question.

Confirming

Confirming statements are used to summarize key interviewee ideas or highlight areas of agreement.

For example, the statement, "You believe that the handling procedure is implemented as written," is a confirming response by the interviewer.

COMMON INTERVIEWER MISTAKES

Talks Too Much

Mistakes can be avoided through careful preparation. One of the commonly made mistakes by new evaluators is to talk too much during an interview. This is often done because of nervousness, but is almost always done when the interviewer is not fully prepared. To avoid this mistake, be sure that you have your objective clearly in mind and your interview guide questions prepared before going to the interview.

Sometimes it helps to consider yourself as an observer to the situation instead of a participant. Remember that the nonverbal signals you receive from the interviewee can tell you as much as the words that are spoken.

Communicates Desired Response

Just as you can learn a lot from the nonverbal signals of the interviewee, your subject can pick up the response you are looking for by the way you phrase your question and by your nonverbal signals. Avoid nodding or shaking your head. Avoid phrasing your questions in a negative way such as, "You don't really have enough time to prepare reports, do you?"

Neutral responses include statements such as "yes," "hmm," or "I see."
Fails to Follow-up Leads

Failing to follow up on leads that you pick up during an interview can be a fatal mistake. It can leave holes in your data collection that cannot be filled once you have left the facility. Even hastily written notes cannot recover the information that was not obtained through thorough follow up.

Concentrate on summarizing information before transitioning to another topic to ensure interviewee’s information is captured accurately.

Interrupts Interviewee

Interrupting the interviewee is rude. It also tends to intimidate the interviewee to the point that useful information can no longer be gained. Respect the interviewee’s right to express ideas completely. If the interviewee becomes too talkative, use closed questions to limit the interviewee’s response in some way.

By listening actively, the interviewer will focus on the interviewee’s message, thereby avoiding an unnecessary interruption.

Manages Time Poorly (i.e., unprepared)

Managing time is a constant challenge to the team member. Interviewing is an enjoyable process, but it must be focused to be effective. Collecting a great amount of information that will not assist you in completing the data collection guidelines is inefficient and counterproductive.

When beginning an interview, it is helpful to explain to the interviewee what information you need and how long you expect the interview to last. This helps program the interviewee and the interviewer to conform to the scheduled amount of time.

 Writes Too Much

While you are conducting the interview, you will be taking notes. Be very careful that you don’t become so involved in what you are writing that you miss some of the nonverbal signals the interviewee is giving.

Record key words and phrases using a personal shorthand that helps you reconstruct the conclusions and follow-up questions later.

Biased

The overall attitude of the interviewer determines the success of the interview. You must believe that conducting an interview is a positive action to help you find the holes in the existing data, clarify vague information, and to find the things that are true vulnerabilities.
While not an audit, things may appear to be wrong; you must be willing and predisposed to gathering data, not finding fault.

Persistence is a personal attribute that you need to develop to conduct good interviews. If you are persistent, you follow up (using secondary questions) to the point of either clearly identifying the vulnerability or becoming thoroughly convinced that no vulnerability exists. This attitude requires thorough follow up to each interview. It requires that you pull every string that might lead to uncovering the vulnerability.

Maintain your objectivity by using neutral responses and confirming statements frequently.

Forms Premature Conclusions

DO NOT make this common mistake - forming premature conclusions. If you take good notes and do a good job of follow up, you will not jump to any unwarranted judgments about the vulnerability or even if there is a vulnerability. Hear the interviewee's response before judging it. Allow the interviewee to complete a sentence before drawing a conclusion.

Expect and insist on excellence from yourself and from the facility at all times. By expecting excellence and not being willing to accept anything less, you have an excellent chance of doing a job without making these common mistakes.
General Directions

Use this job aid as a self evaluation tool to assess your interviewing skills. Use it before an interview to evaluate your knowledge of interviewing skills. Use it after the interview to evaluate how well you performed.

In the list below, each statement represents criteria that has impact on your interviewing effectiveness. Rate your skills using the five point scale. Use the average scores to identify your strengths and weaknesses.

<table>
<thead>
<tr>
<th>INTERVIEW RATING SCALE</th>
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<tbody>
<tr>
<td>5: Excellent 4: Very Good 3: Satisfactory 2: Okay 1: Needs Improvement</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>General</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Talk less than subject.</td>
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<tr>
<td>2. Use brief and concise questions and statements.</td>
<td></td>
</tr>
<tr>
<td>3. Use open-ended questions. (Requires more than a yes/no response)</td>
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<tr>
<td>4. Use well constructed questions.</td>
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<tr>
<td>5. Avoid leading questions.</td>
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<td><strong>Total</strong></td>
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<tr>
<td><strong>Average</strong></td>
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</table>

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<thead>
<tr>
<th>Introduction</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Introduce self.</td>
<td></td>
</tr>
<tr>
<td>2. Establish rapport.</td>
<td></td>
</tr>
<tr>
<td>3. Describe purpose of interview.</td>
<td></td>
</tr>
<tr>
<td>4. Explain why interview is important.</td>
<td></td>
</tr>
<tr>
<td>5. Explain what you know about the job.</td>
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<tr>
<td>6. Explain how information will be used.</td>
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<tr>
<td><strong>Total</strong></td>
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<td><strong>Average</strong></td>
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### INTERVIEW RATING SCALE

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</tr>
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</table>

**Active Listening Skills**

1. Summarize frequently.
2. Summarize tentatively (check for agreement).
3. Paraphrase as an accuracy check.
4. Maintain eye contact.

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<tr>
<th>Total</th>
<th>Average</th>
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</table>

**Conducting the Interview**

1. Follow up leads effectively.
2. Use appropriate terminology.
3. Allow the subject to speak.
4. Avoid criticizing the subject.
5. Use encouraging questions.
6. Start with broad questions before specifics.
7. Ask for examples.
8. Ask "What if..." questions.

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<th>Total</th>
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**Control the Interview**

1. Keep on the subject.
2. Avoid incidental remarks.
3. Get all necessary information.

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<th>Total</th>
<th>Average</th>
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### References

VI. RESPONSIBILITIES:

A. TEAM MANAGER - The ART Team Manager (TM) is responsible for the behavior of all team members during all phases of the ART visit. The TM is empowered to take any appropriate disciplinary action that may be necessary to ensure that ART members maintain a high degree of professionalism. This is especially true during the on-site activities portion of the visit.

NOTE: In situations where there is no designated Team Manager these duties shall be assumed by the designated leader or in the absence of a designated leader these duties shall be assumed by the most senior TAP Staff member present.

B. TAP MANAGER - The TAP Manager provides direction, establishes policy, and provides resolution of issues associated with the conduct of the TAP Staff as they relate to the overall implementation of the DOE Training Accreditation Program effort.

C. TAP STAFF - Shall abide by the guidance offered in this procedure and behave in a professional manner at all times.

VII. REQUIREMENTS:

This section of the procedure delineates the behavioral responsibilities associated with ART activities. These behavioral requirements are divided into the following four areas: Confidentiality, Professionalism, Accountability and Miscellaneous

A. CONFIDENTIALITY

1. Communications - Discussions, comments, memos, phone conversations, or any other form of informal communications containing information gathered during a TAP related activity is prohibited. Only formal communications (those carried out as a normal course of TAP business) or communications specifically authorized by TAP management are allowed.

2. The TAP Staff shall not discuss information gathered during a TAP activity with unauthorized persons inside or outside of the office. Unauthorized persons include everyone not having a "need to know":

TAPP 410, Rev. 0 01/08/93
3. Conversations containing information or activities regarding a specific facility should not take place in public places such as restaurants, hotel lobbies, airplanes, etc. While most accreditation information is not sensitive from a DOE or DOD security standpoint it is unacceptable to discuss this information in public.

4. Memos, reports, facility materials, etc. shall not be transmitted in any fashion to unauthorized persons. Materials that contain facility information of a sensitive nature shall be kept under personal control (not left in hotel rooms, rental cars, unoccupied meeting rooms, etc.). Lost or misplaced materials shall be reported to the TAP Manager and/or the TM as soon as possible.

5. TAP staff should keep in mind that the information gained through personal interviews and/or documentation review is to be shared only with the appropriate levels of facility management and, as necessary, with other TAP staff personnel. For example, information gathered from one department manager should not be shared with other department managers except as necessary to conduct a thorough accreditation visit.

6. Information uncovered by the TAP Staff that may indicate potential violations of local, state, or federal regulations shall be passed on to the Team Manager. The Team Manager shall inform appropriate levels of facility management of the information. The Team Manager shall inform the facility management that the expectation is that the facility will take appropriate actions regarding the information. Normally this will include, as a minimum, a disclosure statement to the appropriate regulatory body. The TM shall document the actions taken by the facility. The Team Manager shall immediately inform the TAP Manager of all communications regarding potential violations discovered by a team member.

7. Team members shall not make informal references or comments (good or bad) concerning other facilities, persons, sites, or organizations at any time. Formal recommendations or references, associated with providing specific TAP assistance to a facility, are encouraged, however.

B. PROFESSIONALISM

1. All TAP procedures and guidelines shall be followed.

2. TAP members, when visiting a facility, shall follow that facility's procedures, policies and instructions.
3. Because TAP members travel to many different facilities, it is always possible that someone will unwittingly violate a procedure, policy, or security requirement. These shall be reported to the Team Manager immediately. The TM shall investigate the situation and notify the TAP Manager immediately. The TM or the TAP Manager shall work with facility management to resolve the situation as quickly as possible.

4. TAP members will not be restricted from fraternizing with facility personnel during lunch or after working hours but they should ensure that they do not violate rules of confidentiality, conflict of interest or professional ethics.

5. Team members shall not accept gifts of any kind from any person representing a facility before, during, or after a team visit.

6. Team members shall wear TAP Staff name tags while at a facility.

7. Team members shall not engage in any type of deception or covert activities to gather information at a facility.

8. Team members shall not make qualitative comments on evaluations conducted by this or other organizations (Assist Visit Teams, Tiger Teams, TSAs; etc.) while at a facility.

9. Team members shall refrain from making uncomplimentary or unprofessional comments concerning any person, facility, site, or organization at any time.

10. All team members shall treat facility personnel, at all levels, with respect and professionalism. Reports of team member rudeness or lack of respect for facility personnel, rules and/or traditions will be investigated by the TM and dealt with appropriately.

11. Team members who believe they have not been treated with respect and/or honesty by a facility person shall report the person and the situation to the TM immediately. The TM shall deal with this in an appropriate manner, which will normally consist of reporting the situation to the appropriate level of facility management for resolution.

12. Team members shall not carry non-TAP related materials into a facility. Items that are prohibited include entertainment equipment of any kind, reading materials that are not job related, and tape recording devices.
13. Team members shall not engage in any arguments, heated discussions, or lengthy debates with facility personnel. If a team member has been unable to avoid a conflict or confrontation with a facility person they shall report the details of the situation to the TM as soon as possible.

C. ACCOUNTABILITY

1. Team members are accountable for the accuracy of the information they gather and the accuracy of any report that is written as a result of that information. Team members shall be able to document, and when necessary, report sources of their information. It is never the intention of any TAP activity to embarrass or attack an individual or group of individuals, therefore names (with the exception of facility key personnel) should not be used (without good reason) in team discussions or in reports. It sometimes becomes necessary to substantiate the background, training, or experience of individuals interviewed or observed during a TAP activity so team members should have this information available if it is needed.

2. Personnel and equipment safety shall not be jeopardized during any TAP activity. Team members shall recommend stopping any activity that, in their judgement, places any person or piece of equipment in an unsafe condition. Team members shall never take physical control of any person or thing during any TAP activity except in a clear and immediate life saving situation.

3. TAP Staff shall utilize the "as low as reasonably achievable" (ALARA) principle regarding their radiation exposure during all TAP activities. Team members should keep in mind, however, that observation of radiological work practices by facility personnel under actual plant conditions is an important part of a thorough training evaluation. When possible, team members should discuss the necessity of entering a high radiation area with the team manager prior to entering if the exposure is expected to exceed 10% of the facility's weekly dose limit.

When visiting facilities that have higher than normal or unusual radiological hazards the team shall plan activities such that a thorough evaluation may be conducted while minimizing exposure to the team.
4. Materials gathered during a TAP visit may be copied and/or removed for official TAP purposes only and only after gaining facility management's approval. If an evaluator would like to copy materials for possible application at another facility, this must be specifically authorized, in writing, by facility management. While sharing materials between facilities is encouraged, team members should not get preoccupied with this during an accreditation visit. A more efficient approach is to put the appropriate people in contact with each other by exchanging phone numbers.

5. All team members shall use the facility's check out method when removing documents from a library or a file. Each team member is responsible to ensure that all materials are returned in the same condition as received, and checked in before the team leaves the facility.

6. Team members that have reported information to the Team Manager that may indicate potential violations of local, state, or federal regulations shall follow up on this information with the TM. If the team member is not satisfied with the resolution of the problem they shall report this to the TAP Manager.

7. Team members shall not direct the activities of any facility personnel. Team members shall not knowingly cause the disruption of any facility work activity, except as officially requested via the TM. Team members should attempt to minimize their impact on facility personnel. Team members, whenever possible, shall not cause facility personnel to work extra hours, miss work breaks, lunches or other important activities or meetings. Team members shall not knowingly violate, or cause others to violate, any work practices or trade union rules.

D. MISCELLANEOUS

1. The dress code for all team members during working hours shall be neat, clean and professional. Men are encouraged to wear a coat and tie. Women are encouraged to wear appropriate business attire. Persons entering operating equipment areas or radiologically controlled areas shall dress accordingly. The facility's guidelines for personnel safety shall be adhered to at all times. Blue jeans, tank tops, shorts, baseball caps, sun glasses (indoors) or other casual or athletic attire shall not be worn on site at any time without specific authorization from the TM.

2. TAP Staff members shall maintain and/or improve their qualifications by participating in an appropriate continuing training program.
VIII. ATTACHMENTS:
   A. None

IX. RECORDS:
   A. None
A.5.22

Conflict Resolution

by

J. Loewen
Assessment Team Training
April 19 - 21, 1994

Conflict Resolution

Presented by:
Jan Loewen

Operations & Training
Technology Applications (OTTA)
Idaho National Engineery Laboratory
EG&G Idaho, Inc.
CONFLICT RESOLUTION

OVERALL OBJECTIVE

- Provide team members with the tools for ensuring open, constructive collaboration and communication.

Purpose

- To help participants recognize that conflict is part of team work
- To understand the importance of resolving conflict using open communication techniques
- To understand the importance of recognizing potential conflict during the assessment process
- To understand the impact of personal perceptions, experience, and assumptions in conflict

Definition

Conflict

A state of open fighting; warfare. A state of disagreement and disharmony; clash.

Collaborate

To work together, esp. in a joint intellectual effort.
Levels of Conflict

Disagreements are natural, and how you solve them can lead to conflict or better ideas and solutions. Conflicting interests, experiences, communications, perceptions, and values greet us at every turn. To be interpersonally effective, you need to understand conflict, and how to effectively manage it.

Conflict is a process that in itself is neither good nor bad, but which has elements and outcomes that may be perceived favorably or unfavorably by those participating in or evaluating it.

Perceptions
- people see what they are looking for.

Assumptions
- the way individuals think things are.

Personal Experience
- the way things have been seen before.

Personal Expectations
- the way people hope things will be.

Values
- what people have been taught to believe is right and wrong.
METHODS OF HANDLING CONFLICT

LCCPC Conflict Model

**Listen**
- to understand what the sender is saying or what the message means.

**Clarify**
- points of agreement.

**Clarify**
- points of disagreement.

**Problem Solve**
- once the cause or issue is known begin to share your thoughts and ideas on methods of solving the problem.

**Conflict Resolution**
- as a result of solving or recognizing the problem, come to a consensus.

**Flight or Fight**

**Avoid**
- setting it aside, assuming you need better or more data

**Accommodate**
- giving in, acquiescing to the situation or person
Attack
- demanding, challenging for attention or recognition

Control
- wins over the expense of others

Collaborate
- reaching a solution through consensus

Open-ended questions
- begin with Is, As, Did, Can, Will, or Shall.

Questions that are answered with "Yes or No."

Closed-ended questions

The person CAN NOT answer with a simple yes or no. It gives them a chance to explain.

Consensus
Consensus is a decision making method which best reflects the thinking of all group members. Consensus is difficult to reach; not every idea will meet with everyone's approval. But each individual should be able to find the proposal acceptable on the basis of logic and feasibility. When all group members feel this way, you have reached consensus.

- Avoid arguing for your own opinion
- Avoid a win-lose attitude
• Don’t just agree to avoid conflict
  - be suspicious of quick solutions
  - explore alternatives
  - identify what is known
• Avoid conflict-reducing techniques
  - majority vote
  - averages
  - coin flips
• Differences of opinion are natural
  - involve everyone
  - disagreement provides wide range of ideas and opinion
  - greater opportunity to ascertain the solution

How to Resolve the Unexpected

Win-Win Attitudes
• Belief in mutually acceptable solution
• Recognition that conflict is natural
• Cooperation rather than competition
• Differences of opinion are helpful
• Minimize power differences
• Self-examination of your own beliefs, attitudes, perceptions.
• Provide "face-saving" situations

Summary

Disagreements are natural, and how you solve them can lead to conflict or better ideas and solutions. At times each one of you may act as a mediator to solve the problem or issue. At best some of you may act as the catalyst to help others work through their differences.

Bibliography


2. Ibid. p. 291.
Conflict Resolution Model

Listen

Clarify (Agreement)

Clarify (Disagreement)

Problem Solve
A.5.23

Forms: Request for Visit Information, Program Feedback
Operating procedures at all DOE complex facilities require a sufficient lead time for processing of a transfer clearance. Although lead time requirements may vary from facility to facility, 3-4 weeks should be adequate. An inquiry with regard to the process time is advised.

Official visits to other facilities requiring access to Exclusion Areas, Materials Access Areas, or special accesses (such as SCI, WNIINTEL, SIGMA, CRYPTO, etc.) that clearances be certified to that specific facility. The individual’s clearance level validation must be received by the facility to be visited before the actual visit commences.

When completing the DOE F-5631.20 form, the dates of the visit must be accurately and specifically noted. If required, SIGMA categories are required to be named specifically (this information is available from the facility contact). The form also requires the full name of the contact at the facility including a telephone number and facsimile number.

The processing of completed forms can only be initiated by the facility where the visitor’s clearance is assigned.
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| Would you like to discuss this personally? With whom? |
A.5.24

Draft: Interim Recommendations for Storage of Plutonium Oxide at Department of Energy Facilities
DRAFT

Interim Recommendations for Storage of Plutonium Metal and Plutonium Oxide at Department of Energy Facilities

The following recommendations are made to improve current plutonium storage safety practices. Until new equipment and facilities become available to package plutonium based upon long-term standards, these recommendations are applicable to plutonium metal or plutonium oxide stored outside of glovebox lines in containments that do not have certified hermetic seals (i.e., per ANSI N14.5').

1. Plutonium solutions, metal turnings, or particles with specific surface areas greater than $1 \text{ cm}^2/\text{g}$ should not be stored outside of gloveboxes.

2. All packages containing plutonium metal should be taped, re-taped, and placed in plastic bags prior to handling.

3. Inspections should incorporate use of adequate personnel protection. Inspection practices should be codified in surveillance plans. These plans should reflect current facility operating status. There must be personnel radiological surveillance during all handling operations. Personnel protection during operations should include protective clothing and gloves; and, if necessary, respiratory protection.

4. Inspection of containers should be integrated with audits for Materials Control and Accountability (MC&A) to minimize container handling and attendant radiation exposure to levels as low as reasonably achievable (ALARA).

5. Containers should be inspected for abnormalities (e.g. mass change, container deformation or discoloration) using visual inspection, weighing, or video surveillance where such capability exists. Findings should be recorded for safety and material control and accountability (MC&A) evaluations. Visual inspections should be made at intervals of 1 week and 1 month after the materials initial containment, and annually thereafter.

6. Packages containing more than 0.5 kg of plutonium metal should undergo an annual surveillance in which the total mass of the package is determined to an accuracy of $\pm 0.5 \text{ g}$ and compared with the preceding year's mass and with the initial (reference) mass at the time of packaging. A storage package should be evaluated (e.g., opened and inspected, radiographed.) if any of the following conditions are evident:

---

a. The outer storage vessel is bulged or distorted.

b. Hydride-catalyzed oxidation is suspected. Such reaction is indicated by a mass increase in either of two circumstances:

i) For item 6 packages whose masses continue to increase since initial packaging or for which historical mass data are unavailable, a mass increase greater than 15 g per kilogram of plutonium over a one-year period indicates a hydride-catalyzed oxidation reaction.

ii) For a package whose mass has remained constant over a period of several years (less than ±0.5 g change) from its reference value, then undergoes an annual mass increase of more than 2 g per kilogram of plutonium, hydride-catalyzed reaction is indicated. Such a package is particularly suspect. The indications are that previously sealed container may now be breached and that the continuing reaction may lead to rapid containment failure within 12 to 24 months.

c. The measured package mass, relative to the reference mass, corresponds to the mass that indicates formation of oxide with a volume exceeding 10% of the free volume of the inner vessel. (Each one-gram increase in mass corresponds to formation of 1.5 cm$^3$ of oxide with a density of 50% of the theoretical value of 11.46 g/cm$^3$.)

7. Inspected containers exhibiting abnormalities (e.g., external contamination, bulging, discoloration, or other anomalies) should be repackaged in accordance with well-defined procedures (Items 3 and 4). Handling such containers outside of a glovebox or conveyor confinement requires respiratory protection use until the package is placed in an over-pack container (e.g., taped metal can or sealed plastic bag) prior to further handling and transport.

8. As an interim measure, material that is repackaged may be placed in a food pack can or slip-fit (Vollrathl container with a secured lid. If possible, metal should be repackaged in a configuration containing at least one gas-tight seal. No plastic material should be in direct contact with plutonium metal or oxide, and use of plastic-in outer layers of packaging should be minimized.

9. When packaging metal, hazardous or pyrophoric material such as plutonium hydride, should be removed. It is not, however, necessary to remove protective oxide film. Metal should be packaged in as dry

---

2A higher oxidation rate may occur if the contained metal exhibits a high-surface area configuration such as sheet or foil. The maximum annual increase for normal (uncatalyzed) oxidation of a given metal geometry can be calculated using a reaction rate of $3 \times 10^{-7}$ g oxygen/cm$^2$-minute measured for alpha-phase plutonium under moist conditions at 50°C.
10. Impure oxide from sources other than metal should be thermally stabilized at 1,000 ± 100 °C for at least an hour, or placed in a combination of a slightly lower temperature (~850 °C) for longer heating time to result in the lowest Loss on Ignition (LOI) practicable with existing equipment. This ensures complete conversion of substoichiometric material, and aid small-particle coalescence which diminishes dispersal risk.

11. Because plutonium oxide has greater potential for dispersion in severe accidents, it should have priority over metal for storage in structurally robust vaults. Metal should be characterized to ensure that it has not converted to oxide while in storage. Stored plutonium will have increasing radiation level because the buildup of Am-241. Therefore, characterization of metal should be done as soon as possible and should make full use of small sample statistical methods to minimize worker exposure. The results of characterization should be integrated with a site's surveillance plan as well.

12. Quality assurance measures, labeling, material characterization are essential. Material and storage packaging specifics should be thoroughly documented.
A.5.25

Assessment of Plutonium Storage Safety Issues at Department of Energy Facilities
DOE/DP-0123T
January 1994
Assessment of Plutonium Storage Safety Issues at Department of Energy Facilities

January 1994

U.S. Department of Energy
Assistant Secretary for Defense Programs
Washington, DC 20585
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Summary

The Department of Energy (DOE) mission for utilization and storage of nuclear materials has recently changed as a result of the end of the "Cold War" era. Past and current plutonium storage practices largely reflect a temporary, in-process, or in-use storage condition which must now be changed to accommodate longer-term storage. This report summarizes information concerning current plutonium metal and oxide storage practices which was presented at the Office of Defense Programs (DP) workshop in Albuquerque, New Mexico on May 26-27, 1993 and contained in responses to questions by DP-62 from the field organizations.

The scope of the presentations and discussions was limited to packaging and interim storage of weapons-grade, fuel-grade, and power-grade plutonium. Consideration was given to current and potential interim storage criteria as they would evolve into longer term storage in Complex 21 facilities. Existing storage and handling requirements for plutonium metal and oxide are currently covered in DOE Orders 5480.3 and 5480.5 as well as orders covering criticality limits, safeguards and security, and transportation. Storage of residues, waste, or pyrophoric plutonium materials are not included. The principal difference between interim and long-term storage is the need for transfer of plutonium from a contaminated glove box environment into an improved, hermetically sealed storage container without the inclusion of plastic or other organic materials. The improved container can then be safely stored within structures and vaults meeting Safeguards criteria.

Material requirements were developed for interim storage of both plutonium metal and oxide. These are:

- Metal must be of a size configuration that makes it non-pyrophoric;
- No plastic or organic materials shall be in direct contact with stored plutonium;
- Thermally stabilize oxide at 1000 °C with subsequent cooling and packaging in a dry atmosphere.

Additional requirements for packaging and storage are:

- Move toward containers which are hermetically sealed and away from containers using organic materials for seals;
- Coordinate plutonium inventories and inspections so as to minimize radiation exposure.

A new interim guidance for the safe storage of plutonium metal and oxide has evolved from the assessments developed within this report.
I. Introduction

On April 30, 1993, EG&G Rocky Flats, Inc., the management and operating contractor at the Rocky Flats Plant, notified the Department of Energy (DOE) that the company had failed to inspect stored metallic plutonium in accordance with schedules established in internal plant safety procedures. Concerns focused on plutonium metal and its corrosion products since they are considered to be pyrophoric and because they might spontaneously ignite in air under certain conditions. As a result, it has been common practice to periodically inspect stored material for signs of corrosion. If remediation was deemed necessary, corrosion products were removed and thermally stabilized by oxidation at high temperature and the metal was repackaged. To remedy the immediate situation, EG&G Rocky Flats was asked to develop a plan and detailed procedures for necessary inspections, cleaning and repackaging.

In order to determine whether similar problems exist at other DOE facilities, the Office of Defense Programs (DP) requested all Operations Offices to provide information on practices at other DP plutonium storage sites and organized a workshop on storage issues. The workshop was held in Albuquerque, New Mexico, on May 26 and 27, 1993:

The objectives of the workshop were to:

1) Identify plutonium (metal and oxide) storage issues at Department of Energy (DOE) sites;

2) Evaluate whether there are any immediate safety concerns for site workers and the public;

3) Initiate development of DOE-wide criteria for interim, safe storage of plutonium metal and oxides, including requirements for surveillance, good practices, etc.; and

4) Discuss the relationships between the requirements for current, near-term, and long-term storage.

The processing and storage of plutonium residues, $^{238}$Pu, and Pu-bearing liquids were excluded from the scope of the workshop and are not considered in this report.

The agenda for the workshop (Appendix A) was developed by an ad hoc steering group of DOE Headquarters personnel and contractors with recognized expertise in plutonium handling and storage. All DOE sites were represented at the workshop as well as non-DP sites at which significant quantities of plutonium are stored. Participants in the workshop, including designated presenters, are also listed in Appendix A. The program was coordinated with representatives from Operations Offices and Headquarters Program Offices. It included a review of the technical basis for plutonium storage practices, descriptions of current and planned near-term storage practices at each facility, and a presentation of advanced concepts for long-term storage being developed as part of the weapons complex reconfiguration (i.e., Complex-21) effort. Based on the presentations and subsequent discussions, a general consensus was achieved on the hazards associated with the storage of plutonium metal and oxide, and on recommendations to DOE for enhancing the safety of the Department's storage practices.

The scope of this report is limited to an analysis of storage practices for extracted plutonium metal and oxide. Materials having distributions of plutonium isotopes in the weapons-grade range are considered; those rich in $^{238}$Pu are excluded. Storage of plutonium in aqueous solution, plutonium in pits, plutonium in residues (less than 50 mass % Pu), and metallic turnings and particles with specific surface areas greater than 1 cm$^2$/g is not included. This report examines issues pertinent to establishing standards for short-term (up to 10 years) and long-term (up to 100 years) storage. The ultimate disposition of plutonium is not addressed.
Information presented at the workshop along with that obtained from written responses to requests from DP is the basis for this analysis. Properties relevant to safe storage of metal and oxide are discussed in Section II. Current storage practices at DOE facilities are reviewed in Section III. Advanced storage concepts and a brief hazard analysis that attempts to bound the risks from the current storage practices are described in Sections IV and V, respectively. Section VI includes recommendations for improving storage practices. Section VII contains a bibliography for further, suggested reading. References cited within the text are found at the bottom of the relevant pages.

The following authors contributed to this report:

Lisa K. Chan, Department of Energy, Office of Defense Programs
Dae Y. Chung, Department of Energy, Office of Defense Programs
Donald T. Chung, SCIENTECH, Inc.
Raymond Cooperstein, Department of Energy, Office of Defense Programs
Rowland E. Felt, Westinghouse Idaho Nuclear Company
John M. Haschke, Los Alamos National Laboratory
Joseph C. Martz, Los Alamos National Laboratory
David Michlewicz, Department of Energy, Office of Defense Programs
Jofu Mishima, Science Applications International Corporation
Thomas O'Connor, Department of Energy, Office of Environment, Safety, and Health
David M. Pinkston, Science Applications International Corporation
Michael F. Stevens, Los Alamos National Laboratory
Alan K. Williams, Science Applications International Corporation

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II. Material Properties Relevant to Storage

II.A. Metal, Oxides, and Oxidation

The chemistry of plutonium is unique, but certain aspects closely parallel those of other actinide elements. Large pieces of plutonium metal react slowly with the oxygen in air at room temperature to form plutonium oxides. The rate of oxidation is dependent on a number of factors. These include: 1) temperature, 2) surface area of the reacting metal, 3) oxygen concentration, 4) concentration of moisture and other vapors in the air, 5) the type and extent of alloying, and 6) presence of a protective oxide layer on the metal surface. The rate of oxidation increases with increases in the first four factors and decreases with the last. Alloying can either increase or decrease the oxidation rate, depending on the alloying metal. The oxide formed on the surface of gallium-containing alloys is very adherent and retards further oxidation. Of all these factors, moisture has a large effect on the oxidation rate and is especially significant in evaluating conditions for storing plutonium metal and oxide.

Several plutonium oxides can be formed from oxidation of metal or decomposition of plutonium compounds. Oxide phases corresponding to sesquioxide (Pu$_2$O$_3$) and dioxide (PuO$_2$) compositions have been identified and are well characterized. Oxides with stoichiometric compositions between the sesquioxide and dioxide form under certain conditions. The phase previously identified as plutonium monoxide (PuO) is actually an oxide carbide (PuO$_{0.6}$C$_{0.4}$). Pu$_2$O$_3$ is pyrophoric in air and rapidly forms dioxide while releasing 54 kcal of heat/mol of PuO$_2$. The dioxide is inert in air, but reportedly reacts slowly with water vapor at elevated temperatures.

---

temperatures to form a higher oxide (PuO$_2.2$) plus hydrogen.\textsuperscript{10} Substoichiometric oxides or "sub-
oxides" with compositions near dioxide (e. g., PuO$_1.98$) oxidize slowly to PuO$_2$. The heat
liberated from the oxidation of PuO$_{1.98}$ is only 4.54 kcal/mol compared to 252.8 kcal/mol for the
oxidation of Pu metal to PuO$_2$.

The formation of oxide from metal is accompanied by a large volume expansion (at least 40 \textsuperscript{o}c
which may bulge or breach the primary container. Case studies show that mechanical wedging
resulting from this expansion can even breach a second metal container, resulting in localized
contamination release and possible exposure of vault personnel.\textsuperscript{11} Oxidation of the metal an-
rupture of the container by mechanical wedging are prevented if the storage container is
hermetically sealed.

Properties of the dioxide may vary with the method of preparation. The particle size distribution
and specific surface area of process oxide prepared by pyrolysis or calcination of a precipitate such
as the oxalate, nitrate or peroxide may differ substantially from those of dioxide obtained by
oxidation of the metal.\textsuperscript{12} Whereas high temperature (> 500 \textsuperscript{o}C) oxidation of metal yields an oxide
with a relatively low specific surface area (< 0.1 m$^2$/g), the product obtained by pyrolysis of
oxalate has a high specific area (10-50 m$^2$/g) that varies with calcination temperature. The specific
areas of oxides formed by oxidation of metal in air at room temperature are typically in the 10-
20 m$^2$/g range.\textsuperscript{13} The purity of process oxides may also vary with the conditions of calcination
due to differences in the amount of anion residues remaining in the product after calcination.

Although chemical corrosion is not a concern with PuO$_2$, reactions involving "oxides" are known.
In addition to the pyrophoric PuO$_2$, oxides generated by the corrosion of metal in oxygen-
deficient atmospheres containing hydrogen may contain metal fines and small amounts of hydrogen.
Experience indicates these products oxidize in a relatively rapid, but safe manner. However, this
general rule should not be considered applicable if the oxide contains large amounts of potentially
reactive impurities such as hydride. Reactive impurities can pose a fire hazard by acting as an
initiation source for combustible materials. The risk of a large fire is virtually eliminated if the
amount of combustible material in the storage environment is limited.

The dioxide has an active surface that strongly adsorbs atmospheric molecular species and the
material is highly reactive from a radiolytic perspective. Together, the adsorption behavior and
high specific surface areas of process oxides can result in adsorption of large amounts of water,
carbon dioxide, organic molecules, etc. from the process environment. Radiolytic decomposition
of adsorbed species by alpha particles from radioactive decay of plutonium generates gases (e. g.,
H$_2$, CO and O$_2$) that are not strongly adsorbed by the oxide. The resulting pressurization of a
sealed container can lead to bulging or rupture. Since adsorbed species are removed by heating

\textsuperscript{10}L. Stakebake, D.T. Larson, and J.M. Haschke, J. Alloys Comp., in publication; also

\textsuperscript{11}J.M. Haschke and J.C. Martz, "Metal-Oxide Chemistry and Storage," presentation to the DO
workshop on plutonium storage, Los Alamos Report LA-CP-93-159, Albuquerque, NM (Ma-
26, 1993).

\textsuperscript{12}J.D. Moseley and R.O. Wing, "Properties of Plutonium Dioxide," Dow Chemical Company

\textsuperscript{13}J.L. Stakebake and M.R. Dringman, J. Nucl. Mat. 23 (1967) 349.
oxide to an elevated temperature in air, thermal processing may be used to remove adsorbates from the oxide prior to storage. Care must be taken to prevent re-exposure of processed material to moisture and other contaminants before packaging. Thermal desorption of gases due to internal or external heating of a sealed storage container can also generate high pressures.

Alpha decay of plutonium provides another potential source for pressurizing sealed containers. Decay of $^{239}$Pu produces helium at a rate of $1.19 \times 10^{-4}$ mol He/kg Pu yr. (1.05 $\times 10^{-4}$ mol He/kg PuO$_2$ yr.). Whereas the helium produced in oxide diffuses out of the solid particles, helium generated in bulk metal is retained and accumulates as small bubbles along grain boundaries. The contribution of helium to pressurization of an oxide storage container is negligible for near-term storage, but must be considered if the storage period is extended.

II.B. Reactions Involving Water

Water vapor accelerates the oxidation of plutonium by oxygen and reacts directly with the metal. The process by which water enhances the rate remains open to debate, but it is generally believed that the process involves formation of plutonium hydride. The net result is that the oxidation rate is about ten times higher in humid air than in dry air at room temperature. For this reason, plutonium metal has routinely been handled in a very dry atmosphere such as one with a $-40^\circ$C dew point. Nitrogen or argon can be effective in reducing oxidation of plutonium in glove boxes and enclosures if water vapor can also be excluded. Rapid oxidation does not occur if oxygen is present at a level of 5% in nitrogen or argon. However, if 1.5% moisture (50% relative humidity) accompanies the oxygen, then rapid metal oxidation can be anticipated. Water is not used in glove box enclosures containing plutonium metal, the principal source of both oxygen and water is diffusion through enclosure gloves and plastic bag-out ports.

Plutonium dioxide is hygroscopic and a high surface area material which can adsorb up to 8% of its weight as water on the surface. The quantity adsorbed is a direct function of the surface area of the oxide. As shown by data in Figure 1, adsorbed moisture can be removed by heating the oxide. Approximately 2/3 of the moisture is only physically adsorbed and can be removed by minimal heating at 50-100°C. Temperatures up to 1000°C are necessary to remove the remaining chemisorbed water.

The principal hazard associated with adsorbed water is pressurization of a sealed oxide container through any of several separate processes including thermal desorption of water, radiolysis to form oxygen and hydrogen, or direct reaction with the oxide to form a higher oxide and hydrogen.

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Storage requirements for oxide have generally required a prior calcination temperature of 650-700 °C to minimize container pressurization. Data for oxide with a specific surface area of 17 m²/g (cf. Figure 1) show that this treatment leaves about 2 mg of water per gram PuO₂. For a typical storage configuration (3 kg of oxide with 2 liters free volume) the pressure could ultimately exceed 60 psig after calcination at 650-700 °C. If the stored oxide has a surface area of 50 m²/g, the pressure could reach 180 psig.

Figure 1. The temperature dependence of water desorption from plutonium dioxide in vacuum. Data are from a sequence of isothermal measurements with a PuO₂ sample having a specific surface area of 17 m²/g.¹⁹

Pressurization of oxide containers might be prevented by use of sealed containers fitted with durable, high-efficiency metal filters. Although radiolytic gases can escape without release of plutonium-containing particles, air (possibly moist) is able to enter the container. Radiolysis of nitrogen/oxygen mixtures forms large amounts of N₂O, NO₂, and N₂O₄.²⁰ When water is present, nitrogen oxides form a highly-corrosive (e.g. HNO₃) environment.²¹ However, a serious concern exists regarding the “masking” of filter media. Sintered metal and fibrous filters can have the pores masked if the surface is covered by a fine powder such as might occur if the container is overturned. Once masked, the filter would only be a structurally weak portion of the container while not allowing the passage of pressurized gases.


II.C. Hydride

Plutonium hydride (PuH\textsubscript{x}, 2 < x < 3) forms during corrosion of plutonium metal by hydrogen from water, organic materials and other sources.\textsuperscript{22,23} The quantity of hydride produced depends on the rate of hydrogen formation and on the magnitude of the hydrogen-containing source. The presence of oxygen or moisture with the hydrogen results in an oxide-hydride mixture. The reactivity of plutonium hydride in air depends on factors such as particle size, presence/absence of protective oxide layer, and hydrogen-plutonium ratio, x. Finely divided hydride is pyrophoric in air at room temperature. Thus, the only safe practice is to handle and store hydride in a dry, oxygen-free atmosphere free of unnecessary combustibles.

Hydride is rapidly oxidized by dry air at room temperature to produce PuO\textsubscript{2} and H\textsubscript{2} and reacts with nitrogen at 250 °C to form plutonium nitride (PuN). Reaction of PuH\textsubscript{2} with O\textsubscript{2} releases 213.5 kcal/mol.

II.D. Plastics and Other Organic Materials in Storage

Contamination-free exterior surfaces have typically been required for containers used in shipment and vault storage of plutonium. This has usually been accomplished by a "bag-out" operation in which a sealed plastic bag is used to contain plutonium contamination. Plutonium metal buttons were bagged out and sealed in food-pack cans for storage. If the button was not placed in a metal can before bag out, it remained in direct contact with the plastic inside the sealed container. The temperature of the stored metal is generally slightly elevated due to the heat from radioactive decay.

Polyethylene and polyvinyl chloride (PVC) are used as bagging materials and both deteriorate under heat and radiation and generate undesirable gaseous products.\textsuperscript{24} Experiments show that low-density polyethylene can be used to temperatures as high as 300 °C without excessive degradation to form hydrogen. The maximum service temperature for PVC is approximately 85 °C. In addition to H\textsubscript{2}, thermal degradation of this plastic produces gaseous HCl that corrosively reacts with other materials to form hydrogen. Polyethylene is the preferred bagging material, but is more difficult to heat-seal. Radiolysis of the two plastics yields large amounts of the same gaseous products as pyrolysis. The radiolysis rate is a function of the surface area of plastic in intimate contact with plutonium-containing material.\textsuperscript{25} Due to the limited escape depth of alpha particles from dense materials, a film of contamination or fine oxide particles deposited on


the plastic is comparable to a massive piece of metal in promoting radiolytic degradation. If the plastic is outside of a sealed can containing the metal button, degradation of the plastic is reduced because the only source of plutonium-containing particles is contamination on the exterior of the can.

Reaction of plutonium with hydrogen is the principal corrosion concern for metal that is not isolated from the gases formed by degradation of plastics. At room temperature, the reaction of metal with $H_2$ is $10^6$ times more rapid than the reaction with $O_2$. Any oxygen initially present in the sealed storage container reacts with hydride or metal to generate an oxygen-free atmosphere in the absence of oxygen all PuO$_2$ remaining on the surfaces of hydride and metal is slowly reduced to pyrophoric Pu$_2$O$_3$. These reactions prevent pressurization of the container and the mixture of metal, hydride and oxide is stable as long as the container is sealed. Once the storage container is opened, airborne hydride and sesquioxide will ignite and burn with formation of sparks. Special precautions are necessary when handling such containers to avoid sparks that spread contamination and might ignite combustible materials.

Plutonium oxide is never "bagged-out" in direct contact with plastic. Cans containing oxide are either sealed by mechanically crimping or by taping on a slip-lid. When the can is "bagged-out" only the inner surface of the plastic bag and outer surface of the can are contaminated. Radiolytic degradation of the bag over time ultimately results in failure of the plastic as a containment barrier. Use of a second sealed can over the plastic bag prevents the release of contamination, but this outer can may pressurize as radiolytic gases are formed.

II.E. Carbides and Nitride

Plutonium carbides, oxy carbides and nitride are reactive and potentially pyrophoric materials that could pose handling problems if exposed to air or oxygen-containing atmospheres. These compounds react readily with moisture to form gaseous products such as methane, acetylene and ammonia. Since plutonium compounds of this type have been prepared at several sites and may have been "temporarily" stored under special conditions (hermetically sealed and handled under an inert atmosphere) without first oxidizing them, caution should be exercised in opening cans that might contain such materials.

II.F. Pyrophoricity

Many elements exist in nature as oxides since the metallic form is chemically reactive in air. Their behavior is described as pyrophoric only if the oxide forms at a rapid, sustained rate at ambient temperature. The alkaline metals such as sodium, potassium and lithium react violently with moist air, forming hydrogen which ignites and burns. Like alkaline earth metals such as magnesium and beryllium, the actinide elements such as thorium, uranium and plutonium will sustain combustion and burn after ignition at elevated temperatures.

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When heated to its ignition temperature, plutonium reacts at an accelerated oxidation rate which sustains continued oxidation.\(^{30}\) Burning metal liberates 1.0 kcal of heat per gram of plutonium. The burning temperature depends on the rate of heat dissipation to the surroundings and the rate of heat generation, which is dependent on the surface area of oxidizing metal. Temperatures of plutonium fires usually exceed the melting temperature of plutonium metal (640 °C) which causes the material to consolidate into a molten configuration. As such, finely divided metal, turnings, and casting skulls tend to ignite readily and achieve a high initial temperature which lasts until melting occurs and the surface area is reduced.

The oxide layer that forms during burning attenuates diffusion of air to the oxide-metal interface and limits the oxidation rate of plutonium. The burning process is similar to that of a charcoal briquette. The oxidation rate of Pu in air at temperatures above 500 °C is constant with a value of 0.2 g PuO\(_2\)/cm\(^2\) min.\(^{31}\) Since a 2 kg plutonium button has an initial surface area on the order of 100 cm\(^2\), a period of 2-4 hours is required for complete oxidation. Thus, the heat of combustion is dissipated over a relatively long period of time.

The ignition temperature of plutonium metal depends on the factors which increase the oxidation rate. As shown by Figure 2, finely divided plutonium metal, such as metal powder or fine machine turnings, ignites near 150 °C. This temperature is easily reached if a coexisting pyrophoric material such as hydride or sesquioxide spontaneously ignites at room temperature. Bulk or massive plutonium metal characterized as having a specific surface area less than 1 cm\(^2\)/g requires temperatures in excess of 400 °C to ignite. Based on Figure 2, Rocky Flats has defined pyrophoric plutonium metal to be "that metal which will ignite spontaneously in air at a temperature of 150 °C (302 °F) or below in the absence of external heat, shock, or friction." Many plutonium fires have occurred because samples containing finely divided metal have spontaneously ignited. Fires have not occurred with clean metal existing in large pieces that have the higher ignition temperature. Thus, massive plutonium is not considered pyrophoric or capable of self-ignition. An investigation of two instances in which kilogram-sized plutonium pieces were observed to "spontaneously ignite" in air at room temperature shows that they had been exposed to unlimited sources of hydrogen for extended periods and that the samples were thermally insulated when ignition occurred. The amount of hydride present on these massive pieces apparently generated heat sufficient to raise the bulk temperature to the point of self-ignition. These observations emphasize the need for well-characterized materials.

Pyrophoric materials have caused numerous incidents in which plutonium chips, lathe turnings and casting crucible skulls have ignited and burned.\(^{32,33,34}\) These ignition sources have resulted in several significant fires at plutonium metal processing facilities. Incidents involving spontaneous


\(^{33}\)S.H. Pitts, Jr., Nuclear Safety, 9 (1968) 112.

plutonium initiation can be explained by the current understanding of the ignition and burning characteristics of plutonium metal.\textsuperscript{35}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Measured ignition temperatures of plutonium as a function of specific surface area and metal dimension.\textsuperscript{36}}
\end{figure}

\section*{II.G. Particle Size}

The physical size of plutonium-containing particles in storage affects two unrelated phenomena. The first is the ability to absorb moisture and the second is the ability to disperse as a source term in accident conditions.\textsuperscript{37} As with absorption, dispersibility increases with decreasing particle size. Massive Pu is not a dispersible form of plutonium; only after reaction to produce oxide particles does the material become potentially dispersible. As discussed in Section II.F, several hours are required to convert a typical 2 kg Pu button to oxide at the maximum oxidation rate in air with a concurrent volumetric expansion of product. Process oxide inherently exists in a potentially dispersible form.

The particle size distribution of an oxide is strongly dependent on the method of preparation.\textsuperscript{38} Oxide particles formed by calcination of oxalate, nitrate or peroxide and those obtained by slow


oxidation of metal by air at room temperature are totally within the dispersible range (< 10 μm geometric dimension). Less than 0.1 mass% of the oxide produced by oxidation of the metal in air at temperatures above 500 °C is in the dispersible range. These data imply that the dispersal risk of process oxide is approximately a thousand-fold greater than for metal in an equivalent scenario.

Heating plutonium oxide at high temperatures increases the particle size of the powder. Particle size data for preparation of oxide from oxalate show a progressive shift in the size distribution with calcination temperature. The percentages of particles with dimensions in excess of 5 μm are 40, 60 and 75% for calcination temperatures of 650, 700 and 1000 °C, respectively. The difference for the respirable size range (< 3 μm geometric dimension) is even more dramatic. As the calcination temperature is increased from 650 to 700, and ultimately to 1000 °C, the percentage of particles in the respirable range decreases from 40 to 25 and finally to 10%. Similar changes in particle size are anticipated if existing oxides are fired at high temperature. Increasing the apparent particle size has a beneficial effect on adsorption and on dispersal because adsorbates are removed, the capacity for readsoption is reduced, and the dispersibility/inhalation risk is decreased. High temperature calcination has been avoided in the past because it reduces the chemical reactivity of the oxide for dissolution and fluorination. However, its suitability for direct oxide reduction (DOR) is enhanced. Advanced dissolution techniques using silver (II) catalyzed nitric acid allow easier dissolution of high-fired oxides.

39R.E. Felt, presentation to the DOE task force on plutonium storage, Germantown, MD (July 20, 1993).
III. Current Storage Practices

Current plutonium storage practices at DP facilities are summarized in Table 1. The content of the table and following discussion are based on information presented at the workshop and contained in written responses to DP requests.

Current plutonium storage practices at DOE sites (DP sites and Argonne West) reflect a balance between desire to maintain the metal for programmatic needs and the desire to avoid unnecessary costs and personnel radiation exposures associated with cleaning and repackaging the metal. Surveillance of stored materials is primarily for security and safeguard/SNM material inventory rather than safety reasons. At most sites, the safety inspections involve periodic manual examination of a statistically significant fraction of the storage containers.

This section includes discussions of the containers used for storage of metal and oxide at DOE facilities and provides information on the experience and practice in storing plutonium at those sites. The specific storage procedures used for metal, for oxide from metal corrosion, and for process oxide are described.

III.A. Containers

Most DOE contractors use low cost containment schemes for the external storage of plutonium in vaults. In most cases this involves the use of taped, slip lid (e.g., Vollrath) cans or crimp-seal (food-pack) cans for the primary containment enclosed by a plastic bag for glove box environment removal. The bagged can is then usually placed in a second metal can (either slip-lid or crimp-seal type) which is placed on the vault shelf. Neither of these schemes may be considered to provide a long-term "hermetic" seal of the material against atmospheric exposure. The food pack cans rely on a latex coating on the lid to provide an initially air-tight seal, but this polymer is subject to radiolytic decay from contact with normal contamination over time. However, the outer container may provide for the necessary air tightness in the event of breakdown of the inner seal, while the inner container will still provide for physical containment of the metal and any generated oxide.

III.B. Metal Storage

Several DOE facilities presently store plutonium as metal. These include Rocky Flats, Los Alamos National Laboratory, Lawrence Livermore National Laboratory, Savannah River, Argonne National Laboratory-West, and Hanford. Proper storage of the metal, either in a vault-type room or within ventilated glove boxes, focuses on preventing contact of the metal with plastics or other organic materials (e.g., hydrocarbon oils) which are radiolytically decomposed by alpha decay to form hydrogen and other gases.

The use of tape to seal slip-lid containers is probably less reliable than crimp-seal cans because tape does not provide even an initial air-tight seal, and allows for gradual degradation and oxidation of the metal over time. Reaction could result in a mechanical wedging-type rupture of the primary and possibly secondary container. Reduced risk to vault operations personnel from such packaging can be controlled with routine visual and non-destructive (e.g., mass measurement) examinations of stored items and with health physics monitoring of these storage areas for release of radioactive contamination. A history of multi-year storage of such items shows that rupture of containers is rare.
Table 1. Plutonium storage practices at DP sites.

**Y-12**
- Minimal quantities (Pu-Be sources and lab solutions)

**LLNL**
- All Pu stored in sealed containers
- Labels and seals checked bimonthly
- Physical inventory of parts and statistical sample of containers
- Inner sealed cans opened if contents suspect
- All inspections in closed glove box or inspection hood (could introduce oxygen into container atmosphere and increase corrosion)
- Procedure for storage area monitoring, cleaning oxides and repackaging
- Over 70% of inventory has been surveyed, consolidated and repackaged in last 18 months
- No requirement for safety inspections of metallic Pu in sealed containers
- No unsafe storage identified in past inspections

**NTS**
- Only waste and weapon components
- No procedures

**SRS**
- SRS-produced buttons packaged in two crimp-sealed, metal food pack cans, with heat sealed plastic around inner can
- SRS metal samples in vials within food pack cans within 5 gallon containers
- Metal from offsite is packaged in two sealed, metal food pack cans
- Confirmatory random sampling of containers checked for contamination, can integrity, SNM and weight gain/loss per standard operating procedure (SOP)
- Bimonthly physical inventory of all containers of process-generated materials (not of containers received from off site) per SOP - check for tamper and mechanical integrity of cans
- Inspections on schedule - latest completed 5/17-18/93
- Substantial amount of material stored from Central Scrap Management Office (CSMO) in sealed shipping containers
- No safety concerns identified

**HANFORD**
- Pu stored and inspected in accordance with procedures in vaults and vault-type buildings at PFP
- Material includes metal, oxide, and other residues
- Stored in two mechanically sealed containers (outer food-pack can)
- Containers inspected before and during storage
- Vault 2 inspected visually, vaults 1, 3 and 4 monitored remotely - 100% coverage on a monthly basis for corrosion, dents, holes, bulges, etc., and repackaged in argon atmosphere, if necessary
Table-1. Plutonium storage practices at DP sites (continued).

**LANL (TA-55)**
- Material includes metal, residue metal, oxides, and other residues
- Metal stored in sealed containers in vaults or inert glove boxes
- Swipes of containers and storage area
- No inspection of metal in storage
- Oxidation reaction/contamination incident in February, 1993, due to container with degraded plastic (hydride) opened in hood rather than glove box
- Material repackaging and consolidation plan for future storage relies on high integrity container and storage environment characterization instead of extensive inspections

**MOUND**
- Metal stored in sealed containers in vaults or inert glove boxes
- Swipes and visual inspections of containers

**PANTEX**
- Metal in sealed (welded) pits
- Pits swiped prior to storage in approved containers and regularly monitored for contamination

**ITRI**
- Very small amount (<10 grams) in approved shipping container

**ROCKY FLATS**
- 27% of metal stored in line, 73% out of line
- 16% of oxide stored in line, 84% out of line
- Various can/plastic/can/can/ri er combinations (up to three)
- Issues include:
  - metal in contact with plastic
  - metal in improperly sealed produce cans
  - inconsistencies with internal procedure HSP 31.11 - reexamining HSP 31.11 to accommodate longer storage rather than time period required for resumption
  - a quantity of oxide calcined at low temperature (not stabilized)
Many sites find it necessary to store plutonium as metal in glove box lines. Since contamination is not a primary concern in this case, attention might be focused on protecting against contact with plastics and other organic materials to prevent hydride formation that may result in sparking. Additionally, such sites should also be clear of other combustibles, such as rags. Experience has shown that the oxidation process can be significantly retarded by cooling the storage environment or dehumidifying the storage atmosphere. A typical glove box atmosphere is either dry air (−40 °F dew point), reduced oxygen in air (3 to 5% O₂), dry nitrogen, or dry argon.

Although the above mentioned packaging methods (slip-fit can with taped lids, heat- or mechanically-sealed plastic bags, crimped food product cans with latex gasket) do not represent unusual hazards, they do not represent optimum methods for the longer-term (> 5-10 years) storage of plutonium metal, especially where retrieval of the intact metal is desired. The preference here again is to ensure good protection of the metal against oxidative degradation, either through fully welded containers, metal gasket seals, or at the minimum, double food pack sealing.

Finally, although not predominantly a safety issue, most contractors use plutonium in its metallic form, and the ability to preserve the metal becomes an economic issue as well as a radiation exposure and waste generation issue, since it is undesirable to needlessly reprocess the material from oxide back to metal.

III.C. Oxide Storage

Throughout the DOE complex during in-process operations, oxides are typically packaged in unsealed (taped) cans. The technical issues regarding reliability and safety are somewhat different than for metal. As with metal, it is strongly advised that the oxide not be directly packaged in plastic or in close proximity to plastic or other organic materials. Under such conditions, hydrogen is generated by the same radiolytic decay process that forms pyrophoric products during metal storage. It should be emphasized that this radiolytic decay does not produce a sparking hazard in stabilized oxide because stoichiometric oxide does not react with hydrogen.

Unsealed containers do not pressurize because hydrogen is able to escape. If the oxide is stored in sealed cans, the hydrogen gas pressure can result in possible breaching. Further, product hydrogen, when mixed with air, could ignite and act as an initiator for other combustibles. Therefore, mandatory repackaging of stored materials should be reviewed carefully and only undertaken after a risk assessment is completed.

Perhaps the more difficult issues to resolve concerning the appropriate storage of oxide are its radiolytic decay and hygroscopic nature. As discussed above, this effect could lead to generation of pressures sufficient to breach a sealed container, resulting in release of contamination to the immediate area. Interim storage of plutonium oxide is safely accomplished in unsealed containers, such as taped slip-lid cans, but caution should be exercised with food pack cans, which are at best a temporary hermetic seal.

III.D. Thermal Processing Practices at DOE Facilities

To prevent pressurization in storage containers, plutonium oxides are normally thermally processed prior to storage outside of Zone 1 HVAC systems (e.g., glove box or in-line vault ventilation systems). Plutonium oxides stored within a Zone 1 system may be vented so that radiolytic decomposition will not pressurize the containers. In this section, two sources of oxide are

discussed. The first source is plutonium oxide produced by the corrosion of plutonium metal. The second is oxide produced from chemical processing, (e.g., by calcination of plutonium oxalate or plutonium peroxide precipitates). Each type of oxide has separate properties. Oxides produced by the corrosion of metal may contain small quantities of metal fines and hydrides, and possibly some sub-oxides, and may gain weight when thermally stabilized. Oxides produced by chemical processing contain impurities which can be decomposed by radiolytic processes. Decomposition products are almost always gases which can pressurize a sealed container. Process oxides lose weight during thermal processing. The remaining impurities may consist of moisture, residual anions (oxalate, nitrate etc.), and organic materials which have not been completely removed in the calcination process.

The principles of thermal stabilization are well known. The pyrophoricity of oxides produced from corrosion of plutonium metal has also been investigated. The basic chemistry and properties of these materials are discussed in Section II.A.

The current practices at various DOE sites for storing plutonium metal and oxides were presented at the workshop. A discussion for each site follows:

III.E. Storage Experience at Individual DOE Facilities

III.E.1. Rocky Flats Plant

The Rocky Flats Plant has been the primary source of pyrophoric plutonium incidents in the weapons complex, because of the nature of its mission. Plutonium metal casting produces casting skulls that are pyrophoric. Machining of plutonium metal produces metal chips or turnings which are pyrophoric and oily. Conveyor lines have been used for plutonium storage. Since plutonium pits were the primary plutonium product shipped from Rocky Flats, all other plutonium metal was considered in-process and was not packaged for long-term storage. The current four year production outage has focused attention on the need for improved storage because of the change in Rocky Flats mission.

Ignition of pyrophoric forms of plutonium has resulted in several major fires and explosions at Rocky Flats since its startup in the mid 1950's. All of these fires have been associated with the pyrophoric forms of plutonium such as casting skulls, turnings and metal fines. A major explosion in 1964 was a result of an operator mistakenly believing that carbon tetrachloride would be a good extinguishing agent for burning plutonium machine turnings.

A major fire in Building 776-777 in 1969 was promulgated by the ignition of a briquette of machine turnings stored on a combustible shielding material. The magnitude of the 1969 fire resulted in multiple improvements in fire safety throughout the DOE complex, especially plutonium metal fabrication. The amounts of combustible materials in glove box lines has been minimized. A nitrogen atmosphere with up to 5% oxygen has been used at Rocky Flats to prevent enclosure fires initiated by ignited plutonium chips. No major fire has occurred in the last 24 years even though pyrophoric chips and turnings have ignited on a frequent basis during production.

Storage of plutonium metal and oxide at Rocky Flats has always been considered temporary. Thus, the containers have not been sealed as at other sites. Storage in slip-lid stainless steel cans with the lid taped has been standard practice. The slip-lid cans are "bagged-out" and tape-sealed in larger produce cans if the material was to be stored outside the zone 1 enclosure system. The current storage situation at Rocky Flats has plutonium metal and oxide stored in and out of enclosure systems. The atmosphere of the enclosures contains approximately 5% oxygen plus

moisture, so that metal corrosion in taped lid cans is a continuing process. The oxide is intermittently brushed from the metal and the metal returned to storage. Plans are now being implemented to improve the storage of metal and oxide in hermetically sealed containers and the overall thermal stabilization of oxide in storage.

Much of the metal in storage at Rocky Flats is packaged not for longer term storage, but for reuse. In some cases, metal is enclosed in plastic, which is then doubly enclosed in metal cans. Previous experience has demonstrated that this method of storage results in severe corrosion of the metal over time. The corrosion products may contain small quantities of metal fines, hydrides, and perhaps sub-oxides. These are reactive and require thermal stabilization. If the corrosion products are not stabilized after removal from the metal, they are considered potentially pyrophoric. In the absence of a stabilization capability during the past four years, the practice has been to store no more than 200 grams of corrosion product in any single container and to place the container on a heat sink equipped with a heat detector head. The bases for this approach are the conservative assumptions that, if the material reacts, it will be an instantaneous reaction, and that there is no heat transfer mechanism for heat removal. In reality, the oxidation of the corrosion products normally occurs at a slow rate with the in-leakage of air and heat transfer mechanisms do exist that, if considered, would allow storage of larger quantities of such materials. Rocky Flats has the capability to thermally stabilize the products from corrosion of plutonium metal. Rocky Flats has believed that there is a potential problem with storage of these products without stabilization.

All process oxide stored in sealed containers is calcined to meet loss on ignition (LOI) requirements. Oxides which do not meet this test are stored in vented containers. Rocky Flats has the capability to calcine oxides and to thermally remove adsorbates from process oxides. Some of these oxides have not been thermally stabilized and remain in-line in vented containers.

III.E.2. Los Alamos National Laboratory

Los Alamos National Laboratory (LANL) has a limited quantity of plutonium which is handled and stored as a result of laboratory-scale operations. Continuous laboratory operation has precluded production shutdowns common with other facilities such as Rocky Flats, Hanford, and the Savannah River Site. Long-term storage has not been a problem and pyrophoric materials have been processed as they were produced.

LANL takes no special precautions for storing or stabilizing oxide produced from the corrosion of plutonium metal. They do not consider the corrosion products to be a safety problem. They recognize that the oxide product may contain some metal fines and hydrides, but experimental work has shown that these are oxidized rather readily to a stable oxide. They have recognized that when oxidized, hydrided, or corroded metal is exposed to an air atmosphere, an exothermic reaction may occur.

Oxide product from chemical processing is usually stored in vented containers, because of the difficulty in preparing material which will be stable during storage. The primary concern is that plutonium oxide has a high affinity for adsorption of water vapor. Even though the moisture can be removed by calcining at high temperatures, it can be re-adsorb during the packaging operations. A qualified oxide suitable for storage in a sealed container is defined as a material that has been fully characterized, meets the loss on ignition test, and is subsequently handled and packaged in an atmosphere which precludes moisture adsorption.
III.E.3. Hanford

Plutonium pit fabrication was performed at Hanford until 1966. Problems associated with metal turnings and fines were common, although no major fire occurred. Since 1966, plutonium operations have been limited to aqueous processing and metal button and oxide production. Storage of plutonium metal and oxide has resulted in several breaches of containment causing contamination spread within storage vaults. The storage of calcined plutonium nitrate containing residual nitrate has caused pressurization and rupture of storage cans. Hanford uses food-pack cans for metal and oxide storage. Seal failure of food pack cans has required repackaging of several metal storage containers every year.

In the Hanford storage vaults, an automated system for monitoring temperature and pressurization is used. Details of this system (the Vault Safety and Inventory System, VSIS) are available elsewhere. In the VSIS system, vault instrumentation including transducers, sensors, multiplexors, analog to digital converters, the communications network, and the SNM storage receptacles are collectively referred to as Canister Monitoring Units (CMUs). The CMU measures canister presence, bulge, temperature, and identification. Pressure data is recorded several times per second, while the remaining inventory information is queried at a rate of 600 items/minute. The storage pedestals are equipped with strain gauges which detect any significant increase in storage weight.

Although corrosion of plutonium metal is recognized, no special procedures are in place to remove corrosion products. The corrosion products formed are considered to not be a safety problem. In recent years, they have had no problems with containers storing metal.

The chemical stability of oxide produced from chemical processing is of concern. Hanford has specified that the volatile content must be 1% or less from loss on ignition at 450 °C for 2 hours. An additional limit is a maximum thermal decay of 15 watts. Plutonium oxide which has been properly stabilized is not considered to be a safety problem while in storage.

III.E.4. Savannah River Site

Handling of plutonium metal at the Savannah River Site (SRS) has involved primarily metal buttons (2 kg) and the scrap associated with metal production. The scrap was immediately recycled to the canyon dissolvers to avoid storage problems and also to recycle the plutonium. Storage and metal handling problems have not occurred at SRS.

Although corrosion of plutonium metal is recognized, there are no special procedures in place to remove corrosion products. The corrosion products are not considered a safety problem.

The chemical stability of oxide produced from chemical processing is of concern. An LOI test is used for assuring stability of stored oxide. At the SRS, there are a number of containers of plutonium residues which were received under the sponsorship of the Central Scrap Management Office (CSMO). These residues remain in the shipping containers in which they were received. SRS assumes that the materials are stable. The materials have not been characterized by SRS.

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III.E.5. Argonne National Laboratory

Argonne National Laboratory has not used plutonium of any magnitude at its facilities near Chicago, Illinois. Research and development involving plutonium have been limited to Argonne-West at the Idaho National Engineering Laboratory near Idaho Falls, Idaho. The Zero Power Physics Reactor (ZPPR) used encapsulated Pu-U-Mo alloy fuel plates which are now in storage. No difficulty in handling or storing this material has been encountered. Fuel cycle R&D with pyrochemical reprocessing of reactor fuel has utilized plutonium, but not in a form that was pyrophoric. Storage of metal and oxide has never been a source of problems.

Material is stored in an argon atmosphere containing < 50 ppm oxygen and < 50 ppm moisture. Inspections are driven by MC&A requirements. Oxide corrosion product from plutonium metal is not considered a problem. Powder may be removed from the metal by brushing, however, no stabilization is performed. The oxide is not considered a safety concern. Other oxides are stored dry, and no problems with pressurization have been encountered.

ANL-W uses some special design cans for storage of oxide and metal. They include the Gavin can for storage of metal and oxide, and the Duncan container used for storage of fuel. The Gavin can consists of two elastomer-sealed vessels nested one inside the other. Three bolts compress the lid against the ethylene propylene o-ring which provides a leak-tight seal. The Duncan container is essentially a closed pipe with a removable, compression seal. A special end-cap fitting allows leak checking of the container and associated welds.

III.F. Applicable DOE Orders.
III.F.1. DOE Order 5480.5

Current DOE requirements for the storage of plutonium are presented in DOE Order 5480.5, SAFETY OF NUCLEAR FACILITIES, 9-23-86. In paragraph 8, BASIC REQUIREMENTS, the requirements for all nuclear facilities and operations are specified as are the requirements for nuclear criticality safety in paragraphs 11 and 12.

Paragraph 13 covers the requirements for the safe storage of unirradiated fissionable materials. Theses requirements do not apply to:

- When materials are in-process as part of production, analytical and developmental procedures (including in-process storage), or transport operations.

- When an assembly cell is used for assembly and/or storage of weapons components made of these materials.

- When the number of packages of materials prepared for shipment is limited in accordance with the requirements of DOE 5480.3 (SAFETY REQUIREMENTS FOR THE PACKAGING AND TRANSPORTATION OF HAZARDOUS MATERIALS, HAZARDOUS SUBSTANCES AND HAZARDOUS WASTES).

- Radioactive waste storage or disposal facilities.
The operating requirements are given in subparagraph b. Operating Requirements for Storage and are summarized below:

(1) Non-essential combustible materials shall not be stored in the storage area.

(2) All unessential extraneous operations and materials (non-nuclear materials, equipment) shall be excluded from the storage area.

(3) Documented periodic inspections, tests and maintenance shall be performed on essential safety components (e.g. criticality control, fire detection, radiation monitoring, etc.,

(4) Limits for criticality safety shall be posted in conspicuous places near the storage area.

(5) Signs or other appropriate devices shall be used at strategic location in or around the area to provide instructions for:

(a) interpretation of, and response to alarms;
(b) evacuation routes; and,
(c) fighting fires.

(6) In conjunction with the site emergency plan, develop a fire fighting plan that includes use of emergency equipment and exercise through periodic drills.

(7) Provide equipment (auxiliary fire fighting, self-contained breathing apparatus, and protective clothing) for manual fire suppression.

(8) Excess fissionable materials shall not be construed to be "In-Process" to circumvent the requirements of this paragraph.

(9) Fissionable materials may be stored in shipping containers to enhance safety but not to negate the requirements of this paragraph.

(10) All materials shall be stored in racks or equivalent equipment (such as birdcages) capable of securely locating stored materials to prevent displacement, to assure spacing control, and to meet design for safety under operational and credible accident conditions. Floor storage within the storage facility will be permitted only where control of location and other safety requirements (equivalent to those of racks) are inherently provided by the individual containers and their restraints.

(11) All pyrophoric materials shall be put into a safe form prior to storage or stored in approved containers that will not permit spontaneous ignition or dispersal. Other dispersible materials must be stored in approved storage containers.

(12) Containers shall be marked or coded for type of material, amount, enrichment (or pertinent data on isotopic composition), and external radiation level. Must be securely closed.

(13) Container design shall be appropriate for form of material stored. Criteria for container integrity shall be developed for required safety analysis and verification of performance of container for the criteria by periodic inspection. Containers involving any significant gas buildup, automatic pressure relief or other venting should be designed to assure that no personnel exposure to any released toxic material will occur under normal storage conditions or, insofar as practical, under accident conditions. Such venting must not permit spread of contamination.
(14) Plutonium or U-233 bearing or contaminated material shall be packaged in a closed metal container. Combustibles within the container shall be minimized.

(15) Plutonium storage facilities and containers shall be monitored and checked periodically to assure continued integrity of containment. When required by form or hazard potential of the stored material, procedures shall be developed to detect contamination or loss of primary containment upon entering the plutonium storage facility.

(16) Plutonium containers in which gas buildup can occur shall be designed to prevent leakage of gas over the maximum storage period or vented to prevent an accumulation of explosive gases; however, such venting must not permit the spread of contamination. [Similar to (13)]

(17) Criteria, such as internal and external corrosion rate for determining the suitability of the plutonium container, shall be developed and set forth in writing. All containers shall be periodically inspected against the criteria. The time between inspections may vary depending upon the container quality and type. [Similar to (13)]

(18) Provisions shall be made in a plutonium storage facility to assure necessary and adequate heat removal for plutonium containers as established by the safety assessment.

Additional requirements are specified for multipurpose facilities (storage and processing) in section c. (Multipurpose Facility (Processing and Storage):

- definition of in-process material shall be established, approved, and maintained thereafter until approved changes are affected.

- shall designate which materials may be termed "in-process" and which may not.

- promptly placed materials in excess of in-process requirements into approved storage facilities.

III.F.2. DOE Order 5480.3

Requirements for packaging and transport of fissionable materials are covered in DOE Order 5480.3 - SAFETY REQUIREMENTS FOR THE PACKAGING AND TRANSPORT OF HAZARDOUS MATERIALS, HAZARDOUS SUBSTANCES AND HAZARDOUS WASTES, 7-9-85.

Fissile materials are defined in paragraph 5, DEFINITIONS, as uranium-233, uranium-235, plutonium-238, plutonium-239, plutonium-241, neptunium-237, and curium-244. Fissile material packages for shipping are divided into three classes:

Fissile Class I. Packages that may be transported in unlimited numbers and in any arrangement and that require no nuclear criticality safety controls during transportation.

Fissile Class II. Packages that may be transported in any arrangement but in numbers that do not exceed a transport index of 50. (Transport index is defined in subparagraph o. as "The number placed upon a package to designate the degree of control to be exercised by the carrier during transport. The transport index of Fissile Class II packages is calculated by dividing the number 50 by the number of such Fissile Class II packages that may be transported together as determined under the limitations of 10 CFR 71".)
Shipments of packages that do not meet the requirements for Fissile Class I or II and that are controlled in transportation by special arrangements between the shipper and the carrier to provide criticality safety.

Most of the stored materials considered in this report fall in Fissile Class III.

Requirements are specified in paragraph 7, REQUIREMENTS. Requirements for plutonium are covered in subparagraph b, Special Packaging Requirements for Plutonium and Plutonium Bearing Waste. The first 2 items concern certification for transport and packages. Item (3) states "Plutonium package requirements for any surface mode of transportation".

(a) Plutonium in excess of 20 Curies per package must be shipped as a solid.

(b) Plutonium in excess of 20 Curies per package must be packaged in a separate inner container placed within outer packaging that meets the requirements of a Type B package for material in normal form. In addition, the following test must be performed on the package design:

1. If the entire package is subjected to the design tests specified in paragraph 11, "Normal Conditions of Transport," the separate inner container must restrict the loss of plutonium to no more than $10^{-6} \text{A}_2$ per hour.

2. If the entire package is subjected to the design tests specified in paragraph 12, "Hypothetical Accident Conditions," the separate inner container must restrict the loss of plutonium to not more than the $\text{A}_2$ quantity in 1 week.

The $\text{A}_1$ and $\text{A}_2$ values for plutonium isotopes are excerpted from Table 2 (IAEA, 1990) below:

<table>
<thead>
<tr>
<th>Symbol of radionuclide</th>
<th>Element number and atomic number</th>
<th>$A_1$ (TBq)</th>
<th>$A_1$ (Ci) (approx.)</th>
<th>$A_2$ (TBq)</th>
<th>$A_2$ (Ci) (approx.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{239}\text{Pu}$</td>
<td>Plutonium (94)</td>
<td>7</td>
<td>$10^2$</td>
<td>$7 \times 10^{-4}$</td>
<td>$1 \times 10^{-2}$</td>
</tr>
<tr>
<td>$^{237}\text{Pu}$</td>
<td></td>
<td>20</td>
<td>500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{238}\text{Pu}$</td>
<td></td>
<td>2</td>
<td>50</td>
<td>$2 \times 10^{-4}$</td>
<td>$5 \times 10^{-3}$</td>
</tr>
<tr>
<td>$^{239}\text{Pu}$</td>
<td></td>
<td>2</td>
<td>50</td>
<td>$2 \times 10^{-4}$</td>
<td>$5 \times 10^{-3}$</td>
</tr>
<tr>
<td>$^{240}\text{Pu}$</td>
<td></td>
<td>2</td>
<td>50</td>
<td>$2 \times 10^{-4}$</td>
<td>$5 \times 10^{-3}$</td>
</tr>
<tr>
<td>$^{241}\text{Pu}$</td>
<td></td>
<td>40</td>
<td>1,000</td>
<td>$1 \times 10^{-2}$</td>
<td>$2 \times 10^{-1}$</td>
</tr>
<tr>
<td>$^{242}\text{Pu}$</td>
<td></td>
<td>2</td>
<td>50</td>
<td>$2 \times 10^{-4}$</td>
<td>$5 \times 10^{-3}$</td>
</tr>
<tr>
<td>$^{243}\text{Pu}$</td>
<td></td>
<td>0.3</td>
<td>8</td>
<td>$2 \times 10^{-4}$</td>
<td>$5 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Paragraph 7b(4) states "Solid plutonium in excess of 20 Curies per package in the following forms is not subject to the requirements of paragraph 7b(3). Item (b) is Metal or metal alloy.

Other relevant paragraph for outer packages are:
Paragraph 8. PACKAGE STANDARDS.
Paragraph 11. NORMAL CONDITIONS OF TRANSPORT
Paragraph 12. HYPOTHETICAL ACCIDENT CONDITIONS
IV. Advanced Storage Concepts

IV.A. Containers

A definite improvement in the use of current slip-lid/food pack cans to store plutonium metal could be obtained by eliminating air from the package atmosphere. This could be accomplished by packaging the metal in helium followed by routine leak testing before and during storage. A true hermetic seal, either in a metal gasket-sealed vessel or an all-welded vessel would provide extra assurance in packaging. Additional confidence is gained from the fact metal has been stored in sealed pits for more than 30 years in the stockpile without incident. Optimally, the gasket-sealed vessel would be QA-certified and leak-tested prior to use, whereas the all-welded vessels would be leak-test certified after final sealing. Also, the optimum atmosphere in the storage container should be a mixture of helium with a mildly oxidizing gas, but dry or any inert fill would be suitable if hermetic sealing is assured.

LANL is currently developing a hermetically sealed package for retrievable storage of metal which allows storage in a dry inert atmosphere and prevents corrosion for both short duration and long periods of time (10 years or more). Figures 3 and 4 show the concepts for these containers. The principal difference between these concepts is the exclusion of organic bagging from the long-term container. Implementation of this concept (figure 4) will require development of specialized packaging and handling procedures which might include bagless transfer or decontamination techniques.

As with metal, if the use of a hermetic container such as a fully welded vessel or a metal gasket-sealed container is contemplated for storage of oxide, consideration must be given to quantifying the amount of residual water left on the oxide, (e.g. certified LOI evaluations) so that the container is able to accommodate the maximum possible pressure accumulation due to desorption or radiolysis. Alternative approaches for storing uncharacterized oxide include the use of sealed storage cans with metal frit filters which would allow for atmospheric pressure equilibration. Such frits have been used for prevention of contamination migration in various weapons program applications in the past. Since substoichiometric oxide or unreacted metal may be present in uncharacterized oxide, thermal stabilization is recommended to ensure that the material is completely converted to the dioxide. Conversions of this type may be accomplished by roasting at modest temperatures (300 to 500 °C) in air. If other plutonium compounds (e.g., nitrates or sulfates) are present, higher temperatures may be necessary.

LANL is also developing new containers for the storage of oxide. For stabilized, unqualified oxide, they are developing a vented container to allow for release of gases from radiolytic decomposition. Figure 5 shows the concept for this container. For stabilized, qualified oxide, LANL is developing a sealed container in which the oxide is stored in an inert atmosphere. Figure 6 shows a concept for this vessel. As with the long-term metal storage container, bagless transfer or other specialized handling will be required to implement this concept.

Additional improvements allow for improved labeling of vault stored items, including internal packaging details, and appropriately integrated surveillance and inspections to satisfy not only MC&A, but also container integrity and contamination detection. For long-term (> 5 yrs.) storage scenarios, only fully stabilized and loss-on-ignition qualified oxide should be stored and use of hermetically sealed containers is recommended. At present, most contractors storing metal and oxide rely on routine MC&A-based inspection and audits to provide integrity assurance of vault items. In addition, Zone 2 type rooms such as storage vaults receive routine health physics surveys for contaminations. In combination, these provide a reasonable minimum surveillance activity. Balanced MC&A surveillance, including weight measurements, automated room contamination monitoring, and random visual and perhaps radiographic package inspections are considered the optimum oversight of these items.
All containers 6" maximum diameter, 12" maximum height, packaged in inert atmosphere.

Figure 3. Plutonium metal storage container, short-term duration.

Figure 4. Plutonium metal storage container, intermediate to long-term duration.

Figure 5. Storage container for stabilized, unqualified oxide, short-term duration.

Figure 6. Storage container for qualified oxide, short-term, intermediate, and long-term duration.
The quantity of material stored in each individual container will be determined by criticality safety concerns. Historically, these limits have varied from an extremely conservative 3 kilograms to as much as 6 kilograms of Pu metal per vessel. Similar quantities of oxide will likely be permitted per container. Recent limits near 4.5 kilograms per container have been established.

IV.B. Material Form

In the absence of a facility fire hazard, the dominant hazard from storage of plutonium arises from the dispersibility of the oxide powder. Some concepts are discussed below for reducing this potential hazard. They include converting the oxide to a stable physical form with low dispersibility and preventing its generation from the metal. The benefits of these concepts would need to be weighed against the costs of implementing them, including the potentially large doses to workers and large amounts of generated wastes resulting from processing to various forms.

IV.B.1. Pelletizing

Plutonium oxide can be converted into a mechanically stable form with reduced dispersibility by sintering it into a ceramic form (e.g., pellets) under pressure. Oxide powder is vacuum degassed, milled or ground to the appropriate particle size, placed in a die, and simultaneously compressed and heated at 50-60 kpsi at 1,500 °C for an appropriate period of time. The resulting pellets are packaged in a hermetically sealed container under an atmosphere of inert gas or dry air.

Storage of sintered pellets in hermetically sealed containers would ensure their long-term stability. However, data for 238Pu oxide indicate that degradation of the pellets may occur with time as a result of helium production from alpha decay. The 238Pu oxide pellets were found to swell and become somewhat friable and, under some circumstances, were highly strained. Though the helium production rate in weapons grade plutonium is lower than that for 238Pu by a factor of nearly 300 because of the difference in decay rates, the significance of this effect to long-term storage of the sintered material would need to be assessed.

Sintered pellets may fragment under crush-impact forces when new and may become more susceptible to fragmentation with age. Accordingly, they might require protection from forces present during collapse of a storage facility. Issues of through-put, waste generation and personnel exposure to radiation must be considered and weighed against the advantage of pelletizing. Pressing is a time-consuming operation and pelletizing of a large quantity of oxide may not be achievable on a reasonable time scale without investment in facilities and equipment. The existing capability for converting plutonium oxide to sintered pellets at DOE facilities is described along with process conditions and equipment requirements in Appendix B.

IV.B.2. Sintering

As discussed in Section II.G, calcining of oxide powder at a temperature of 950-1,000 °C for one hour affords certain advantages for mitigating the dispersal risk. In addition to increasing the effective dimension of oxide particles, thermal processing of this type simultaneously removes adsorbates. As such, the risk and degree of potential pressurization is reduced and the


qualifications for certification are met. Equipment and basic techniques currently used for calcination at lower temperatures can normally be used up to 1100-1200 °C and could be readily implemented at most facilities with minimal development effort.

IV.B.3. Reduction of Oxide to Metal

Plutonium oxide can also be converted to a mechanically stable form with reduced dispersibility by reduction to the metal. The conditions and equipment for direct oxide reduction (DOR) are widely available and capable of handling necessary throughput.

In comparison to normal process oxide, the dispersibility risk is low if metal is exposed to the atmosphere by a breach of containment or if the incident involves both a breach and a fire. Experience with typical (4 kg, 7 cm diameter) castings of unalloyed metal shows that less than 100 g of oxide forms over a period of one year. The maximum oxidation rate calculated on the basis of this observation is 1x10⁻⁴ g PuO₂/g Pu day. At this rate, the amount of dispersible oxide available after exposure of a 4-kilogram casting to air for ten days is a thousand-fold less than for process oxide and is equal to the dispersible quantity formed if the casting had burned immediately in a fire.

The reduction in dispersibility risk by formation of metal is substantial, but the disadvantages of worker radiation exposure and waste generation during processing must also be considered.

IV.B.4. Alloying or Coating of Plutonium Metal to Reduce Corrosion

Addition of certain elements to metallic plutonium can alter the room-temperature corrosion rate. Gallium-containing alloys show a reduced corrosion rate at temperatures below 250 °C (Section II.A.). However, the corrosion rates of alloyed and unalloyed material converge at elevated temperatures. Addition of other elements can increase the plutonium ignition temperature slightly. For example, plutonium-aluminum alloys show an ignition temperature in the range of 575-600 °C, compared to 475-500 °C for unalloyed material.⁴⁶ The advantages of alloying plutonium to either slightly decrease the low-temperature corrosion behavior or to slightly increase the ignition temperature must be carefully considered. Other methods may be available to mitigate corrosion problems such as storing plutonium in certified, sealed containers.

Coating plutonium with various materials has been investigated to mitigate dispersal and corrosion hazards. If great care is taken, pinhole-free nickel coatings obtained by chemical vapor deposition of nickel tetracarbonyl can be prepared. Attempts to prepare similar, defect-free coatings with other elements have been largely unsuccessful. Further, routine preparation of acceptable nickel coatings has thus far proven difficult. There is no current capability to produce coatings of necessary quality within the DOE complex.

IV.C. Complex-21 Criteria

Efforts under way to evaluate storage needs for Complex-21 storage of plutonium metal and oxide are systems-level oriented. Material characterization, qualification, containerization, facility superstructure, and infrastructure considerations are integrated. The storage facility, to be co-located with the plutonium manufacturing and processing facility, is conceptually designed to accommodate items which would be remotely placed and accessed by means of unmanned

vehicles. This building would accept plutonium in the form of pits, metal, oxide, and stable compounds. The Complex-21 facility is intended to store plutonium forms in a stable manner for up to 50 years. Interim storage by contractors must address periods of at least 7 to 15 years, the time-frame between now and when Complex-21 is prepared to accept these materials.

Currently, the plutonium storage facility is expected to become operational in 2001. The storage facility is envisioned to initially contain 40,000 storage positions, with a capability to receive 6,000 pits and 1,000 other containers per year. The initial shipping capability is estimated to be 1,000 containers per year with the provision to convert receiving to shipping capacity at a later date.

Requirements for Complex-21 structure, containment, material, packaging, and automation are summarized below.

General requirements:

- Storage container is designed for dual use as a primary containment vessel for both shipping and long-term storage.

Structural requirements:

- Vessel meets the requirements of the ASME Boiler and Pressure Vessel Code as specified by UCID-21218, NUREG/CR-3019 and NUREG/CR-3854
- Vessel capable of opening without damage to or expelling of inner contents.
- Vessel capable of welding closure without damage to inner contents.
- Vessel capable of being reused after being opened one time.
- Resealed vessel identical in size to original vessel within original fabrication tolerances.
- Minimum design life of 50 years with no routine maintenance.
- Vessel fabricated of material to provide a corrosion resistant containment boundary.
- Vessel meets storage requirements after the following normal occurrences:
  - 4' drop
  - 2' crush with primary containment vessels interacting (heaviest vessel interaction)
  - vehicle vibration
  - handling shock
  - compression weight of 5 primary containment vessels
- Vessel remains leak tight as defined by ANSI N14.5 after the following one time occurrences:
  - 30' free drop (maximum vault ceiling height)
  - 30' crush with primary containment vessels interacting (heaviest vessel interaction)
  - vehicle crash as defined in safety analysis report (SARP)
  - puncture as described in safety analysis report (SARP)
Containment Requirements:

- Provisions provided for purge and backfill.
- Vessel can be resealed to original integrity after gas sampling operation is complete.
- Nondestructive examination of resealed vessel is possible to determine integrity of resealed vessel.
- Sealed vessel tests leak tight as defined by ANSI N14.5.

Design Temperatures and Pressures:

- Oxide/metal container currently designed for 1,000 psig internal at 204 °C for long-term storage. An internal design pressure of 50 psig at 204 °C is to be used for testing and certification as a primary containment vessel for shipping.
- Pit container designed for 100 psig internal pressure at 204 °C for long-term storage. An internal design pressure of 15 psig at 204 °C is to be used for testing and certification as a primary containment vessel for shipping.
- Oxide/metal container and pit container designed for 25 psig external pressure for shipping and storage.

Dimensional Requirements:

- The pit container meets the following dimensional requirements:
  - Minimum internal height of 18.5"
  - Maximum external height of 23" for assembled storage package
  - Minimum I.D. of 13"

- The oxide/metal container meets the following dimensional requirements (based on single containment):
  - Maximum I.D. of 5-1/4"
  - Maximum O.D. of 6"
  - Maximum external height of 17" for vessel as a shipping container
  - Maximum external height of 23" for assembled storage package

- All exterior surfaces of the vessel shall be equal to or better than a number 4 mill finish.

Packing Requirements:

- All packing materials non combustible per NFPA.
- All packing materials non organic.
- Steady state storage temperature of pit surface not to exceed 60 °C.
- Vessel loaded with an internal atmosphere to be specified.
- Oxide/metal container capable of holding 4.5 kg of Pu as oxide with 2.5 liters of free volume. Free volume includes space interior to oxide container.
- Vessel meets requirements of 10 CFR 71, 49 CFR 173, and DOE 5480.3.
- Vessel provided with all welded closures and ports.

Automation Requirements:

- Container design compatible with automatic handling equipment.
- Bar code for identification and accountability placed on container for remote handling by robot or automatic guided vehicle.
- Bar code permanent (i.e., life expectancy of 50 years).
- Surface of container uniform in color except for vision targets.
- Vision targets have a permanent high contrast color relative to container.
- Accessibility provided for in situ material control and accountability (MC&A) measurements.
- Self locating interfaces for mating parts.
- Minimize alignment and orientation constraints for assembly interfaces.

As of this time, $^{238}\text{Pu}$ will be excluded from the storage facility. The presence of $^{238}\text{Pu}$ would require water in the vault area. However, water is currently excluded because of criticality safety concerns.

Because of the vault design concept, all primary containers will qualify for dual use in storage and shipping, and will provide for direct NDA measurements. This degree of specialization will almost certainly mean that materials and containers currently existing in the complex will not meet the acceptance criteria and will likely require repackaging before shipment to the Complex-21 facility. This requirement could result in costly duplication of extensive repackaging facilities at each of the contractor sites. It may be more cost effective to establish the final repackaging capability at the ultimate storage site and only require individual contractors to package to the minimum standards required for shipment to the Complex 21 facility.

The present concept requires that materials be stabilized, characterized, and certified prior to acceptance at the storage facility, and oxide/metal be packaged in an inner container devoid of plastics, elastomers, tape, etc., and hermetically sealed in a primary containment vessel by the shipper. The packaging will be suitable for direct vault-location storage of the primary container and will fully meet pressure vessel design requirements per American Society of Mechanical Engineers Boiler & Pressure Vessel Code, Sec. III.
V. Hazard Analysis

A comprehensive hazard analysis is essential to ensure that all significant safety issues are addressed. Indeed, recent workshops sponsored by DP and this report itself are intended to identify any potential safety issues which are not addressed in DOE DP storage operations. This section presents a brief hazards analysis that attempts to bound the risks from practices used throughout the DOE weapons complex. In general, conclusions are presented in this section regarding the severity and probability of various hazards while accompanying relevant calculations may be found in appendices to this report. Much of the material contained in this chapter expands upon information presented in Section II of this report. This duplication arises from the desire to emphasize those material properties of Pu and PuO₂ which are important in a credible hazards analysis.

V.A. Hazard Identification

The scope of this analysis is limited to storage of plutonium metal and plutonium oxide. Each of these materials falls into two general categories. For metals, a basic distinction is whether the material is alloyed or not. Certain alloys (such as Pu-rich gallium material) exhibit markedly different corrosion behavior at room temperature when compared to unalloyed, α-phase material (though corrosion of all common alloys converges to the same rate at elevated temperatures). As such, the chemical reactivity of metallic forms is dependent on chemical composition. However, most other relevant physical properties are similar for metallic forms of plutonium, including densities, surface areas, melting points, etc.

For oxides, the most basic distinction is whether the oxide is relatively free of adsorbed species or has adsorbates that might radiolytically, chemically, or thermally decompose and thus generate reactive, corrosive, or pressure-generating species. In addition, the composition of the oxide may present a hazard if substoichiometric material or unreacted anions (nitrate, oxalate, etc.) are present. The presence of such material is largely dependent on the process and storage history of the oxide. As outlined in Section II, certain physical properties of plutonium oxide are highly variable and depend on the particular conditions in which it was made. The surface area and particle size distribution of oxide (physical properties which directly influence the radiolytic reactivity and dispersibility of the material) are strongly dependent on the formation technique. In general, two categories of oxide are cited: 1) "certified" or "qualified" oxide in which the recent process condition and storage history are known or loss-on-ignition standards satisfied and the presence of foreign contaminants (adsorbates, anions) has been minimized and quantified; and 2) "uncharacterized" oxide in which the above conditions are not met. The majority of oxide possessed by the complex is uncharacterized. Conversion of material to "certified" oxide frequently involves a calcination process in which material is exposed to an oxidizing environment at elevated temperatures (e.g., bakeout at 1,000 °C for 1 hour in air, see Section II).

The spectrum of storage conditions and the severity of the storage environment can be characterized by three factors: (1) the material form, (2) the preparation and certification of the form for storage, and (3) the storage container, packaging, and environment.

For metal, the primary concern centers on corrosion reactions with gases such as oxygen and hydrogen. Potential hazards from such corrosion include ignition of the material in an oxidizing environment, formation of dispersible and/or pyrophoric products, and mechanical breach of a storage container as a result of volumetric expansion during reaction. Note that gas-phase pressurization of the storage environment is not a credible hazard since the stored metal itself serves to getter any potential pressurizing species. An additional potential concern in metal storage involves the reaction of molten plutonium with the storage container itself. The products of the reaction between Pu and container materials such as Fe or Ni are low melting compounds (e.g.,
PuFe) or eutectics. However, the formation of these compounds appears to be controlled by other factors such as the reduced temperature at the molten Pu/metal interface or the absence of other necessary elements which prevents eutectic formation. Further, at lower temperatures (and during ambient storage), these eutectic formation reactions are not considered a hazard since the rates are extremely slow as a consequence of the limited solid/solid diffusion between the reacting materials. As such, the possibility of container breach due to eutectic formation is considered negligible:

For storage of oxide, corrosion is a lesser concern; but radiolysis, chemical reaction, or desorption of adsorbates (e.g., water) and radiolytic decay of organic materials (e.g., plastic bagging, sealing tape, or elastomer O-rings) could lead to pressurization and rupture of the storage container. Further, the products of these reactions may be corrosive to the storage container itself which could lead to a loss of container integrity. Release of oxide to the ambient environment is of particular concern because process oxides (e.g., those formed by calcination of oxalates) are extremely fine powders with a high propensity for dispersal.

Certain hazards are common to both storage forms. For example, loss of containment due to mechanical breach (as a result of a fall, earthquake, tornado, etc.) is nearly independent of the storage form. However, subsequent dispersion of material is strongly dependent on characteristics such as the particle size distribution. Other hazards include loss of containment and dispersal of material in a fire, the presence of ionizing radiation and the associated exposure of personnel, the remote possibility but serious consequence of a criticality incident, and numerous accident scenarios which result in plutonium dispersal. In each case (except for personnel exposure), the ultimate concern is the potential release of nuclear material into the environment. All of the specifically identified phenomena above are considered hazards because of the potential for plutonium release.

The sections that follow present a semi-quantitative analysis of numerous hazards identified in plutonium storage. An initial overview of fundamental hazards associated with material form is followed by a definition of material at risk (MAR) and a summary of plutonium dispersal hazard from several possible abnormal events.

V.B. Fundamental Hazards Associated with Material Form
V.B.1. Chemical Reactivity

Chemical reactivity is often the preeminent (and only) issue considered in evaluating the suitability of a material for storage. An assessment of reactivity for a material must consider both thermodynamic and kinetic concerns in the specific storage environment. Plutonium oxide is the most stable form of plutonium in air and other oxygen-rich media. Metal and all other plutonium-containing compounds except fluorides (PuF₃, PuF₄ and PuF₆) are unstable relative to oxide in air. Even under stringently inert conditions, the surfaces of all candidate materials are covered by oxide films. Although PuO₂ is more stable than other potential storage forms and is considered to be the equilibrium oxide phase in air, recent results for the reaction of water vapor indicate the presence of a thermodynamically-favored, higher valent oxide, a mixed-valent compound with the Pu(IV)₄Pu(VI)O₁₁ composition (PuO₂₁).  


Oxidation reactions of candidate storage forms exhibit a broad spectrum of kinetic behavior. Plutonium metal > 0.5 mm thick reacts slowly with oxygen and is routinely handled in air without risk of rapid reaction. Spontaneous ignition is only observed if the metal is in a finely divided (<0.2 mm thick) state and if the temperature also exceeds 150 °C. In comparison, plutonium hydride is pyrophoric and reacts violently upon exposure to air at room temperature. Nitride and carbide also spontaneously react with air and moisture. Chemical reactivities of alloys are difficult to evaluate because information on most alloy oxidation kinetics is unknown. A particularly important reaction of oxide and oxide-coated materials is the rapid and tenacious sorption of water from the atmosphere; several monolayers of water remain irreversibly bound at 100 °C in high vacuum.

Several reactions of plutonium and its compounds are of interest because of their potential safety impact. Loss of containment may occur with oxide powders during a fire or extended storage due to generation of high pressures from adsorbed species. These and other pressurization processes are discussed in Section V.B.4. Plutonium metal provides a measure of inherent protection from pressurization because of its ability to getter reactive surface species without forming secondary gases such as H₂, N₂ or C₂H₂.

V.B.2. Radiolytic Reactivity

Radioactive decay of plutonium alters the chemical behavior and makeup of molecular and organic compounds in a storage vessel and may alter the stored material or lead to loss of containment. Radiolytic chemistry is influenced by particle dimension as well as isotopic composition and age of the plutonium. Powdered samples emit a larger fraction of the 5.1 Mev alpha decay particles than do bulk forms. As such, radiolytic reactivity from ²³⁹Pu is enhanced in finely divided forms.

compared to bulk samples. Because the high surface area of finely divided plutonium oxide promotes adsorption of large amounts of water, organic molecules, etc., alpha particles from radioactive decay have ample opportunity to interact with adsorbed species in the storage environment. The presence of adsorbates is not limited to fine powders: adsorption is observed for all candidate materials because of ready formation of surface oxide. However, the quantity of adsorbate on massive samples such as alloys or metal is small compared to PuO$_2$ and other finely divided forms. Dioxide products with specific surface areas in excess of 50 m$^2$/g are common.$^{59,60}$ When exposed to ambient glove box atmosphere for several hours, the mass of a typical oxide sample may increase by more than 1% due to water adsorption.$^{61}$

Interaction of alpha particles with adsorbed species, organic materials (e.g., plastics), or gases in contact with the nuclear material leads to cleavage of chemical bonds and formation of gaseous products.$^{62,63,64}$ Low-molecular-weight species (e.g. O$_2$ and N$_2$) primarily dissociate to form gaseous products (e.g., NO$_2$), while heavier molecules tend to polymerize. Radiolysis of water generates hydrogen and oxygen;$^{65,66}$ alpha interaction with air produces large percentages of dinitrogen monoxide (N$_2$O) and nitrogen dioxide (NO$_2$).$^{67}$ Products formed by radiolysis of plastics and other organic materials depend on the chemical composition of the source materials and typically include hydrogen.$^{68}$ Radiolytic decomposition of polyvinyl chloride (PVC) apparently forms gaseous hydrogen chloride (HCl).


Radiolytic decomposition of molecular and organic species in a storage vessel may have severe consequences. Gaseous radiolysis products will either react with the stored material and/or the storage vessel or will lead to pressurization. The risks associated with low-surface-area samples of metal or alloy are different from those encountered with finely-divided compounds. The low surface area of massive samples limits the quantity of adsorbate in the storage vessel. Further, gettering of hydrogen by plutonium metal reduces risk of container pressurization and container corrosion (though pyrophoric hydride is produced). Plutonium readily reacts with HCl and NO₂ and thus getters these materials as well. Non-metallic powders such as oxide nearly always carry large amounts of adsorbates. These materials typically cannot react with radiolytic gases (e.g., H₂) or exchange one gas for another (e.g., reaction of PuN with O₂ yielding N₂). Mineral acids formed by radiolytic generation of HCl or NO₂ in the presence of moisture may result in container corrosion.

In sum, the magnitude of radiolytic effects is influenced by two important properties of the material to be stored: the specific surface area (and the associated quantity of adsorbates), and the ability of the material to getter radiolytic products. In both cases, plutonium metal and alloys are expected to have considerably fewer problems with radiolytic phenomena than more finely divided Pu forms.

V.B.3. Helium Release.

Helium formed by alpha decay of ²³⁹Pu and other isotopes provides an additional source for pressure generation during storage. Although the process is slow (\( t_{1/2} = 2.4 \times 10^4 \) years), the quantity of helium may become significant if the storage period is long and the fraction of helium released by the solid phase is large. The release behavior of massive metal differs from that of oxide because the diffusion rate of helium in metal is relatively slow, and hence, helium is only able to escape from the near-surface region of the solid. By contrast, diffusion of helium in oxide is comparatively rapid and the small particle dimensions allow ready release of all helium created by alpha decay. Experimental data for both ²³⁶Pu and ²³⁹Pu show that helium is readily released from oxide but is retained as microscopic bubbles at grain boundaries in Pu metal.

Calculations based on the alpha decay rate and helium release kinetics of metal and oxide show that helium pressures slightly greater than one atmosphere are anticipated for oxide in a typical storage configuration after 100 years. By comparison, the pressure rise expected for storage of an equivalent amount of metal is approximately 0.001 atmosphere. Although the helium release behavior of massive alloys and non-metallic powders is expected to parallel those of the metal and oxide, experimental data are not available.

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The potential for pressurization of storage containers is a serious concern. As outlined in preceding sections, processes such as chemical reaction, radiolytic decomposition, and alpha decay may produce substantial gas pressure in a container. Concern is greatest for storage of oxide and other finely-divided forms because of their high surface areas and inability to getter gaseous species. Although the rate is likely slow at the storage temperature, chemical reaction of PuO₂ with adsorbed water (to form higher-stoichiometry oxides) also produces hydrogen. For example, an H₂ pressure that might be generated in a typical oxide storage configuration (3 kg of PuO₂ with a specific surface area of 5 m²/g and a single monolayer of adsorbed water in a vessel with 1.5 liter of free volume) is 3.7 atmospheres at 25 °C. Significant, larger pressures of O₂/H₂ mixtures are produced if H₂O radiolysis is the dominant process. As with helium generation, these reactions become increasingly important with time. Another pressure generation process, thermal desorption of water at high temperatures created by a fire or self-heating, is capable of rapidly generating excessively high pressures. This specific mechanism has caused several notable failures of plutonium storage containers.

Risk of pressurization also exists for storage of plutonium metal and alloys. Even an extremely small leak in a container can lead to extensive oxidation of stored metal. This process is enhanced by fluctuations in atmospheric pressure. Oxidation of metal or alloys leads to volumetric expansion of the material. The forces associated with this expansion could (and have) ruptured a storage container. A recent failure of a storage container holding a kilogram-size ingot of Pu metal has been attributed to this mechanism.

Appendix C presents calculations which quantify the degree of pressurization in the storage of qualified and uncharacterized material. These calculations are worst-case estimates which should bound the pressurization which might occur.


Release of plutonium-containing materials to the environment is a serious potential hazard. The two most likely situations that may lead to release are mechanical breach of a storage container and exposure to a fire. These and other scenarios are addressed in more detail in subsequent parts of this section. Once plutonium has been released to the environment, further spread of material is of prime concern. As such, the dispersal risks associated with various forms are directly related to the particle size and form of the material.


76J.Lowe, private communication, Atomic Weapons Establishment, Aldermaston, UK (December 17, 1992).


The risk associated with mechanical dispersal is different for storage of massive plutonium metal or alloy than for storage of finely-divided compounds. Although some oxide will likely be mechanically dislodged from the surface of massive samples, the fraction of plutonium that might be dispersed is limited to 0.01 mass% by the thickness of a typical oxide layer. Further extrapolation of rate data below 150 °C shows that oxidation of the metal after exposure to air at ambient temperature is slow and will not contribute significantly to oxide dispersal even after several days.\textsuperscript{81}

In contrast to metal or alloys, relatively large fractions of finely-divided forms are in the dispersible range.\textsuperscript{82} Whereas 20-25 mass% of the PuO\textsubscript{2} formed by oxidation of the hydride consists of particles with dimensions less than 10 μm,\textsuperscript{83} 100 mass% of the oxide formed by pyrolysis of precipitates (e.g., hydrated plutonium oxalate) from aqueous processing is in the potentially dispersible range.\textsuperscript{84}

Upon release of plutonium metal to the ambient environment, the potential for oxidation and subsequent dispersal by aerosolization exists. The oxidation rate of Pu in air at 500 °C and above is modest and constant (0.2 g PuO\textsubscript{2}/cm\textsuperscript{2} of metal surface).\textsuperscript{85} The oxide product formed at these temperatures is relatively coarse with less than 0.1 mass% in the dispersible range.\textsuperscript{86}

The possibility of container rupture exists for other powdered forms because of increased gas evolution and pressure and decreased container strength at high temperatures. The pressure is a combined effect arising from chemical reaction, radiolytic decomposition, helium release, thermal desorption, and thermal expansion. Rupture is expected to result in the dispersal of a larger fraction of powdered forms than would be released from massive metal or alloys. On the basis of relative particle size distributions, the quantity of plutonium-containing material released to the environment is 1,000 to 10,000 times greater for process oxide than for massive metal. The possibility of pressurization could also be reduced for powdered materials by certification to verify that significant quantities of adsorbates are not present.\textsuperscript{87}

\textsuperscript{79}J.L. Stakebake and L.M. Steward, J. Electro. Soc. 119 (1972) 730.


\textsuperscript{82}J.L. Stakebake and M.R. Dringman, J. Nucl. Mat. 23 (1967) 349.


\textsuperscript{84}J.D. Moseley and R.O. Wing, "Properties of Plutonium Dioxide," 1965, ibid.


Use of vented containers for powder storage must be evaluated in light of reduced structural integrity of the container, masking of pores by powder intrusion, and the consequences of radiolysis-enhanced corrosion of the nuclear material or the container. Formation of nitrogen oxides from air in a radiolytic environment produces nitric acid if water is also present. When used in conjunction with a filter, rupture disks which function only on pressurization may alleviate the risk of catastrophic container failure during fires or other accidents while preventing exposure of the nuclear material to external ambient storage environments under normal conditions.

V.B.6. Other Environmental, Safety, and Health Issues.

Other ES&H hazards related to storage include nuclear criticality safety, radiation exposure to personnel, and contamination control. Criticality safety procedures are well established for all candidate storage forms. Primary controls include limiting the quantity of stored material and careful inventory and control of physical storage and locations. As an added precaution, storage of plutonium metal and alloys as castings with critically-safe geometries (e.g., thin-walled rings) can reduce the possibility of a criticality incident by deliberate or accidental violation of safety procedures. Criticality safety for finely-divided forms must rely on administrative controls that establish handling procedures and mass limits.

Procedures for limiting worker radiation exposure and controlling spread of radioactive contamination have been well established in the last 40 years. Faust, et al, provide useful guidance on good health physics practices for plutonium operations. The ingrowth of $^{241}\text{Am}$ in plutonium that contains a few weight percent $^{241}\text{Pu}$ is of particular significance. $^{241}\text{Am}$ emits a large number of 60 Kev photons that can be a significant source of exposure to the hands and forearms in glove box operations. Such plutonium becomes more difficult to handle with time and, at some point, may require remote handling. The corollary of this is that any repackaging should be done while the available equipment can still provide adequate protection, and the need for future handling should be minimized.

Increasingly more stringent requirements for control of occupational exposure and contamination are anticipated (e.g., the DOE RadCon Manual) and hence, consideration of advanced material handling technologies which reduce these exposures and risks is worthwhile. The advantage of automation in distancing operators from nuclear material and reducing the likelihood of operator error is widely recognized. Castings of metal or alloy are amenable to automated handling as are powdered materials. Procedures differ for handling finely-divided forms and in some instances are more complex than for transfer of discrete metal components. However, care must be taken in automation to ensure high reliability of robotic components because frequent breakdowns in automated equipment would only transfer radiation exposure from operating to maintenance personnel.

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V.C. Material at Risk

The fundamental hazards outlined above allow semi-quantitative calculation of the potential for material dispersal. As a basis for these calculations, mass limits are identified for hazardous material in Table 3.

Table 3. Definition of mass limits for material at risk.

<table>
<thead>
<tr>
<th>Type of Material</th>
<th>MAR Range</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal</td>
<td>1 - 10 kg</td>
<td>Physical size of components generated or handled. Typically components with mass &gt; 2 kg will be alloyed material as alloying occurs during generation from smaller components.</td>
</tr>
<tr>
<td>Oxide</td>
<td>0.1 - 3 kg</td>
<td>Upper range based on common use of generic criticality limits for boxes based on metals. Lower range based on collection of oxide from metals.</td>
</tr>
<tr>
<td>Impure oxide</td>
<td>1 - 500 g</td>
<td>Range based on plutonium component of contaminated oxides (i.e. mixed with other material) being a small weight % of the total material.</td>
</tr>
</tbody>
</table>

V.D. Fires

Detailed consideration is given to this issue because of the large quantity of bulk plutonium stored throughout the DOE weapons complex. Dispersal of material as a result of container breach during a fire is covered in section V.E. This section focuses on reaction and pressurization of metal and oxide in storage during a fire. Actual fires involved more complicated scenarios and did not involve materials discussed here.

V.D.1. Metals

Two cases are examined for metals. The first is a theoretical model of a bulk piece of plutonium metal contained in a typical storage can. A generic quantity of plutonium hydride or plutonium metal fines is assumed to use up all available oxygen in the storage can in an instantaneous reaction. The second is a model based on instantaneous reaction of bounding corrosion values estimated at Rocky Flats. It should be emphasized that instantaneous reaction is not physically realistic and is used only as an extremely conservative bound. An alternative description of this assumption is to state that all reactions occur adiabatically.

The basis for this assessment is one kilogram of unalloyed, bulk alpha phase plutonium in a typical food-pack storage can. Heat loadings from corrosion reactions are estimated to demonstrate that maximum obtainable temperatures are below bulk plutonium ignition temperature and that heat losses will effectively prevent ignition of all or portions of the plutonium metal. Details of this calculation, including relevant parameters, are presented in Appendix D.

In sum, the temperature rise attributed to adiabatic reaction is less than 30 °C. As such, this factor does not significantly impact the hazards analysis. Heating as a result of the oxidation reaction does not present a credible risk. This calculation assumed even heat distribution throughout the sample. In an effort to address this limitation, the effect of localized heating on a small portion of the sample has been examined. Details of this calculation are also available in Appendix D.
All of the temperature increases calculated were well below the ignition temperature for bulk plutonium (∼ 500 °C) as well as typical combustibles found in a processing glove box line. Further, the simple heat loss calculation for a small portion of the metal indicated that minimum heat losses from a small portion of the metal to the bulk of the metal and ambient air amounted to 30% to 60% of the total heat available from instantaneous reaction. In experimental studies the flame from a carbon-arc torch was directed onto insulated bulk metal for almost two minutes before self-sustaining ignition occurred.\textsuperscript{92} The simple mathematical examination shown in Appendix D, while not definitive, indicates that the corrosion reactions associated with plutonium metal do not represent a significant plutonium fire hazard in the absence of a large quantity of readily combustible material in proximity of stored material.

V.D.2. Oxides

The maximum temperature for oxide reactions is not as significant a concern as for metals since the ignition of oxide, a stable material, is not an issue. However, the pressurization of an oxide storage container during a fire is a credible hazard which must be addressed. Thermal desorption of adsorbates during a fire could lead to large pressure increases which might burst a storage container. Decreased material strength at high temperature compounds this problem. Appendix C presents a calculation of worst-case pressure rises for both qualified and uncharacterized oxide. Note that the values in Appendix C assume room temperature. In the elevated temperature of a fire, these pressures might increase by a factor of two to three as a result of temperature/pressure relationships.

V.E. Material Dispersal

A simple hazard evaluation of material dispersal, focused primarily on metal corrosion and oxide reactions, has been conducted using a systematic "What-If" technique. A brief summary of the main results is presented in this section. It should be noted that the types of accidents discussed are bounding representations of the spectrum expected to be associated with the corrosion issue. All bounding airborne release fractions (ARFs) and respirable fractions (RFs) are derived from draft DP guidance.\textsuperscript{93}

V.E.1. Material Dispersal in Fires

The fire hazard of bulk metal remains controlled by fires external to the metal itself as the corrosion phenomenon is incapable of igniting bulk material. Therefore, no significant safety concern exists in this area. Small plutonium turnings or chips could potentially ignite from the heat generated by corrosion phenomena and such occurrences have been experienced in the history of the DOE complex. The airborne hazard may arise from two situations: self-sustained oxidation and suspension from metal; and suspension from a heated, non-reactive powder (PuO\textsubscript{2}). Airborne release fractions (ARFs) and the Respirable Fraction (RF) of the airborne particles vary for the two situations. However, such material is not typically stored for long periods in vaults unless it has been processed to oxide. Existing safety analyses typically assume up to 1,000 grams of turnings


\textsuperscript{93}Mishima, J., "Recommended Values and Technical Bases for Airborne Release Fractions (ARFs), Airborne Release Rates (ARRs), and Respirable Fractions (RFs) for Materials from Accidents in DOE Fuel Cycle, Ex-Reactor Facilities, Revision 2," DOE-HBK-00913-93 (April 21, 1993).
with an ARF of $5 \times 10^{-4}$ and a RF of 0.5, generating a maximum initial airborne source term of 0.25 grams.

Oxides cannot burn as they are already thermally stable, except for minor sub- and superstoichiometric reactions. Oxides can be driven airborne by heating if material entrained in the oxide burns or a fire external to the oxide heats the storage can. Using the estimated oxide MAR of 500 - 3,000 grams and an ARF of $6 \times 10^{-3}$ and a RF of 0.01 yields an initial airborne source term range of 0.03 to 0.18 grams.

V.E.2. Explosions and Pressurization

There are no explosive phenomena associated with metal storage and corrosion reactions. However, a significant pressurization reaction is possible if wet oxides are stored. Similar events could also be caused by storage of oxide containing other reactive impurities. The pressurization could conceivably result in energetic venting of the container. The venting energy itself would present no threat as can be demonstrated by a simple TNT-equivalent estimation using the equation for isentropic expansion of an ideal gas. Details of this calculation are shown in Appendix D.4.

Venting of a 150 psi gas is equivalent to less than 0.25 g of TNT explosion. This value is a credible, upper-limit for storage of a qualified oxide. Unqualified oxide might yield pressures of several thousand psi (see Appendixes C and D.4), equivalent to nearly 15 g of TNT on venting. However, most containers would likely vent before the maximum pressure could be reached. Radiolytic generation of hydrogen/oxygen mixtures could result in the formation of explosive gas mixtures. The energy equivalent from recombination of these gases could be considerably higher than the mechanical energy released from depressurization.

The main concern with these pressure releases is the potential for plutonium oxide entrainment in the ambient air. Release fractions based on experimental data are likely to overstate the amount of material released as the actual venting does not duplicate the ideal dispersal conditions in the release experiments. For the MAR range from 500 to 3,000 grams, an ARF of 0.05 and a RF of 0.4 yield initial airborne source term in the range of 10 to 60 grams. If process oxide is assumed, and ARF approaching 1.0 is expected, the airborne respirable source term ranges from 200 to 1,200 g. Data presented in Section II suggest that sintering the oxide at 1,000 °C could reduce the source term to the 50 to 300 g range.

V.E.3. Spills

Two major spill scenarios were examined for metal: rupture as a result of a fall, and rupture as a result of metal oxidation and volumetric expansion. In analyzing the fall of a storage container, it is assumed that metal is essentially intact with a surface layer of corrosion products. An estimate of 45 grams oxide per 1 kg of metal is believed to represent an adequate bound for current conditions and an extremely conservative bound if assumed to represent all metal stored. This estimate yields 45 to 450 grams of oxide over the MAR range of 1 to 10 kg. Assuming that 5% of this material exists as hydride (an extremely overstated estimate) yields hydride quantity ranging from 2.3 to 23 grams.

Free-fall during transport or handling could rupture a storage container. The impact of metal in a can on an unyielding surface could suspend the powdery corrosion products (i.e., oxide, hydride and metal fines) from the surface of the metal. No consequences are postulated for the metal itself from the impact. If the can maintains its ability to retain particles, no airborne consequences would
result. Note that unsealed slip-fit cans retained their contents (1 lb of ceramic oxide or sand) after free-falls of 4 ft onto an unyielding surface.\(^{94}\)

If the can looses containment upon impact with the surface, the contents would likely spill onto the floor from the breach. The ARF for 10-ft free-fall spills of powder is not a good representation of the stress imposed on the contents. A very conservative estimate can be obtained by using the ARF/RF for the suspension of a powder from the impact of falling debris, \(1 \times 10^{-2}/0.3\). For the potential MARs above (1 to 10 g of metal with 4.5% of the mass as oxide, 5% as hydrides, and 0.5% as metal fines), the airborne suspension would range from 0.05 to 0.3 grams of plutonium.

Initiation of a truly rapid, pyrophoric reaction of hydride, metal fines, and intermingled oxide would likely result in direct dispersal of the material into the air. The thermal energy from oxidation of the airborne pyrophoric material (hydrides and metal fines) ranges from 1.9 to 19 calories. If the heat generated is assumed to be uniformly radiated in all directions at a distance of 30.4 cm (1 ft) from the metal, the heat energy impacting the metal surface would range from 0.008 to 0.08 cal; insufficient to raise the temperature of the bulk metal to ignition. Considering the suspension of oxide from a surface of metal undergoing a self-sustained oxidation (ARF/RF = \(5 \times 10^{-4}/0.5\)), the additional source from this scenario would be insignificant.

The second mechanism for a metal release assumes that extended time in a heavily corrosive environment has caused all of the metal to react to oxide. Then the can is either spilled or the volume expansion associated with oxide breaches the can at a seam and all of the oxide is subsequently released from the can. For a MAR range from 1 to 10 kilograms and an ARF of \(2 \times 10^{-3}\) and a RF of 0.3 the initial airborne source term range is 0.6 to 6 grams. This number is based on ARF and RF values from spills of approximately 10 feet.

Free-fall spills are also a hazard in storage of oxide. Using the same ARF and RF for the MAR range from 500 to 3,000 grams yields an initial source term range of 0.3 to 1.8 grams. However, the airborne release fraction for process oxide is considerably higher than for oxide derived from oxidation of metal. For example, 100% of the oxide derived from calcination of oxalate is in the aerosolizable range. As such, the ARF for process oxide may be as high as 1.0. In this case, a source term of 250 to 1,500 grams is found assuming a respirable fraction of 0.5 [the assumption that the small forces involved in a free fall spill of this short distance would deagglomerate half the fine powder involved (generally deagglomeration would involve forces that could be imposed upon the individual particles such as ultrasound) is extremely conservative].

\[\text{V.E.4. Results}\]

The bounding initial airborne source terms estimated for the events associated with metal and oxide storage range from 0.01 to 1500 grams. Although 1500 grams is associated with the upper end of the spectrum, all of the values obtained are within the range of typical bounding initial source terms that can be estimated for events at non-reactor nuclear facilities.

The potential dose (Effective Dose Equivalent) to the public from these events was estimated by a simple Gaussian atmospheric dispersion model assuming limiting weather conditions of stability class F, 1 m/s wind speed, and a receptor at 1 km from the facility. As none of the events specifically discussed in this analysis would be expected to breach facility confinement, it was assumed a standard minimum arrangement of 2 HEPA filters was available to filter the release. Conservatively assuming 99.9% efficiency for the first and 99.8% efficiency for the second yields a combined filtration factor of \(2 \times 10^{-6}\). Calculated doses are given in the table below.

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The calculated doses are orders of magnitude below the DOE siting guideline of 25 rem. The one potential exception to this would be for severe events that breach building confinement involving complete oxidation of a significant amount of metal or process oxide.

Doses are not calculated for in-facility workers as such calculations are completely assumption driven and difficult to relate to meaningful expectations. However, the assessment indicates that (at least theoretically) a real contamination and inhalation risk exists for workers. This indication is supported by historical experience in the weapons complex where contaminations and associated inhalation doses have occurred. Based on historical experience, however, these events are not anticipated to produce a prompt fatality and the possibility of a large annual committed dose is considered small.

Table 4. Material at risk as a result of certain accident scenarios.

<table>
<thead>
<tr>
<th>Event</th>
<th>MAR Range (grams)</th>
<th>Dose Range (mrem)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Metal turning fire</td>
<td>0.25</td>
<td>3x10^{-3}</td>
</tr>
<tr>
<td>2. Heated oxide</td>
<td>0.03 - 0.18</td>
<td>4x10^{-4} - 2x10^{-3}</td>
</tr>
<tr>
<td>3. Pressurized oxide, 5% ARF</td>
<td>10 - 60</td>
<td>0.1 - 0.6</td>
</tr>
<tr>
<td>4. Pressurized oxide, 100% ARF</td>
<td>200-1,200</td>
<td>2.0 - 12.0</td>
</tr>
<tr>
<td>5. Metal shock</td>
<td>0.01 - 0.14</td>
<td>1x10^{-4} - 2x10^{-3}</td>
</tr>
<tr>
<td>6. Oxidized metal spill</td>
<td>0.6 - 6</td>
<td>7x10^{-3} - 7x10^{-2}</td>
</tr>
<tr>
<td>7. Oxide spill, 4% ARF</td>
<td>0.3 - 1.8</td>
<td>4x10^{-3} - 2x10^{-2}</td>
</tr>
<tr>
<td>8. Oxide spill, 100% ARF</td>
<td>250 - 1,500</td>
<td>3.3 - 16.7</td>
</tr>
<tr>
<td>9. Oxide from metal in severe event*</td>
<td>0.3/kg</td>
<td>1,900/kg</td>
</tr>
</tbody>
</table>

*Assumes unfiltered
VI. Recommendations

Current plutonium storage practices at Department of Energy facilities can be upgraded to ensure significantly improved levels of safety. The Office of Defense Programs is developing a standard for the anticipated long-term storage of plutonium. This long-term standard will include safety criteria developed as part of the Weapons Complex Reconfiguration (Complex 21) program. As such, material packaged to the long-term standard will be acceptable for storage in the future Complex 21 storage facility. However, new equipment and facilities will be required to fully implement this long-term standard. Phase-in of procedures and processes to meet this long-term standard is expected to take several years at a minimum. As such, a number of short-term actions are suggested to improve the safety of current plutonium storage practices. Numerous references are available for further information associated with these recommendations.95,96,97,98,99,100,101,102 These recommendations were formulated to allow near-term implementation to provide an increased level of safety until such time as equipment and facilities become available to package plutonium to the upcoming long-term standards. They are applicable to all operations in which plutonium metal or plutonium oxides is stored outside glove-box lines in containment vessels which do not have a certified hermetic seal (e.g., per ANSI N14.5).

- Plutonium metal or plutonium oxides should not be stored in the form of, metal turnings, or particles with specific surface area greater than 1.0 cm²/g.


97DOE. 1984. ENVIRONMENTAL PROTECTION, SAFETY, AND HEALTH PROTECTION STANDARDS, DOE Order 5480.4, Department of Energy, Washington, DC.


99DOE. 1986. SAFETY OF NUCLEAR FACILITIES, DOE Order 5480.5, Department of Energy, Washington, DC.


• Direct handling of material should be minimized (can result in exposure of 30 to 100 mrem/handling operation).

• Adequate inspection of containers for abnormalities (e.g. mass change, deformation, discoloration) should occur through means such as visual inspection, weighing, or even video surveillance where such capability exists. These data should be recorded for safety and Material Control and Accountability (MC&A) evaluations. The Task Force considers reasonable visual inspection requirements to be one week and one month after initial containment of material from processes, and yearly thereafter.

• All packages containing more than 0.5 kg of plutonium metal should be placed on an annual surveillance schedule in which the total mass of the package is determined to an accuracy of ± 0.5 g and compared with the mass determined in the preceding year, and if possible, with the initial (reference) mass determined at the time of packaging. A storage package should be evaluated (e.g., opened and inspected, radiographed, etc.) if any of the following conditions are met:

  a. The outer storage vessel is bulged or distorted.

  b. Hydride-catalyzed oxidation is suspected. Such reaction is indicated by a mass increase in either of two circumstances.

    i) For packages whose mass continues to increase since initial packaging or for which historical mass data is unavailable, a mass increase greater than 15 g per kilogram of plutonium over a one-year period indicates a hydride-catalyzed oxidation reaction.103 Continuing mass increase is indicative of a leaking container.

    ii) For packages whose mass has remained constant over a period of several years (less than ±0.5 g change) at the reference value, an annual mass increase of more than 2 g per kilogram of plutonium is evidence of hydride-catalyzed reaction. Such packages are particularly suspect since they indicate that a previously sealed container may now be breached and that the reaction could lead to rapid failure within 12 to 24 months.

  c) If the measured package mass relative to the reference mass corresponds to formation of oxide with a volume exceeding 10% of the free volume of the inner vessel. (Each one-gram increase in mass corresponds to formation of 1.5 cm³ of oxide with a density at 50% of the theoretical value.)

• Inspection practices at sites should be codified in surveillance plans. These plans should reflect facility operating status. Personnel protection practices should include radiological surveillance during all handling operations, anti-contamination clothing, gloves and, if necessary, respiratory protection.

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103 A higher oxidation rate may occur if the metal is in a high surface area configuration such as sheet of foil. The maximum annual increase for normal (uncatalyzed) oxidation of a given metal geometry can be calculated using a reaction rate of $3 \times 10^{-7}$ g oxygen/cm²·minute measured for alpha-phase plutonium under moist conditions at 50 °C.)
• Inspection of containers should be integrated with inspections for MC&A to minimize container handling and attendant radiation exposure to levels as low as reasonably achievable.

• Containers identified in inspection as possessing abnormalities should be repackaged in accordance with well-defined procedures. When handling these containers outside of glove box or conveyor confinement, the potential for airborne contamination and personnel inhalation must be explicitly evaluated with respiratory protection requirements specified accordingly.

• Examination and repackaging should be carried out in a glove box, preferably inert (<100 ppm O_2 if possible), and in accordance with well-developed procedures to minimize worker risk. Due to the potential for pyrophoricity of plutonium metal fines, accumulations of combustible material, such as rags, should not be permitted in repackaging areas. Even bulk metals should be treated as potentially having surface metal fines due to corrosion.

• As an interim measure, material that is repackaged may be placed in food pack cans or slip-fit (Vollrath) containers with secured lids. If at all possible, metal should be repackaged in a configuration containing at least one gas-tight seal. No plastic should be in direct contact with plutonium metal or oxide, and use of plastic in outer layers of packaging should be minimized. QA measures, labeling, and material characterization are essential. It is important that the material and storage packaging specifics be thoroughly documented to avoid future uncertainties requiring additional handling solely for characterization.

• When packaging metal, hazardous or pyrophoric material, such as plutonium hydride, should be removed. It is not, however, necessary to remove protective oxide film. Metal should be packaged in as dry and inert an environment as possible to minimize corrosion (<100 ppm H_2O).

• It is strongly advised that impure oxides from sources other than metal be thermally stabilized at 1000 °C ± 100 °C for 1 hour. This process serves to remove excess moisture, ensure complete conversion of substoichiometric material, and aids small-particle coalescence which partially mitigates the dispersal risk. If a capability for high-temperature firing does not exist, oxides can be stored inside Zone 1 confinement systems without stabilization provided slip-fit containers are used to preclude pressure build-up. Oxides outside of Zone 1 confinement should be stored in food pack or other sealed cans and, therefore, should be stabilized if at all possible.

• Due to its greater potential for dispersion in severe accidents, oxide should have priority over metal for storage in structurally robust vaults. To insure significant corrosion of oxide has not occurred in stored metal, the material should be characterized. Due to the buildup of impurities such as Am-241, the characterization should be performed in the immediate future and should make full use of small sample statistical methods. This study should be integrated with a site's surveillance plan as well.
VII. Bibliography

General Plutonium Technology:


Plutonium Storage:


# Appendix A. Attendance List and Agenda for Plutonium Storage Workshop.

**ALBUQUERQUE, N.M.**  
May 26-27, 1993

<table>
<thead>
<tr>
<th>NAME</th>
<th>AFFILIATION</th>
<th>TELEPHONE</th>
<th>FAX</th>
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<tbody>
<tr>
<td>David Michlewicz</td>
<td>DOE/DP-62</td>
<td>(301) 903-5519</td>
<td>3-7065</td>
</tr>
<tr>
<td>Dae Chung</td>
<td>DOE/DP-62</td>
<td>(301) 903-3968</td>
<td>-7065</td>
</tr>
<tr>
<td>Valerie Maness</td>
<td>LLNL</td>
<td>(510) 423-3208</td>
<td>(510) 424-6889</td>
</tr>
<tr>
<td>Brian R. Fitzpatrick</td>
<td>WHC</td>
<td>(509) 373-4119</td>
<td></td>
</tr>
<tr>
<td>Lisa Chan</td>
<td>PP-42</td>
<td>(202) 586-9637</td>
<td>-1217</td>
</tr>
<tr>
<td>William C. White</td>
<td>DOE/DP-273</td>
<td>(301) 903-5522</td>
<td>-5821</td>
</tr>
<tr>
<td>Leonard W. Gray</td>
<td>LLNL</td>
<td>(510) 422-1554</td>
<td>(510) 422-3165</td>
</tr>
<tr>
<td>Daniel E. Glenn</td>
<td>DOE/LAAO</td>
<td>(505) 665-6351</td>
<td>(505) 667-4872</td>
</tr>
<tr>
<td>Kurt T. Juroff</td>
<td>DOE/DP-6.1</td>
<td>(301) 903-2636</td>
<td>(301) 903-3186</td>
</tr>
<tr>
<td>Rowland Felt</td>
<td>WINCO</td>
<td>(208) 526-3409</td>
<td>(208) 526-0665</td>
</tr>
<tr>
<td>August J. Stapf</td>
<td>WSRC</td>
<td>(803) 952-4798</td>
<td>(803) 952-4747</td>
</tr>
<tr>
<td>Jeffrey B. Schaadt</td>
<td>WSRC</td>
<td>(803) 952-4758</td>
<td>(803) 952-4429</td>
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<tr>
<td>H. Allen Gunter</td>
<td>DOE/SR</td>
<td>(803) 725-8834</td>
<td>(803) 725-5017</td>
</tr>
<tr>
<td>John E. Myers</td>
<td>DOE/SF</td>
<td>(510) 422-3357</td>
<td>(510) 423-5650</td>
</tr>
<tr>
<td>Corey A. Cruz</td>
<td>DOE/AL</td>
<td>(505) 845-4282</td>
<td>(505) 845-4722</td>
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<tr>
<td>John M. Haschke</td>
<td>LANL</td>
<td>(505) 665-3342</td>
<td>(505) 665-8002</td>
</tr>
<tr>
<td>Thomas Wright</td>
<td>DOE/HQ/DP-6.2</td>
<td>(301) 903-3661</td>
<td>(301) 903-9471</td>
</tr>
<tr>
<td>Paul Hartman</td>
<td>DOE/ONS-Rky Ft</td>
<td>(303) 966-5379</td>
<td>(303) 966-7890</td>
</tr>
<tr>
<td>Thomas J. O'Connor</td>
<td>DOE/ONS-NS-10</td>
<td>(301) 903-6781</td>
<td>(301) 903-7358</td>
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<tr>
<td>Bob Reece</td>
<td>DOE/RF</td>
<td>(303) 966-6728</td>
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<td>Harry F. Lutz</td>
<td>LLNL</td>
<td>(510) 423-2968</td>
<td>(510) 424-6889</td>
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<tr>
<td>Michael F. Stevens</td>
<td>LANL/NMT-5</td>
<td>(505) 667-4414</td>
<td>(505) 665-8002</td>
</tr>
<tr>
<td>Jofu Mishima</td>
<td>SAIC</td>
<td>(509) 943-3133</td>
<td>(509) 943-5121</td>
</tr>
<tr>
<td>Name</td>
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<tr>
<td>Joe Woods</td>
<td>DP-682</td>
<td>(301) 903-5354</td>
<td>(301) 903-8047</td>
</tr>
<tr>
<td>William Miller</td>
<td>DP-65</td>
<td>(301) 903-9841</td>
<td>(301) 903-6628</td>
</tr>
<tr>
<td>Francisco C. Cheng</td>
<td>DP-643</td>
<td>(301) 903-7097</td>
<td></td>
</tr>
<tr>
<td>David Nickless</td>
<td>DOE/RFO</td>
<td>(303) 966-5221</td>
<td>(303) 966-5857</td>
</tr>
<tr>
<td>Alan K. Williams</td>
<td>SAIC</td>
<td>(301) 358-8228</td>
<td>(301) 428-0145</td>
</tr>
<tr>
<td>Randy M. Bigler</td>
<td>WSRS</td>
<td>(803) 952-4542</td>
<td>(803) 952-4205</td>
</tr>
<tr>
<td>Beth Conrad</td>
<td>CAI</td>
<td>(303) 966-3007</td>
<td>(303) 966-4673</td>
</tr>
<tr>
<td>Gregg Nishiimoto</td>
<td>RFO</td>
<td>(303) 966-7022</td>
<td>(303) 966-5887</td>
</tr>
<tr>
<td>John C. Breteke</td>
<td>SUEC/AL</td>
<td>(505) 845-4610</td>
<td>(505) 845-4609</td>
</tr>
<tr>
<td>Raymond P. Wagner</td>
<td>LANL</td>
<td>(505) 667-0645</td>
<td>(505) 665-6160</td>
</tr>
<tr>
<td>Brent H. Ives</td>
<td>LLNL</td>
<td>(510) 423-2636</td>
<td>(510) 423-1685</td>
</tr>
<tr>
<td>Mel Taie</td>
<td>LLNL</td>
<td>(510) 423-1679</td>
<td>(510) 423-2204</td>
</tr>
<tr>
<td>Liz Roybal</td>
<td>DOE/AL/SPD</td>
<td>(505) 845-5684</td>
<td>(505) 845-6431</td>
</tr>
<tr>
<td>Paul Groves</td>
<td>HQ DOE/DP20.1</td>
<td>(301) 903-8237</td>
<td>(301) 903-5604</td>
</tr>
<tr>
<td>Steve Goodrum</td>
<td>DOE/AL</td>
<td>(505) 845-5282</td>
<td>(505) 845-4837</td>
</tr>
<tr>
<td>Dan Rose</td>
<td>DOE/AL/WMOSD</td>
<td>(505) 845-5179</td>
<td>(505) 845-4664</td>
</tr>
<tr>
<td>Lou Rodgers</td>
<td>Westinghouse</td>
<td>(509) 373-2185</td>
<td>(509) 373-2150</td>
</tr>
<tr>
<td>Earl Whiteman</td>
<td>DOE/AL</td>
<td>(505) 845-6280</td>
<td></td>
</tr>
<tr>
<td>John Hargreaves</td>
<td>EG&amp;G-Rky Flts</td>
<td>(303) 966-2889</td>
<td>(303) 966-4063</td>
</tr>
<tr>
<td>John R. Winkle</td>
<td>EG&amp;G-RFP</td>
<td>(303) 966-2636</td>
<td>(303) 966-6022</td>
</tr>
<tr>
<td>James E. Selle</td>
<td>EG&amp;G RFP</td>
<td>(303) 966-4227</td>
<td>(303) 966-2982</td>
</tr>
<tr>
<td>Warren Wood</td>
<td>LANL</td>
<td>(505) 665-8996</td>
<td>(505) 665-8991</td>
</tr>
<tr>
<td>Don Brunell</td>
<td>DOE-NS</td>
<td>(505)667-3527</td>
<td>(505) 665-7709</td>
</tr>
<tr>
<td>David N. Olsen</td>
<td>Argonne</td>
<td>(208) 533-7459</td>
<td>(208) 533-7151</td>
</tr>
<tr>
<td>Gail Jackson</td>
<td>Argonne</td>
<td>(208) 533-7044</td>
<td>(208) 533-7577</td>
</tr>
<tr>
<td>John Krsul</td>
<td>Argonne</td>
<td>(208) 533-7318</td>
<td>(208) 533-7577</td>
</tr>
</tbody>
</table>
DAY 1

8:00 Opening Remarks D. Chung, DOE/DP-626
- Workshop Background
- Workshop Objectives/Desired Outcome
8:30 Review of Plutonium Metal and Oxide Properties Relevant to Storage A. Williams, SAIC
- General Metal and Oxide Corrosion J. Mishima, SAIC
- Pu Fires/Metal Interactions/Oxide Experience R. Felt, WINCO
- Metal/Oxide Chemistry and Storage J. Haschke, LANL

10:30 BREAK

Presentations on Pu/Oxide Storage at DOE Sites
10:45 Rocky Flats D. Nickless, DOE/RFO
12:15 LUNCH
1:15 LANL M. Stevens, LANL
Savannah River J. Stapf, WSRC

3:15 BREAK

3:30 Hanford L. Rodgers, WHC
LLNL M. Taie, LLNL
Argonne J. Krsul, ANL-W
1969 Rocky Flats Fire R. Felt, WINCO

DAY 2

9:00 Presentation of Advanced Storage Concepts W. White, DOE/DP-273
Interim Storage L. Chan, DOE/DP-42
Complex-21 Pu Storage Facility W. Wood, LANL
Overview L. Gray, LLNL
Materials Identification and Acceptance Criteria R. Bigler, WSRC
Containment Concepts
10:30 BREAK

Development of "Strawman" Criteria

10:45 Metal and Oxide Working Group Breakout (consider impact on/of ALARA, criticality, and safeguards and security)
- Containers
- Inspections
- Modeling
- Material Qualification
- Atmosphere Qualification

12:00 LUNCH

1:00 Working Group Reports

3:00 BREAK

3:15 Discussion (approach toward consensus)

5:00 Assignment of Action Items

5:30 Adjourn Workshop
Appendix B. Pelletizing of Plutonium Oxide.

Conditions and equipment required for pelletizing plutonium oxide are:

- Powder receipt, measurement, and handling capability,
- Vacuum degassing equipment (if the oxide cannot be certified to be free of moisture),
- Powder milling and grinding equipment to attain small particle sizes required for successful sintering,
- Furnaces for temperature in the range of 1700 °C,
- Presses capable of loads on the order of 60,000 psi to compress the powder,
- Molds and dies for forming the pellets at temperature in the range of 1700 °C,
- Pellet inspection, handling and packaging capability; packaging should be in hermetically sealed containers in an inert or dry air atmosphere,
- Glove box atmosphere should be inert or dry air, and
- Glove boxes should be shielded to reduce dose from $^{241}$Am ingrowth, but totally remote operation may not be necessary.

Concerns include:

- The technology was developed for space heating/power generation. How much effort is required to apply the technology to stabilization of oxide powder?
- Developmental efforts are necessary to determine the correct level of pellet porosity (as measured by density) to ensure release of helium formed by alpha decay.
- Additional processing increases the cost, complexity, and radiation exposure of the process operators.
- Product is still susceptible to fragmentation by crush-impact forces.
The existing capability to convert plutonium oxide to sintered pellets at DOE facilities is as follows:

**Rocky Flats**

- All required equipment except for powder presses, sintering furnaces and molds and dies,
- Compression presses which could be used to press pellets.

**HANFORD - Fuel Materials Examination Facility**

- Existing fuel fabrication facility for the Fast Flux Test Facility - never been operated,
- Facility meets most of DOE Order 6430.1A requirements except for Class 1E power supplies,
- Vault with 3-4 MT oxide storage capacity,
- Large sintering furnaces, pellet presses and dies for small (approx. 5/8 inch diameter by 1/2 inch long) pellets,
- Production capacity of 6 MT/yr; could be more than 10 MT/yr if larger pellets are manufactured,
- FMEF rough costs: $30-40M and 2 years to prepare, and $15-20M per year to operate.

**LANL**

- Capability for gram quantities only (Pu-238) and facilities are in use to meet Cassini mission requirements,
- Previous oxide fuel R&D equipment no longer available.

**Savannah River - Puff Facility**

- Furnace capable of temperature up to 1,600 °C,
- Press to make 1 inch diameter by 1 inch long pellets and inerted glove boxes, but only in batch sizes of a fraction of a kilogram,
- Facility in very poor condition; feasibility, cost and schedule to refurbish is uncertain.
Appendix C. Calculation of Worst-Case Pressure Rise for Stored Plutonium Oxide.

The four most likely pressurization mechanisms in the storage of nuclear material are helium release due to alpha decay, chemical reaction of material within the storage container, radiolytic reaction of components within the storage container, and thermal desorption of species from the stored nuclear material. The rate of pressurization (per kg of plutonium) for each of these terms is dependent on the particle size and surface area of the stored material. Further, the latter three terms are strongly dependent on the quantity of foreign material introduced into the storage container. High-surface-area media (such as PuO₂) have the capacity to introduce large amounts of other compounds into the storage environment. As such, the potential for pressurization is considerably larger in the storage of oxide than in the storage of metal. We briefly outline the degree of water absorption on PuO₂ before discussing each of these mechanisms.

Plutonium dioxide can absorb in excess of 25 mg H₂O/g PuO₂. Some of this moisture is released by heating to various temperatures. The material which is removed by heating from room temperature to 50 °C is termed "physisorbed". Stakebake and Steward⁴¹ have shown the physisorbed portion to be near 18 mg H₂O/g PuO₂. Further heating results in continued desorption of water as shown in figure 1 (see Section II). On heating to 1,000 °C an additional 10 mg H₂O/g PuO₂ is removed. This water is termed "chemisorbed".

However, the concern in storage of PuO₂ is not with what was removed prior to storage, but with what remains and is introduced into the storage vessel. Several researchers have reported that water is irreversibly bound on the PuO₂ surface and that desorption experiments only measure removal of water which was absorbed during the previous single exposure to H₂O. Water remaining from exposures prior to the last is not removed on heating. Such data give some concern in the storage of uncharacterized material in which the process history is unknown and the quantity of adsorbed species cannot be determined.

As is seen below, the pressurization which could result from uncharacterized material is large. Conversely, the pressurization from characterized and controlled material is small. For the purposes of calculation, we assume that 30 mg H₂O/g PuO₂ is introduced in the worst case for uncharacterized oxide, while suitably prepared and characterized PuO₂ contains less than 1 mg H₂O/g PuO₂.

C.1. Helium release

In metal storage, little if any pressure rise is anticipated because helium is retained in the metal and does not reach the gas phase. For oxide, a pressure increase of 1.055x10⁻⁴ mol helium/kg PuO₂ per year is expected since all helium escapes. Assuming 4.5 kg of PuO₂ in a storage can with a total volume of 1,850 cm³ yields a pressure rise of 5.54 torr/yr, or a total pressure rise of 277 torr (5.35 psia) after 50 years. This is the only certain source of pressure rise since alpha-decay of ²³⁹Pu is assured.

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C.2. Chemical reaction

It is difficult to predict the pressure increase arising from chemical reaction. A calculation must assume a quantity of adsorbate which reacts with the stored nuclear material. Further, the kinetics of the reaction will determine the rate of pressure increase. Certain materials and reactions are well characterized (such as the reaction of H₂O with Pu metal), while others are suspected but the rates unknown (such as the reaction of H₂O with PuO₂, 5PuO₂ + H₂O → Pu₅O₁₁ + H₂). In the worst case, it is assumed that all species react and give gaseous products. For uncharacterized material containing 30 mg H₂O/g PuO₂, complete reaction with PuO₂ would yield 1.67 mole H₂/kg PuO₂ or, in the specified storage container (4.5 kg PuO₂, 1,850 cm³ total volume), a total pressure of 115.3 atm (1,695 psia). The chance that such complete reaction would occur during storage is unknown but expected to be very small. More likely is partial reaction giving a much lower hydrogen pressure.

Indeed, the buildup in hydrogen pressure seen in past storage of plutonium oxide may be due in part to this mechanism (as opposed to radiolytic decay of water or organic materials as sometimes suggested). A more credible pressure rise expected for well-characterized material (1 mg H₂O/g PuO₂) is 0.056 mole H₂/kg PuO₂. In the given configuration, this yields a total pressure rise of 3.84 atm (56.5 psia). This latter number also assumes complete reaction of moisture with PuO₂, something which is difficult to predict but probably not likely.

Note that if complete chemical reaction of moisture occurs, there is no remaining adsorbate for either radiolytic reaction or thermal desorption.

C.3. Radiolytic reaction

Radiolytic decomposition of water and other organic materials is also difficult to predict. In the worst case, one can assume that all species are radiolytically decomposed. As such, the worst-case for radiolytic decomposition is 1.5 times that for chemical reaction (each H₂O radiolyzes to 1 H₂ and 1/2 O₂) (2,543 psia for uncharacterized material, 84.8 psia for certified).

An alternative approach involves calculating the rate of radiolytic decay. This calculation is more involved and requires a specification of surface-area of the material and the G-value for hydrogen production from organic and water decay. One can assume an infinite sink of radiolizable material to predict a worst-case pressurization (a near-infinite sink might be the presence of plastic bagging, for example). Using a surface area of 50 m²/g PuO₂, an escape depth of 0.2 μm, and a G-value of 2.0 H₂/100 eV α particle emission, a hydrogen generation rate in excess of 2,400 mol H₂/year is found. Obviously, this number is excessive (since it assumes that radiolizable material is in intimate contact with Pu throughout the 50 m²/g surface area). Hence, it must be assumed that all radiolizable material can react and the numbers stated in the paragraph above are the worst-case pressurizations.
C.4. Thermal desorption

If material is characterized and processed to remove physisorbed components, little if any pressurization is expected upon heating. Conversely, uncharacterized material could release as much as 20 mg H₂O/g PuO₂ on heating (see figure 1). This corresponds to a water release of 1.11 mol H₂O/kg PuO₂ or a pressure rise of 76.9 atm (1,130 psia) in the specified storage container. Note that several previous container ruptures have been attributed to this mechanism, including the 1979 incident at Hanford which prompted the Van Tuyl investigation. The above calculation is extremely simplistic and does not account for equilibrium conditions and condensation on other surfaces. These issues are extremely complex and beyond the scope of this analysis.

C.5. Summary

Under worst case conditions, the total pressure rise involves total release of helium and complete reaction of adsorbates on the PuO₂ surface. For uncharacterized material, a pressure rise of 1700 to 2550 psia is calculated after 50 years of storage. This term is dominated by the 1695 to 2543 psia pressure rise due to reaction, decomposition, and desorption of the 30 mg H₂O/g PuO₂ present in the initial material. The released gas is composed of either water or hydrogen, depending on which mechanism pressurized the container. Though these are worst-case estimates, the likelihood of a pressurization of this magnitude is considered small.

Well characterized material (1 mg H₂O/g PuO₂) is expected to have a much lower pressurization. Under the worst case, a total pressure rise of 61.8 to 89.8 psia is calculated after 50 years. This term is also dominated by the 56.5 to 84.5 psia rise from reaction, decomposition, and desorption. Again, the likelihood of a pressurization of this magnitude is difficult to predict but the likelihood is considered extremely small. This statement is supported by the years of successful storage experience with well-characterized oxide.

D.1. Initial Calculational Assumptions

D.1.a. Plutonium Properties
from\textsuperscript{D1,D2}

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<td>Specific Heat</td>
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<td>Heat of Oxidation PuO\textsubscript{1.98}</td>
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<td>Pu</td>
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<td>Bulk Ignition Temp.</td>
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D.1.b. Can Properties
from\textsuperscript{D3,D4}

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<tr>
<td>Density</td>
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<td>Specific Heat</td>
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D.1.c. Bounding Corrosion Estimates for Rocky Flats Unalloyed Metal Storage

| Quantity\textsuperscript{D5} | - 45 g oxide/kg of metal |
| Composition                   | - 5\% PuH\textsubscript{2}, 0.5\% Pu metal fines |

It is recognized that the above estimates cannot be called definitive. It is the judgment of the experts in the DP task force that these estimates are highly conservative.


D.2. Temperature Rise Sample Calculation

1. Volume of Plutonium
   
   \[ \text{Volume of Plutonium} = \frac{1,000 \text{ g}}{19.86 \text{ g/cm}^3} = 50 \text{ cm}^3 \]

2. Volume of Can
   
   \[ \pi (5.15 \text{ cm})^2 \times 11.9 \text{ cm} = 1,000 \text{ cm}^3 \]

3. Air in Can
   
   \[ 1,000 \text{ cm}^3 - 50 \text{ cm}^3 = 950 \text{ cm}^3 \]

4. Oxygen Available in the Can
   
   Assume the can is filled with air at 25 \(^\circ\)C, 1 atmosphere pressure, and 100% relative humidity.
   
   a. Oxygen in Air
      
      i. liters/mole of air at 25 \(^\circ\)C = 22.4 l/(298 K/273K) = 24.5 liters
      ii. air in can = 0.95 l/24.5 l/mole = 0.04 moles
      iii. oxygen available = 0.04 moles \times 0.21 = 8 \times 10^{-3} \text{ moles O}_2
   
   b. Oxygen from Water Vapor
      
      i. Saturation water pressure at 25 \(^\circ\)C = 3.2 kPa
      ii. Mole % water vapor in air at 1 atm = 100 \times 3.2 \text{ kPa}/101.3 \text{ kPa} = 3.2%
      iii. Water vapor in can = 0.04 moles air \times 0.032 = 1.0 \times 10^{-3} \text{ moles}
      iv. Assume all water vapor disassociates due to radiolysis
         
         \[ 2 \text{ H}_2\text{O} \rightarrow 2 \text{ H}_2 + \text{ O}_2 \]
         
         \[ \text{O}_2 \text{ available} = 1.0 \times 10^{-3} \times 0.5 = 5 \times 10^{-4} \text{ moles} \]
   
   c. Total oxygen = 8 \times 10^{-3} + 5 \times 10^{-4} = 8.5 \times 10^{-3} \text{ moles}

5. Heat generated
   
   Assume: (1) instantaneous reaction, and (2) all oxidizing material is plutonium hydride.

   The stoichiometric reaction of concern is
   
   \[ 2 \text{ PuH}_2 + 3 \text{ O}_2 \rightarrow \text{ PuO}_2 + 2 \text{ H}_2\text{O} \]
   
   a. Maximum hydride that can react = 8.5 \times 10^{-3} \text{ moles} \text{ O}_2 \times \frac{2}{3} = 5.7 \times 10^{-3} \text{ moles}
   
   b. Heat liberated = 5.7 \times 10^{-3} \text{ moles} \times 273,200 \text{ cal/mole} = 1560 \text{ cal}

   - D2 -
6. Temperature rise

Assume: (1) heat is equally absorbed by an insulated system consisting of the can and the plutonium since the reaction is instantaneous, and (2) the heat absorbed by the air in the can is ignored.

a. Mass of the can

i. Volume of structural metal in can = Volume of cylindrical portion + volume of ends + volume of crimp seals

(1) Cylindrical can volume = \( \pi (5.15 \text{ cm})^2 \times 11.9 \text{ cm} - \pi (5.15 \text{ cm} - 0.025 \text{ cm})^2 \times 11.9 \text{ cm} = 10 \text{ cm}^3 \)

(2) Can end volumes = 2\( \pi (5.15 \text{ cm})^2 \times 0.025 \text{ cm} = 4 \text{ cm}^3 \)

(3) Assume crimp volumes equal to one can end to estimate equivalent weight.

(4) Total volume = 10 + 4 + 2 = 16 \text{ cm}^3

ii. Weight of structural metal in can = 16 \text{ cm}^3 \times 8 \text{ g/cm}^3 = 130 \text{ g}

b. System heat capacity

System heat capacity = \((1000 \text{ g/1130 g}) \times 3.6 \times 10^{-2} \text{ cal/g K} + (130 \text{ g/1130 g}) \times 0.12 \text{ cal/g K}) = 0.05 \text{ cal/g K}

c. Temperature Rise

Temperature rise = \(1560 \text{ cal}/(0.05 \text{ cal/g K} \times 1130 \text{ g}) = 30 \text{ K} \)

D.3. Conduction and Radiation Sample Calculations

In response to potential concerns that uneven heat distribution across the metal could allow ignition to occur in an isolated area, the following calculation was performed to support experimental observations that bulk temperature must approach the ignition point before a significant metal fire can be sustained.

Conduction losses are estimated assuming the heat of reaction has been concentrated in one cubic centimeter at the corner of the plutonium piece sufficiently to allow the temperature in that corner to reach 500 °C (i.e. just below the ignition temperature). The opposite sides of the plutonium piece are assumed to be at ambient temperature (35 °C). The only conduction initially considered is
through three one square centimeter rectangles aligned with the three sides of the heated cube facing the metal. The heat transfer rate through any one of these rectangles can be determined from the equation

\[ Q/A = k \times (T_1 - T_2)/B \]

where

- \( Q \) = heat flow (calories/sec),
- \( A \) = Surface area of transfer (cm²),
- \( k \) = thermal conductivity (cal/cm sec °C),
- \( T_1 \) = warm face temperature (°C),
- \( T_2 \) = cold face temperature (°C), and
- \( B \) = thickness (cm).

A typical value for plutonium thermal conductivity between the assumed temperature values would be 0.03 cal/cm sec °C. The thickness of the rectangles on any side of the heated cube is 2.7 cm, resulting in a heat flux of 5.2 cal/cm² sec. For the three one square centimeter faces of the cube, the total heat flux is ~940 cal/min.

Radiation heat losses from the heated cube can be estimated from the equation

\[ Q/A = s \times E \times (T_1^4 - T_2^4) \]

where

- \( Q \) = heat flow (calories/sec),
- \( A \) = Surface area of transfer (cm²),
- \( s \) = 1.355 x 10⁻¹² cal/sec cm² K⁴,
- \( E \) = emissivity (dimensionless),
- \( T_1 \) = radiating temperature (K), and
- \( T_2 \) = ambient temperature (K),

The metal surface must be considered to be heavily oxidized to support the reaction being postulated, so an average emissivity value of 0.8 for oxidized metal surfaces is assumed. For the 3 square centimeters of radiating surface, the radiant heat loss is 68 cal/min. Without considering conductive heat losses to the majority of the plutonium, radiative heat losses from the majority of the plutonium, or convective heat losses at all, it is easy to postulate a total heat loss of at least 1000 cal/min for a small, high temperature portion of a plutonium mass.

**D.3.a. Results**

Additional calculations were performed for a 1 kilogram mass of plutonium. Estimates for heat liberation were performed for oxygen limited reactions for hydride and for plutonium metal converting to oxide in instantaneous reactions that are not physically credible. Additional estimates were performed for instantaneous reaction of an estimated bounding corrosion composition of 2.3 grams plutonium hydride, 0.2 grams plutonium metal fines, and 42.5 grams of sub-stoichiometric oxide. For the oxygen limited hydride case, the maximum temperature rise of the plutonium was 30 - 43 °C, depending on whether the heat liberated was presumed to be transmitted to the can and the plutonium or the plutonium only. The heat liberated was 1,580 calories. For the metal oxidation case, the temperature rise and heat liberated were 43 - 61 °C and 2,200 calories respectively. The values for the bounding corrosion estimate were 68 - 97 °C and 3,500 calories.

The venting energy itself would present no threat as can be demonstrated by a simple TNT-equivalent estimation using the equation for isentropic expansion of an ideal gas:

\[
E = [(P_1 \times V_1)/(y-1)] \times [1 - (P_2/P_1)(y^{-1})y]
\]

where

- \(E\) = energy released (liter-atm),
- \(P_1\) = maximum pressure in can at time of venting (atm),
- \(V_1\) = volume of container (l),
- \(y\) = heat capacity ratio of gas = 1.4 for air, and
- \(P_2\) = ambient pressure vented to (atm).

As shown in Appendix C, a typical maximum pressure within a can of certified oxide might be as high as 150 psi (10.2 atm). The typical primary container has a volume on the order of 1 liter, and the ambient pressure is 1 atm. With 1 liter-atm being equivalent to 24.1 calories, and 1,120 calories being equivalent to one gram of TNT, the maximum TNT equivalent of this venting would be \(\approx 0.25\) grams of TNT, a value well below the average firecracker. However, storage of uncharacterized oxide could potentially yield far greater pressures. For example, the maximum pressure that might occur in the storage can with 3000 g of oxide is derived from Figure 1. The oxide is assumed to be "wet" and to have a specific surface area of 50 m\(^2\)/g (a value commonly seen for process oxide). Since the amount of water remaining after evacuation at room temperature is 28 mg/g for a specific surface area of 17 m\(^2\)/g, the loading on a 50 m\(^2\)/g oxide is nearly 82 mg H\(_2\)O/g PuO\(_2\). For 3 kg of oxide, the total amount of water in the container is, thus, 246 g (13.7 moles). If this quantity of water is radiolyzed to H\(_2\) and O\(_2\), the internal pressure in a 1 l container is approximately 7500 psi at 25 °C. However, since radiolysis is a slow process and containment will likely be lost at lower pressure as a result of structural failure, explosive release of gas at this pressure is highly unlikely. Simple thermal desorption of this quantity of water could result in a rapid rise in steam pressure to nearly 5000 psi. This event could result in considerable plutonium dispersal, equivalent to 14.8 g of TNT.

Last, recall that the radiolytic generation of hydrogen and oxygen could result in the formation of explosive gas mixtures. The energy equivalent in such mixtures would be considerable. It is difficult to quantify this process. A worst-case estimate yields nearly 150 g TNT-equivalent if all of the water present on oxide is radiolytically converted to hydrogen and oxygen in a typical storage container. Further work is necessary to determine the probability of this occurrence. Some evidence suggests that the plutonium dioxide surface may act as a catalyst for hydrogen/oxygen recombination.
A.5.26

Errata Sheets for Project Plan and Assessment Plan
1. **Table of Contents, Attachments:**
   - Attachment 1: Methodology Process
   - Attachment 2: ES&H Vulnerability Assessment Form
   - Attachment 3: Working Group Assessment Team Report and Site Assessment Team Report Outlines
   - Attachment 4: Proposed Agenda for Working Group Assessment Teams

2. **Page 2, column 1, under "Roles and Responsibilities," first bullet, last line.**
   Strike the word co-leader and replace with "leader and deputy leader."

3. **Page 3, column 1, five lines from bottom, replace "three" with "two."**

4. **Page 3, column 2, last two lines, change Attachment 2 to Attachment 1 and Attachment 3 to Attachment 2.**

5. **Page 5, column 1, first line.**
   After "documents." add the sentence "Table A1 provides information on certain types of plutonium-containing materials."

6. **Page 5, column 1, fifth and sixth lines from the top.**
   Replace "Table A1 provides a key to assist in package definition" with "Tables A2 and A3 provide keys to assist in package and material definitions, respectively."

7. **Page 5, column 1, second paragraph, line 7.**
   After the word "codes," insert parenthetically (See Table A4).

8. **Page 6, column 1.**
   - Paragraph 2, line 5, replace "Attachment 4" with "Attachment 3"
   - Paragraph 3, last line, replace "Attachment 1" with "Attachment 4"

9. **Page 7, column 2, paragraph 1, replace "Attachment 1" with "Attachment 4."**

10. **Page 9, column 2, paragraph 1, replace "Attachment 2" with "Attachment 1."**
    Make same replacement in column 2, paragraph 2, 6th line from bottom.

11. **Page 10, column 1, last paragraph, lines 9 and 10.**
    Replace "Attachment 2" with "Attachment 1" and "Attachment 3" with "Attachment 2."
12. Page A1-1, Day "0", second bullet, lines numbered 1, 2, 3, and 4. Change parenthetical "co-lea-" to "deputy leader."

13. Page A1-1, Day 1, "In-Briefing." (a) Insert a new first bullet to read "Team meets with the host and external stakeholders; host and team make brief introduction covering background, purpose, and activities; and external stakeholders provide their comments." (b) Under the current first bullet, change "processes" to "proceeds," and add "with the Site Assessment Team" at the end of the sentence. (c) Strike the current second bullet ("Leader/host ...") and third bullet ("Leader provides ...").

14. Page A2-9, box titled Question 2, last line, replace "maximum" with "design life and current." Also last column of table titled "Maximum Age," replace with two columns titled "Design Life" and "Current Age."

15. Replace all page A1-x with A4-x, all page A2-x with page A1-x, all page A3-x with A2-x, and all A4-x with A3-x. Also, change all the "Attachment" headings at the top of the pages as follows: Attachment 1 becomes Attachment 4, Attachment 2 becomes Attachment 1, Attachment 3 becomes Attachment 2, and Attachment 4 becomes Attachment 3.
Page A1-2, first column, delete the title and the paragraph for the section "Sealed Sources."
A.5.27

U.S. DOE Criteria for Storage of Plutonium Metals and Oxides
Draft, March 31, 1994
U. S. Department of Energy
Criteria
for
Storage of Plutonium Metals and Oxides

DRAFT
March 31, 1994
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Appendix A. Bases for Plutonium Storage Criteria ........................................ A1

The following authors contributed to this document:

Randy Bigler, Westinghouse Savannah River Corp.
Dennis Brandt, Los Alamos National Laboratory
Lisa Chan, Department of Energy, Defense Programs
Dae Y. Chung, Department of Energy, Defense Programs
Donald T. Chung, SCIENTECH, Inc.
Thomas J. O'Connor, Department of Energy, Nuclear Safety
Raymond Cooperstein, Department of Energy, Defense Programs
Scott H. Davies, Rocky Flats (EG&G)
Richard J. (Jack) Erfbrdt, Rocky Flats (EG&G)
Rowland E. Felt, Westinghouse Idaho Nuclear Company
Leonard W. Gray, Lawrence Livermore National Laboratory
John M. Haschke, Los Alamos National Laboratory
Joseph C. Martz, Los Alamos National Laboratory
David Michlewicz, Department of Energy, Defense Programs
Jofu Mishima, Science Applications International Inc.
David M. Pinkston, Science Applications International Inc.
Jerry Stakebake, Rocky Flats (EG&G)
Michael F. Stevens, Los Alamos National Laboratory
Joseph A. Teal, Westinghouse-Hanford
Alan K. Williams, Science Applications International Inc.
Warren Wood, Los Alamos National Laboratory
Foreword

Plutonium storage practices at Department of Energy (DOE) facilities evolved over decades during which the objectives of Department programs were to support nuclear weapons development and production. These storage practices reflected a desire to primarily maintain plutonium in metal form for prompt recycling into weapon components. Weapon-grade plutonium generally was considered to be either "in-process," or "in-use". Prevailing procedures and safety requirements addressed only short-term storage. The end of the Cold War and the new arms control agreement are leading to the retirement of large numbers of nuclear weapons resulting in an excess of plutonium that will require management.

This standard establishes safety criteria for long-term safe storage of plutonium metals and plutonium oxides at existing DOE facilities. Plutonium materials packaged to meet these criteria should not need subsequent repackaging to ensure safe storage for at least 50 years or until final disposition plans for the plutonium is decided.
1.0 PURPOSE AND SCOPE

1.1 Purpose

This standard provides for safe storage of plutonium metals and oxides for at least 50 years. To meet the criteria, DOE facilities will have to place stable plutonium-bearing forms in containers designed to maintain their integrity both under normal conditions and during postulated accidental conditions. Use of the containers should also eliminate the need to repackage the materials for transport and minimize the need for additional handling during storage.

Surveillance, inspection, and documentation requirements related to the safe storage of plutonium are also identified.

1.2 Scope

This standard applies to plutonium metals, selected alloys (e.g. gallium and aluminum alloys), and stabilized oxides that contain a minimum of 50 weight-percent plutonium. It does not apply to plutonium-bearing liquids, residues, waste, sealed weapons components containing plutonium, or material containing more than three weight-percent plutonium-238. Required safeguards and security considerations are not stressed in these criteria. This standard is subject to review and update as needed.

The nominal plutonium isotopic composition (by weight-percent) for various grades of plutonium are typically as follows:

<table>
<thead>
<tr>
<th>Isotope (weight %)</th>
<th>$^{238}\text{Pu}$</th>
<th>$^{239}\text{Pu}$</th>
<th>$^{240}\text{Pu}$</th>
<th>$^{241}\text{Pu}$</th>
<th>$^{242}\text{Pu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weapons Grade</td>
<td>0.01</td>
<td>93</td>
<td>6.0</td>
<td>0.75</td>
<td>0.01</td>
</tr>
<tr>
<td>Fuel Grade</td>
<td>0.1</td>
<td>86</td>
<td>12</td>
<td>1.6</td>
<td>0.2</td>
</tr>
<tr>
<td>Power Grade</td>
<td>1.0</td>
<td>62</td>
<td>22</td>
<td>12</td>
<td>3.0</td>
</tr>
</tbody>
</table>
2.0 DEFINITIONS AND ACRONYMS

ALARA - As low as reasonably achievable. A radiological control concept to manage and control exposures to work force and to the general public at levels as low as is reasonable, taking into account social, technical, economic, practical and public policy considerations.

Alloy - A substance composed of two or more metals form by melting and dissolution of components in each other when molten.

ANSI - American National Standards Institute.

Bagless Transfer Can - An option for an externally uncontaminated boundary container. (See Figure 1.) A bagless transfer can may be placed directly into the primary containment vessel. It would be used to remove plutonium metals and oxides from a glove box enclosure without the use of any plastic bag or other organic or degradable material container within the transfer can.

Boundary Container - A hermetically sealed container placed into the primary (outermost/shipping) containment vessel to provide the inner-most barrier against contamination. (See Figure 1.)

Complex 21 - Future reconfigured nuclear weapons complex.

Conversion - An operation for changing material from one physical or chemical form, use, or purpose to another.

Database - A computerized listing of retrievable information for analysis or materials management. The data base will identify the location and characteristics of individually stored material containers for analysis, assessment and management.

Design Basis Accident (DBA) for Container - Any credible accident involving a container (e.g., drop, crush, fire, earthquake).

DOE - United States Department of Energy.

In-Process, In-Use Material - Material that is integral to the continuing manufacture or recycle processes involved in the nuclear weapons complex.

Long-Term Storage - A storage duration of greater than 10 years.

Loss on Ignition (LOI) - Percentage loss of weight associated with heating a specified quantity of plutonium-bearing material to a specified temperature and holding it at that condition for a specified period of time.

Material Container - The container that is in contact with the stored plutonium material. (See Figure 1) This may either be the boundary container, or a container that resides inside the boundary container. If the material container is not the boundary container, it does not have to be hermetically sealed.

MC&A - Material Control and Accountability.

NFPA - National Fire Protection Association
Plutonium Oxide - Oxide mixtures of plutonium, which are stable and contain at least 50 weight-percent plutonium. Such materials consist primarily of plutonium dioxide, but may contain minor concentrations of other inorganic compounds.

Primary Containment Vessel - The outer most containment boundary for long-term storage in a uncontaminated area. This container will also be the primary containment vessel in a shipping package for offsite transportation. (See Figure 1.)

Process - To extract, separate, purify or fabricate a material by physical, chemical, or mechanical means.

Residue - Excess process material or recyclable scrap from manufacturing or purification operations, which is not classified as waste.

SARP - Safety Analysis Report for Packaging. UCID 21218 provides the guidance for preparing a SARP.

Storage - Any method for safely maintaining items in a retrievable form for subsequent use.

Storage Facility - The building structure and other confinement systems in compliance with requirements that house the storage containers.

Thermal Stabilization - A process that exposes a plutonium-bearing material to high temperature in an oxidizing atmosphere to remove adsorbed moisture, and occluded gases and compounds; and chemically converts other plutonium compounds to oxide, thereby producing a less reactive chemical form.
3.0 RELEVANT ORDERS, STANDARDS, AND DOCUMENTS


DOE 5480.11, Radiation Protection for Occupational Workers, Change 3, June, 1992.

DOE 5480.23, Nuclear Safety Analysis Reports, April, 1992.


DOE 6430.1A, General Design Criteria, April, 1989.


4.0 CRITERIA

To minimize hazards to workers, the public, and the environment associated with the storage of plutonium metals and oxides, the following specific criteria are established. The bases for the criteria are provided in Appendix A.

4.1 Material Form

A. General

1) The stored materials are in solid metal or oxide (powder or solid) form.

2) The stored forms are readily retrievable.

3) The quantity of stored plutonium (metals or oxides) per primary containment vessel is as close as possible to but not greater than 4.5 kg (9.9 pounds) of plutonium equivalent. Actual operating limits are facility-specific.

B. Metal

1) Stored metal pieces have thicknesses greater than 1.0 mm or have specific surface areas less than 1 cm²/g.

2) Plutonium metal is free of loose oxide.

3) Plutonium metal is packaged and stored in a dry (preferably mildly oxidizing) atmosphere having a moisture content less than 100 ppm.

C. Oxides

1) Plutonium oxides are thermally stabilized to 0.5% loss on ignition (LOI). This can be accomplished by heating the material in an oxidizing atmosphere to a temperature of no less than 1,000 °C (1,832 °F) for at least 1 hour.

2) Following stabilization, the cooled oxide is handled and packaged for storage in a dry atmosphere so 0.5% LOI is retained.

4.2 Packaging

Packaging criteria for safe, long-term storage of plutonium call for two protective barriers. Design of the barriers allows for inspection and surveillance. Both barriers are hermetically sealed. The space between the inner barrier and outer barrier is free of transferable contamination. The inner barrier is the boundary container. The outer barrier is the primary containment vessel, which will also serve as the primary shipping package. Material containers that do not meet the boundary container criteria are not credited as barriers. (See Figure 1.)
4.2.1 Material Container

A material container is any container in contact with the stored material. It is packaged as a boundary container for long-term storage. It is free of all organic material such as plastic bags, organic coatings or residues, and gaskets.

A material container may also be the boundary container, if it is sealed and meets the boundary container requirements in Section 4.2.2.

If a material container is not the boundary container, it must be sized to fit inside the boundary container. The material container for oxides may be equipped with a center post to aid heat transfer.

4.2.2 Boundary Container

A boundary container fits directly into the primary containment vessel and provides an inner barrier against external contamination.

A boundary container meets the following requirements:

A. **General Requirements**

At the time of emplacement in the primary containment vessel, the exterior of the boundary container, shall be free of any transferable contamination as defined by *DOE Radiological Control Manual, DOE/EH-0256T*.

B. **Dimensional Requirements**

Boundary container shall be sized to fit into the primary containment vessel with allowances made for internal packing and clearances for welding the primary containment vessel closed. The following are the maximum boundary container dimensions:

- Maximum outer diameter of 12.5 cm (4.9 in)
- Maximum external height of 25.4 cm (10 in); with a hemispherical bottom the maximum height can be 27.9 cm (11 inches)

C. **Containment Requirements**

Boundary containers shall be hermetically sealed and tested after initial fill to be leak-tight as defined in ANSI N14.5.

D. **Structural Requirements**

Boundary containers for plutonium metals and oxides shall be of corrosion-resistant material.

E. **Container Packing Requirements**

1) Boundary containers for plutonium metals or oxides shall be free of all organic material such as plastic bags, organic coatings or residues, and elastomeric gaskets.
2) Material and boundary containers shall have a dry, inert atmosphere (can be mildly oxidizing).

F. Other Requirements

1) The contents of each boundary container shall be marked on its exterior and noted in the database referred to in Section 4.5. Markings shall be of a permanent nature, e.g. etched, or engraved.

2) Boundary containers for plutonium metals and oxides storage shall be designed to allow for ready retrieval of their contents.

3) QA documentation of materials and packaging shall be provided for a boundary container.

4.2.3 Primary Containment Vessel Criteria

The primary containment vessel is relied on to provide the outer containment barrier for safe long-term storage in a noncontaminated area. (See Figure 1) This vessel also serves as the inner container in a shipping package for plutonium transportation as required by 10 CFR 71. The vessel is designed for periodic leak testing and gas sampling.¹

The primary containment vessel meets the following requirements:

A. General Requirements

1) Storage container (primary containment vessel) shall be designed for dual use as a primary containment vessel for shipping and for long-term storage

2) Primary containment vessel shall meet the following:

   10 CFR 71, Packaging and Transportation of Radioactive Material.

   49 CFR 173, DOT requirements for offsite transportation of packages.

   DOE 5480.3, Safety Requirements for Packaging and Transport of Hazardous Material, Hazardous Substances and Hazardous Waste.

3) Maximum equivalent mass of fissile plutonium shall be 4.5 kg (9.9 pounds) plutonium per primary containment vessel

4) Oxides and metals shall be contained in an inner boundary container.

¹The primary containment vessel contains a sample tube attached to the top head of the vessel. This tube is penetrated by a laser beam through a sealed chamber used for collecting gas samples and for leak testing operations. After leak testing and gas sampling operations are completed the laser beam is refocused and the tube is resealed. The tube length permits penetration and resealing operations in a large number of locations on the tube. This eliminates having to penetrate and reseal in the same location each time the vessel is sampled.
B. **Dimensional Requirements**

The dimensional requirements for primary containment vessel is based on the size limits set by existing licensed secondary shipping container. The dimensional requirements are as follows:

1) Maximum inside diameter of 13.3 cm (5-1/4 in.)
2) Maximum outside diameter 15.2 cm (6 inches)
3) Maximum external height of 43.2 cm (17 inches) for vessel configured for shipping

C. **Containment Requirements**

1) Provisions shall be provided for purge and backfill.
2) Vessel shall be resealable to original integrity after gas sampling operation is complete. (See foot note on page 7)
3) Nondestructive examination of resealed vessel shall be possible to determine integrity of resealed vessel.
4) Sealed vessel shall be leak-tight as defined by ANSI N14.5.
5) Vessel shall be outfitted with all welded closures and ports (hermetically sealed).

D. **Structural Requirements**

1) The primary containment vessel meets the following requirements:
   - NUREG/CR-3854, Fabrication Criteria for Shipping Containers.
2) Vessel shall be capable of being reused after being opened once.
3) Minimum design life shall be 50 years with no routine maintenance.
4) Vessel shall be fabricated of material that would provide a corrosion-resistant containment boundary.
5) Vessel shall meet dimensional and containment requirements after the following anticipated occurrences:
   - 122 cm (4 ft) drop
   - 61 cm (2 ft) crush in which primary containment vessels collide
   - Vehicle vibration
• Handling shock
• Compression weight of five (5) primary containment vessels

6) Vessel shall remain leak-tight as defined by ANSI N14.5 after the following one-time, abnormal occurrences:
   • 9 meter (30 ft) free drop
   • 9 meter (30 ft) crush in which primary containment vessels collide
   • Vehicle crush as defined in the SARP
   • Puncture as described in the SARP

E. Design Temperature and Pressure Requirements

1) Primary containment vessel shall be designed to withstand 3,450 Kpa (500 psig) internal pressure at 204 °C (400 °F)

2) Primary containment vessel shall be designed to withstand 147 Kpa (21 psig) external pressure

F. Vessel Packing Requirements

1) All packing material shall be noncombustible per NFPA

2) All packing material shall be inorganic.

3) Steady-state plutonium metal temperature shall not exceed 100 °C (212 °F).

4) Vessel shall have a dry, inert atmosphere (can be mildly oxidizing).

5) Primary containment vessel shall be capable of holding 4.5 kg (9.9 lb.) of plutonium metal, or plutonium as oxide, with adequate free space remaining to prevent container pressure from exceeding the design limit.

G. Other Requirements

1) Vessel design shall be compatible with automated handling equipment.

2) Bar codes for identification and accountability shall be placed on vessel for direct or remote reading by robot or automated guided vehicle.

3) Vision targets shall have a permanent high-contrast color relative to container.

4) Vessel surface shall be uniform in color, except for vision targets.

5) Bar codes shall remain legible for more than 50 years.

6) Accessibility shall be provided for insitu material control and accountability measurements.

7) QA documentation of materials and packaging shall be provided.
4.3 Storage Facility

New storage facilities or significant modifications to existing storage facilities shall meet the requirements of DOE Order 6430.1A.

4.4 Inspection and Surveillance for Safety

A. Inspection and surveillance procedures identify:
   1) Prerequisites
   2) Acceptance criteria
   3) Specific instructions to ensure that rejected items are repackaged and reinspected for acceptance after identification.

B. Inspections and surveillance for safety are performed only by professional workers.

C. Formal methods and responsibilities are documented and maintained for independent review and evaluation.

D. Inspection of primary containment vessel is integrated with inspections for Material Control and Accountability (MC&A), as called for in DOE Order 5630 series, to minimize container handling and attendant radiation exposure to levels as low as reasonably achievable (ALARA).

E. Surveillance testing frequency, container sample size, and container selection are established using a statistical approach to ensure that primary containment vessel integrity is maintained with a high degree of confidence. Testing frequency is adjusted to account for surveillance failures.

F. Initial container inspections are performed within a fixed time following container closure. Subsequent inspections and surveillance are performed with established frequencies.

G. Baseline container weight and outer diameter are recorded as references for checking weight changes and container distortion.

H. Surveillance of containers is performed to determine container integrity and condition of the contents. Tests can be either intrusive or non-intrusive. Non-intrusive testing methods can include the following:
   - Digital radiography to observe oxide growth on plutonium metal, and bulges in the material/boundary container, which indicate a pressure increase.
   - Acoustic resonance spectroscopy to detect pressure changes.
   - Weight measurements to detect oxide growth, which indicates a breach in the container.
Intrusive test methods include gas sampling of the space between the primary containment vessel and the boundary container to detect leaks in the boundary container. Destructive testing of sample containers also may be performed to evaluate the long-term performance of the container design.

I. Actions taken for inspection and surveillance failures are in accordance with approved procedures and DOE reporting requirements.

4.5 Documentation

A. A schedule is maintained of safety and accountability surveillance testing.

B. A database is maintained to serve as a master list of relevant information about stored plutonium materials and containments. For completeness MC&A documentation is maintained along with the database.

C. The database contains as a minimum:

1) Identification of the following material characteristics:
   - Chemical form and isotopic content
   - Quantity
   - Source of stored material (who generated the material)
   - Specific process condition
   - LOI test results
   - Backfill gas composition and pressure
   - Package configuration (material container and/or boundary container)
   - Date and condition of packaging
   - Radiation field
   - Other pertinent information relative to the contents

2) Documentation of the types of inspection tests performed, individuals performing inspections, and the dates of inspection.

3) Records of safety inspections
Figure 1. Packaging Options for 50-Year Storage

Option 1

Plutonium is packaged in a material container. The material container (or containers) does not meet the criteria for boundary container. Thus, the material container(s) is sealed in a boundary container. The boundary container is then stored in a primary containment vessel.

Option 2

Plutonium is packaged in a material container. The material container package meets the criteria for a boundary container. Thus, no additional boundary container is needed. The material container (or containers) is stored directly in a primary containment vessel.

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Barrier provided by the primary containment vessel
Barrier provided by a boundary container
Barrier provided by a material container that does not qualify as a boundary container
APPENDIX A

BASES FOR PLUTONIUM STORAGE CRITERIA

1.2 Scope

Weapon grade, fuel grade, and power grade plutonium generally contain less than 3 percent plutonium-238. (Higher concentrations of plutonium-238 present both radiation and heat-removal problems.)

Power grade plutonium contains higher concentrations of higher plutonium isotopes than plutonium-239 resulting from the prolonged neutron irradiation of target elements. It does not include recycle Mixed Oxide (MOX) fuel.

The minimum 50 weight-percent value for plutonium in oxides is based on analyses of the plutonium inventories throughout the DOE Complex. Most oxides are either rich (>70% Pu), or lean (<30% Pu). The 50 weight-percent value is considered a minimum value, as indicated in the presentation of the Team Summary Report on the Complex-21 Plutonium Storage Facility Materials Identification and Acceptance Criteria (MIAC) at the Albuquerque, NM, workshop in May 1993. Section I of the "Assessment of Plutonium Storage Safety Issues at Department of Energy Facilities" (DOE/DP-0123T) states that residues less than 50 weight-percent Pu are excluded.

4.1 Material Chemical Form

4.1.A1 Metal or stabilized oxide can be stored safely for long periods of time as discussed in the Assessment Report.

4.1.A2 Ultimate disposition of the stored plutonium is currently undefined. If the plutonium materials are to be used in civilian applications, such as for reactor fuel, the material may require some processing before use. If the material is to be discarded, the criteria for discard require development. Encapsulating plutonium in inert materials, such as by vitrification, is not considered in these criteria.

4.1.A3 This is to minimize the number of containers required for storing plutonium.

4.1.B.1 The specified thickness and surface area are discussed in the Assessment Report, Section II.F, "Pyrophoricity" and Section V.B.1, "Chemical Reactivity." (DOE/DP-0123T)

4.1.B.2 Only loose oxides are considered detrimental. An oxide layer which adheres to the stored metal is considered beneficial because it retards further oxidation. Prior to repackaging, loose oxide may be removed from the metal by brushing.

4.1.B.3 The Assessment Report, Section II.B, describes the reactions of plutonium metal with moisture, resulting in its degradation and creation
of pyrophoric hydrides (see Section II.C of the Assessment Report) in
the container.

4.1.C.1 The Assessment Report, Section II.B, states that temperatures up to
1,000 °C (1,832 °F) are necessary to remove adsorbed and chemically
bound water.

4.1.C.2 The Assessment Report, Appendix C and Appendix D, provide
calculations for determining loss on ignition values (LOI).

4.1.C.3 The Assessment Report, Section VI.B provides the permissible limit for
storing qualified, stabilized oxides. Section VI.B proposes criteria for
minimizing moisture for both oxide and metal handling and storage.

4.2 Packaging Criteria

The packaging criteria are based on requirements developed for the Complex-21 Plutonium
Storage Plant.

4.2.1 Plastic bags are no longer allowed for packaging plutonium for long-term storage.
Material containers will be in direct contact with stored plutonium (metal or oxide). The containers hold plutonium, and transfer plutonium out from glovebox
confinement. The material containers do not have to be free of contamination if
they are placed inside a boundary container. The dimensional limits for material
container are based on the boundary container design.

4.2.2 A container removed from a plutonium glovebox may be contaminated by the
materials in the glovebox. Because plastic bags will not be used to bag-out
containers for long-term storage, an additional container may be required to provide
the barrier.

4.2.2A This requirement serves two purposes. First, it enable the assembly and
welding of the primary containment vessel to be performed clean. Second, since the surfaces inside the primary containment vessel are
free of transferable contamination at time of packaging, subsequent
detection of radioactivity during gas sampling can be used as an
indicator of boundary container failure.

4.2.2B The dimensional limits for the boundary container are based on the
primary containment vessel design. The primary containment vessels
will be fabricated from 5 inch schedule 40 pipes that has an inner
diameter of 12.7 cm (5 inches). The available volume in the boundary
container is 3,424 cm³ (209.7 in³). Storing 4.5 kg of metal plutonium
in this boundary container would take up about 7 percent of the
container space.

4.2.2C Leak testing of containers is necessary to ensure hermetic seals.

4.2.2D The requirement for a corrosion resistant boundary container is based on
operational experience and current evaluations of technology for storing
plutonium materials.
4.2.2E1 The Assessment Report, Section II.D, describes the radiolytic effects with plastics, hydrogenous compounds, and organic materials in long-term storage of plutonium. Long-term storage requires exclusion of all of these materials from all containers.

4.2.2E2 An inert atmosphere provides several functions. First, it precludes oxygen, moisture, or other reactive gases from being trapped in a storage container, which could produce reactive and corrosive compounds or gases that increase the pressure in the container. Secondly, an inert atmosphere assists in the removal of decay heat from the contents to the surroundings. Finally, the gas functions as an internal tracer necessary for leak-checking operations. Ideally, an internal atmosphere should consist mainly of helium because it is inert, has the highest thermal conductivity of the inert gases, and is excellent as a leak test tracer gas.

4.2.2F1 The contents of the boundary container need to be identified both on the container and in the database. Proper container identification is needed not only for storage safety, but also for Materials Control and Accountability.

4.2.2F2 Future personnel exposure resulting from retrieval of stored plutonium should be minimized.

4.2.2F3 QA requirements are to be developed.

4.2.3 Primary Containment Vessel Criteria

4.2.3A.1 Dual use of the storage container as a primary containment vessel for shipping reduces costs, and avoids the additional personnel exposure, operational risk, and waste generation associated with repackaging material for shipping.

4.2.3A.2 For the storage container to also be the primary containment vessel for shipping plutonium offsite, it has to meet packaging and transportation requirements. United States Code of Federal Regulations, Title 10, Part 71 (10 CFR 71) and Title 49, Part 173 (49 CFR 173) pertain to transportation of radioactive materials. DOE 5480.3 sets out additional Department of Energy requirements for transportation of radioactive material.

4.2.3A.3 The maximum fissile unit for an isolated sphere of pure plutonium-239 that is water-reflected and has a 0.05 margin in $K_{eff}$ is calculated at 4.53 kg.

4.2.3A.4 Oxides and metals shall be packaged in an inner boundary container free of organic or combustible materials and of external contamination.

4.2.3B1 The maximum criticality-safe diameter for fissile plutonium is generally regarded as 13.3 cm (5-1/4 inches). This diameter is the maximum allowed for the DOT Spec. 2R primary container for fissile shipments.
4.2.3B2 The maximum outer diameter of each primary containment vessel is the largest vessel diameter that will fit inside the second containment vessel of existing shipping packages, e.g., SAFKEG, 9968.

4.2.3B3 The maximum height of each primary containment vessel is the greatest vessel that will fit inside the secondary containment vessel of existing shipping packages, e.g., SAFKEG, 9968.

4.2.3C.1 A storage container must be purged during closure weld operations. An inert purge prevents oxidation of the weld metal on the interior of the container and ensures weld quality. A purge also vents welding fumes to prevent pressure buildup inside a container during closure operations. Evacuation and back-fill allow a non reactive gas atmosphere inside the sealed container after the closure weld has been made.

4.2.3C.2 If a vessel has been in storage, gas sampling is required prior to shipping. Gas composition and primary containment vessel pressure are indicators for detecting leaks. Gas sampling also may be required during storage for statistical container integrity evaluations. Original vessel integrity must be ensured for transportation and continued long-term storage.

4.2.3C.3 Each vessel design must account for nondestructive examination techniques. This will ensure that each container can be examined nondestructively and ensure vessel integrity.

4.2.3C.4 ANSI N14.5, American National Standard for Radioactive Materials - Leakage Tests on Packages for Shipment, specifies test methods to demonstrate that shipping packages comply with the containment requirements of 10 CFR 71. The maximum leak rate is $1 \times 10^{-7}$ std. cc/sec air.

4.2.3C.5 All welded closures and ports provide the highest integrity and longest life seals possible. It eliminates gaskets, which are prone to degradation and leakage, and mechanical devices such as bolts or screwed connections that are prone to wear, creep relaxation, seizure, or other mechanical failure.

4.2.3D.1 Shipping containers shall comply with ASME Boiler and Pressure Vessel Code as specified in Nuclear Regulatory Commission NUREG/CR-3019, "Recommended Welding Criteria For Use in the Fabrication of Shipping Containers for Radioactive Materials and NUREG/CR-3854, Fabrication Criteria for Shipping Containers." These documents specify fabrication in accordance with Section III of the ASME Code with modifications for shipping container application. These requirements also are cited in DOE UCID-21218, Packaging Review Guide for Reviewing Safety Analysis Reports for Packaging.

In addition, DOE Order 6430.1A requires safety class items for a plutonium storage facility to be fabricated to Section III of the ASME Code. The storage containers are expected to be classified as safety class items for mitigation of nuclear criticality. Final determination of safety class items will not be made until a safety analysis has been performed.
4.2.3D.2 The requirement that each primary containment vessel is reusable after being open once will result in cost savings and waste reduction. Before a vessel is reused, its physical condition (e.g., structural integrity, damage, contamination) must be reevaluated to determine if it is suitable for reuse. A container may be reused in routine unpacking and repackaging operations. A container could require reuse if the closure weld were found to be defective subsequent to the initial loading. This would require the weld to be cut out and the container rewelded.

4.2.3D.3 A design life of less than 50 years would necessitate maintenance or repackaging of the vessel during the 50-year duration of storage. This would involve significant cost, waste generation, operational risk and personnel exposure.

4.2.3D.4 Operating history shows that currently used containers are subject to corrosion. A corrosion-resistant container would minimize the potential for a breach in confinement by minimizing the potential corrosive effects of the contents on the walls of a container. Corrosion-resistant containers also will provide good surfaces for decontamination, if needed.

4.2.3D.5 The list of normal occurrences consists of the events that are postulated as possible during routine handling within a storage facility. Each vessel shall be designed to withstand these normal occurrences and also meet the storage requirements. Actual occurrences will require careful procedural evaluation prior to allowing a vessel into long-term storage. This is a design goal.

4.2.3D.6 The list of abnormal occurrences consists of the postulated design basis accident events that are judged credible, but not likely to occur within a plutonium storage facility. This requirement states that each vessel must remain leak-tight after such events. (However, damage to the vessel and its contents is likely and repackaging is expected to be necessary.)

4.2.3E.1 Design pressure is based on current specifications for 0.5 % maximum loss on ignition tests of plutonium oxide. The internal pressures could be generated by several mechanisms including helium generation by alpha decay of the plutonium, radiolysis products of residual adsorbed water or other contaminants, and temperature of 204°C (400°F) that result from a major facility fire.

4.2.3E.2 The US. Code of Federal Regulations, Title 10, Part 71 (10 CFR 71) requires that each primary containment vessel be designed for submergence in 15.2 meters (50 feet) of water. An external pressure of 147 Kpa (21 psia) is considered to meet these conditions. Each vessel shall be capable of evacuation for back-filling operations resulting in a minimum of 101 Kpa (1 atmosphere) of external pressure.

4.2.3F.1 The storage vault compartments are currently considered to be low fire hazard areas not requiring fire suppression systems. The use of combustible materials in the vault compartments, such as packing materials, will jeopardize the low hazard classification. Combustible
loading will be analyzed during the Fire Protection Design Analysis required by DOE 5480.7.

4.2.3F.2 Long-term radiation exposure degrades organic packing materials. The magnitude of this effect depends on the specific material. Radiolysis of organic material can produce combustible or corrosive gases and increase pressures within sealed storage container. Also, radiation can change the composition of organic materials so that they no longer have the same dimensional, chemical, or physical properties and therefore do not perform their packing function as originally designed.

4.2.3F.3 The transformation temperature of plutonium metal from the α-phase to the β-phase is approximately 117°C (225 °F). The metal expands significantly during transformation, which is to be avoided. A container will provide sufficient heat dissipation to maintain α-phase plutonium metal below 100 °C (212 °F) in the shipping and storage environment.

4.2.3F.4 An inert atmosphere provides several functions. First, it precludes oxygen, moisture, or other reactive gases from being trapped in a storage container, which could produce reactive and corrosive compounds or gases that increase the pressure in the container. Secondly, an inert atmosphere assists in the removal of decay heat from the contents to the surroundings. Finally, the gas functions as an internal tracer necessary for leak-checking operations. Ideally, an internal atmosphere should consist mainly of helium because it is inert, has the highest thermal conductivity of the inert gases, and is excellent as a leak test tracer gas.

4.2.3F.5 Design limit is based on the worst case pressurization scenario, which assumes 100% radiolysis of retained moisture, helium generation for 50 years and 400°F temperature. (Free volume includes space interior to boundary and/or material containers and the interstitial space of the oxide). For 4.5 kg (9.9 lb.) of plutonium as oxide, the minimum free volume required is 2.5 liters (153 in³). A primary containment vessel is required to have a free volume of 2.5 liters (153 in³) to provide space for gas generation and to ensure that the design pressure is not exceeded under worst case conditions.

4.2.3G.1 Use of automated handling equipment would reduce personnel radiation exposure. Vessel design must be capable of interfacing with various types of automated handling equipment that might be used in future facilities. Such equipment includes stacker/retrievers, automated guided vehicles, and stationary robots.

4.2.3G.2 Bar codes will allow the automated remote inventorying of containers thereby minimizing personnel exposure and the time normally associated with this task. Containers should be traceable through all stages of handling within the vault preparation areas as well as in the vault compartments themselves.
A bar code should remain intact for the life of a facility to ensure the positive identification of each vessel and its contents at all times.

Many types of positioning sensors for automatic handling require contrasting colors for recognition. Stray markings or discoloration on a container confuse or misguide automated handling equipment.

A vision target (bar code) must have a distinct and contrasting color relative to the container to be recognizable by automated remote handling equipment. Markings must be permanent so that routine replacement can be avoided.

Material Control and Accountability inventoring performed by automated equipment within a storage vault will reduce personnel radiation exposure. Security will also be increased by minimizing human access into the vault. The vessel and attached fixtures must be designed to permit access by in-situ accountability instruments.

QA requirements are to be developed.

4.3 Storage Facility Criteria

4.3.A Basis is DOE 6430.1A

4.3.B Basis is DOE 6430.1A

4.4 Inspection/Surveillance Criteria

Items in this section are based on the NRC Inspection and Enforcement Manual, Inspection Procedures 61700, 61701 and 61725.

4.5 Documentation Criteria

Based on sound Records Management practices within the nuclear industry.
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