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Cocordinated Safeguards for Materials Management in a Mixed-Oxide Fuel Facility

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COORDINATED SAFEGUARDS FOR MATERIALS MANAGEMENT IN A MIXED-OXIDE FUEL FACILITY

EXECUTIVE SUMMARY

The problems of safeguarding nuclear materials against unauthorized diversion and use have been described in many ways: by characterizing the diversion threat as overt or covert, the adversaries as terrorists or insiders, or by dividing the protective measures themselves into the categories of physical protection and materials accountability. Effective management of nuclear materials can be accomplished without unacceptable legal, political, and societal consequences. Covert diversion by trusted insiders on a piecemeal basis or blackmail threats by terrorist groups are more insidious problems than forcible theft, and it is the former threats for which materials control and accounting systems provide a solution.

This report provides generic designs and evaluation methods for advanced nuclear materials management systems to safeguard in-process materials in commercial mixed-oxide (MO_2) fuel refabrication facilities. The generic designs are based on a thorough evaluation of proposed plant designs, and represent minor extrapolations of existing fuel fabrication technology and state-of-the-art nondestructive assay (NDA) and data processing systems. The designs are applicable to commercial facilities to be built in the next decade and have been evaluated with simulated production data. Construction details are taken from the latest version of the Westinghouse Corporation's Recycle Fuels Plant (RFP).

This study shows that a near-real-time materials accounting system based on unit process accounting and conventional and NDA measurements can provide effective materials accountability in MO_2 facilities at reasonable cost, and without disrupting

production or requiring major process modifications. The materials accounting system complements significantly the level of control provided by physical protection and personnel control systems. The proposed materials measurement and accounting system (MMAS) closes materials balances about each of the unit processes required for recycle fuel production, processes these data, and reports the results of some 8000 material transfers each week to a central safeguards coordination system (SCS).

Dynamic material balances are drawn as often as possible around each unit process, using interim historical data when necessary, pending measurement of minor sidestreams. Measurements and data processing and handling are automated wherever possible, and a dynamic materials balance is struck for each unit process during each normal shift of operation, or more frequently if process conditions permit. For the main process stream, which has a canyon configuration, simple and reliable neutron and gamma-ray instruments and weighing devices provide timely data on process materials and holdup. Sophisticated NDA devices in the Analytical Services Facility (ASF) perform rapid analysis of process samples for verification and for the calibration of process-line NDA instrumentation.

The sensitivity to a single plutonium theft in each of the MMAS five major unit processes is given in Table I. The values shown are for the detection of a single, randomly timed and unrepeatable theft of plutonium-bearing material at the 50% detection probability level and with a false-alarm rate of 1/1000. For comparison, the throughput of plutonium oxide is 168 kg/wk. Attempts to remove from the facility amounts of material shown in Table I should be detectable by the physical protection systems described in the companion Sandia Corp. report if the systems are functioning properly and have not been circumvented. The sensitivity of the MMAS to diversion of sub-threshold quantities of plutonium is shown in Table II. Here somewhat larger total quantities may be removed from a process over a period of 1-4 wk if the single-theft threshold is not exceeded.

TABLE I

MATERIALS MEASUREMENT AND ACCOUNTING SYSTEM: SENSITIVITY OF
THE GENERIC MMAS TO SINGLE THEFT (PER BALANCE PERIOD)

<u>Unit Process</u>	<u>Detectable Theft Level (g Pu)</u>	<u>In-Process Material Not Measured (g Pu)</u>
PuO ₂ unloading	110	18 ^a
MO ₂ blending	130	15 ^b
Pelleting	150	33 ^b
Grinding	80	22 ^b
Clean scrap recovery system	200	5 ^b

^a Accumulated and measured each shift.

^b Accumulated and measured weekly.

TABLE II

MATERIALS MEASUREMENT AND ACCOUNTING SYSTEM: SENSITIVITY OF
THE GENERIC MMAS TO LONG-TERM DIVERSION (PER BALANCE PERIOD)

<u>Unit Process</u>	<u>Weekly Diversion (total g Pu)</u>	<u>Monthly Diversion (total g Pu)</u>
PuO ₂ unloading	16(350)	3(700)
MO ₂ blending	20(400)	10(800)
Pelleting	20(400)	10(800)
Grinding	12(250)	6(500)
Clean scrap recovery system	10(200)	5(400)

Accumulation of these totals by a diverter would require his repeated exposure to detection by other means and the availability of a continuing series of diversion opportunities. The average amounts shown per balance period can be detected with a probability of 85% at a false-alarm rate of 1/6. Again, attempts to remove these quantities from the facility would be detected by effective physical protection systems. For example, quantities of plutonium greater than 1 g are readily detected by portal monitors.

The safeguard system is implemented through a parallel management hierarchy consisting of a Safeguards Officer and staff for each operating shift. The Safeguards Officer reports to the regulatory authority and to plant management, and provides human modulation of the safeguards decisions. Plant operations are directly affected by safeguards (without human input) only in the case of an extreme emergency, such as a fire; otherwise, the safeguards system functions in a permissive rather than a use-denial mode, and interacts with the process functions only to accumulate information. High reliability and a low false-alarm rate are assured by operating the safeguards computers in a triple-modular redundancy mode (TMR) and by directing all computer-originated commands through the human decision process.

The burden of safeguards on plant operations consists of the autonomous safeguards staff (less than 10% of the total plant operations staff, exclusive of security guards), the cost of the measurements and data processing system (less than 5% of the total plant cost), and a very infrequent false-alarm rate owing to conservatism in design, performance goals, and selection of demonstrated technology.

The cost benefits of an effective materials safeguards system cannot be rigorously defined. If no diversion threat is made, there is no benefit; if a threat is thwarted, the benefits are nearly limitless. Because of the open-ended consequences of a successful diversion and the importance of plant

productivity to the cost of operation in any commercial facility, the worth of a safeguards system is best measured by its effectiveness and its cost best measured by the system's unobtrusiveness. For this reason, we have chosen a materials control system that complements the existing processing and management structure of the baseline plant and provides additional important benefits for production operations. The cost of an alternative non-process-integrated safeguards system might, of itself, be affordable, but if it adversely affects the plant output unnecessarily, the cost of reduced production is directly chargeable to safeguards, and is intolerable.

In addition to providing working generic safeguards designs for MO_2 facilities and the means to evaluate them, these studies have defined the materials control architecture, evaluation methodology and logic, and operational procedures necessary to extend the concept of near-real-time safeguards on a unit process basis to other production facilities throughout the fuel cycle.

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GLOSSARY

A/D	analog/digital
AGNS	Allied-General Nuclear Services
AL	alarm level
APAS	Automated Plutonium Assay System
ASF	analytical services facility
BG	background
BNL	Brookhaven National Laboratory
CA	chemical analysis
CMHS	central material handling station
CRT	cathode-ray tube
CSRS	clean scrap recovery system
cusum	cumulative sum
D&R	decontamination and repair
DBM1B	duplex system with buffer memory and single backup
DP	detection probability
DYMAC	Dynamic Materials Control
FAP	false-alarm probability
FBR	fast breeder reactor
FFTF	Fast Flux Test Facility
FG	foreground
HEDL	Hanford Engineering Development Laboratory
HEPA	high efficiency particulate air
HPFL	High Performance Fuel Laboratory
I/O	input/output
ICA	item control area
ID	item identification
IOC(S)	item operation control (system)
LAA	limited access area
LASL	Los Alamos Scientific Laboratory
LLL	Lawrence Livermore Laboratory
LWR	light-water reactor

LWT	liquid waste treatment
MAC	materials accounting computer
MACSIM	material accounting and control simulation
NBA	material balance area
MEGAS	multi-energy gamma assay system
MGMT	management
MNAS	materials measurement and accounting system
MO ₂	mixed oxide
MOXSIM	baseline plant simulation code
MT	metric tonnes
MTBF	mean time between failures
MTTR	mean time to repair
MWT	miscellaneous waste treatment
NAA	normal access area
NDA	nondestructive assay
NDP	nondetection probability
NRC	Nuclear Regulatory Commission
PCC	process control coordination
PC(S)	personnel control (system)
PNL	Pacific Northwest Laboratory
PSC	physical security computer
QC	quality control
RAA	restricted access area
RAM	random-access memory
RFP	Recycle Fuels Plant
ROM	read-only memory
RSD	relative standard deviation
S	simplex
SAI	Science Applications, Inc.
SBM	simplex with buffer memory
SCC	safeguards coordination computer
SCN	safeguards computer network
SCS	safeguards coordination system
SGS	segmented gamma-scanner
SNAP	shielded neutron assay probe

SNM	special nuclear material
TMR	triple-modular redundancy
TRU	transuranic
TU	metric ton of uranium
UPC	unit process controller
V	voter
ZPPR	Zero Power Plutonium Reactor

COORDINATED SAFEGUARDS FOR MATERIALS MANAGEMENT IN A MIXED-OXIDE FUEL FACILITY

by

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ABSTRACT

A coordinated safeguards system is described for safeguarding strategic quantities of special nuclear materials in mixed-oxide re-cycle fuel fabrication facilities. The safeguards system is compatible with industrial process requirements and combines maximum effectiveness consistent with modest cost and minimal process interference. It is based on unit process accounting using a combination of conventional and state-of-the-art NDA measurement techniques. The effectiveness of the system against single and multiple thefts is evaluated using computer modeling and simulation techniques.

I. INTRODUCTION, BACKGROUND, AND SUMMARY

The processing of recycled nuclear fuels and the use of plutonium in light-water power reactors (LWRs) has become the key issue among the proposed solutions to this nation's energy shortfall. Objections to plutonium recycle are usually based on public perception of environmental and safety considerations and generally fall into three categories: reactor safety, waste management, and effective safeguarding of nuclear materials.

This study is part of a continuing effort by the Los Alamos Scientific Laboratory (LASL) to apply current technology to problems associated with the implementation of nuclear energy. This report is one of a series devoted to the conceptual design of effective safeguards systems for nuclear materials throughout the fuel cycle (see Fig. I-1).¹ It specifically addresses the problem of nuclear materials accountability and control in a facility designed for conversion of uranium oxide and recycled plutonium oxide powders to MO_2 fuel; the physical security aspects of safeguarding the MO_2 fuel conversion facility are addressed in a companion report.² Other facilities, which perform the remaining nuclear fuel cycle functions, are scheduled for similar safeguards studies as part of this series.

The facility used for this generic study is of hypothetical design representative of a state-of-the-art MO_2 fuel refabrication facility that might be built in the 1980s. For realism, and to quantify material flows, processes, and procedures, the generic design relies heavily on extrapolations of the design of the Westinghouse RFP.^{3,4}

A. Objectives of the Study

Many studies have been devoted to safeguarding MO_2 fuel fabrication facilities (see Sec. I-B), but they have not

Fig. I-1. The light-water reactor nuclear fuel cycle.

succeeded in addressing the problem quantitatively. This report identifies the techniques and instrumentation required and provides generic designs for coordinated safeguards systems. The stated objectives of the study are to:

- Provide technical expertise for independent evaluation of relevant studies.
- Integrate the safeguards and facility functions of realistic materials control and accounting systems for generic baseline facilities.
- Refine proposed design concepts and economic impact considerations.
- Define the necessary R&D effort required to meet planned objectives.
- Provide the base for a coordinated approach to safeguards aimed at the licensability of generic facilities.

These objectives have been addressed in a manner consistent with the requirements of ERDA-DSS (Division of Safeguards and Security) and the recommendations of their Technical Advisory Committee on Safeguards (TAC). This committee was formed by DSS in 1975 to serve as an efficient means for obtaining safeguards requirements and views from NRC, ERDA-DRDD (Division of Reactor Development and Demonstration), and ERDA-DNFCP (Division of Nuclear Fuel Cycle and Production) and for coordinating the efforts of various participating R&D organizations.

B. History of Previous Work

In July 1973, the license application for the Westinghouse RFP³ stimulated a review of the problems of the large-scale use of plutonium within the LWR fuel cycle.

One year later, the AEC Regulatory Division (the predecessor of NRC) issued Volume 4 of the draft GESMO,⁵ addressing the safeguards and environmental implications of plutonium recycle as well as alternative uses of the plutonium. The report made the following conclusions:

- Timely recycle of plutonium is clearly the most advantageous alternative from the standpoint of both economics and conservation of energy resources.

- No significant additional environmental impacts should be associated with plutonium recycle if currently available measures and controls are fully exploited.

- Current safeguards measures will not meet safeguards objectives for plutonium recycle. However, a careful review of present development programs has revealed concepts that would significantly improve safeguards. The Commission was confident that the safeguards objective for plutonium recycle could be met through the implementation of some combination of (these) concepts.

The need for improved safeguards was stressed throughout the GESMO report. Additional safeguards measures emphasized by the GESMO and relative to this study were to incorporate materials inventory features into the plant design and to require improved materials control and accounting.

In effect, the RFP license application in 1973--followed by Willrich & Taylor's book⁶ and the GESMO in 1974--triggered the assessment of issues very basic to the AEC's overall safeguards program. Accordingly, under the authorization of a Special Safeguards Study⁷ a total of 8 private and ERDA contractor organizations were given a comprehensive series of 19 tasks that were directed toward (1) setting the safeguards objective, (2) establishing the range of threats with which the safeguards system will have to cope, (3) performing a vulnerability analysis of safeguards systems based on the range of threats and the facilities to be protected, and (4) analyzing the 17 options outlined and discussed in Chap. IV of GESMO.

Work on most of the special safeguards studies began in March 1975 and was completed by September of that year. The chronology of the nuclear-materials-related studies and other reports is outlined in Fig. 1-2; the final reports are summarized below.

Fig. 1-2. Chronology of publications on recycle fuel utilization.

1. The Lawrence Livermore Laboratory (LLL) Report. The final report of "Material Control and Accounting Systems" by LLL consists of an Executive Summary,⁸ an associated Technical Appendix,⁹ and the Science Applications Inc. report.¹⁰ The study used the Westinghouse RFP license application for a baseline MO₂ facility, RETIMAC,¹¹ as a baseline real-time materials accounting system, and computer simulations. Consultations with the staff of Westinghouse's Plutonium Fuels Development Laboratory, Cheswick, and the NRC/ERDA review provided the necessary tie to reality. The reports describe in detail the processes and material flows in a recycle fuel plant, discuss the criteria and provide guidelines for a real-time materials control system as applied to such a facility, examine in detail the physical protection and theft indicator structure, and provide estimates of the economic implications. Following are selected findings.

- Deployment of effective real-time materials control and accounting systems in commercial nuclear material processing plants is feasible in the 1980-1990 time frame.

- As tradeoffs and changes in the design of the real-time system took place, it became obvious that an intelligent balance between materials control and accounting measures and physical security measures was required to define an adequate and economical plant safeguards system.

- Scrap, waste, holdup, and in-process material inventories are the most important parameters affecting the sensitivity and timeliness of the real-time system material balance capability.

- The ranges for material balance uncertainties in mainstream process areas are 20-400 g of plutonium, or 0.2-4.0% of throughput.

- Uncertainties associated with weekly material balance area inventories after runout generally range from 300-1500 g of plutonium, or from 0.2-1% of throughput. One special case involving several large PuO₂ bulk storage vessels, which are normally 67% filled, gave a material inventory uncertainty

of 3 kg of plutonium, or 2.0% of weekly throughput and 0.5% of monthly throughput.

- The proper use of short- and long-term diversion detection algorithms provides a real-time safeguards system for detecting theft of nuclear material. This, coupled with physical security, makes the theft of significant amounts of material virtually impossible.

- The study indicated that the cost of installing a real-time materials control and accounting system in a new plant may be as much as 10% of the original cost of the plant.

- In addition to the installation cost, the estimated annual operating costs amount to about \$1.6 million.

- It was concluded that no additional cost penalty would result from the insertion of a real-time safeguards system in the production line, i.e., the plant production would not be diminished by the presence of the monitoring system.

- The economic impact on electric utility rates would be 0.015 mil per kWh, or a 0.04% increase over present rates.

2. The Mound Laboratory Report. The second study concerned with materials control and accounting systems was performed by Mound Laboratory.¹² The major objective of the study was to promote the use of calorimetric assay in a recycle fuel plant. For this NDA technique, full isotopic control is necessary because isotopic variations are the main source of error. Isotopic control is to be achieved by first blending large quantities of plutonium to a uniform isotopic composition and then instituting administrative and physical controls to prevent mixing of plutonium from different blend lots. On the premise that the specific power of the plutonium from a single isotopic blend is constant, calorimetry can be used for the assay of all plutonium-bearing material - feed, product, or scrap. The study draws the following conclusions.

- If these measures were instituted in the proposed Westinghouse Anderson RFP, the uncertainties in material

balances could be reduced to 0.19%, or 2.3 kg of plutonium with currently available NDA technology.

- Further reductions of measurement uncertainties for plutonium in future fabrication plants can be achieved by developing improved NDA instrumentation, especially calorimetry. For example, it is estimated that uncertainties can be reduced to 0.14% within 5 yr.

- The accuracy of plutonium NDA can be improved by using isotopic control and calorimetry measurements. The calorimetry measurements would provide frequent checks of the NDA instruments and serve as highly representative standards for calibration purposes. This improved measurement accuracy can be used at those points in the process where more accurate measurements will improve timeliness of the plutonium accounting or will help localize accounting discrepancies.

- Uncertainties in the quantity of material held up in the process must be kept to the minimum practicable (84% of materials discrepancies are due to errors in determining holdup).

3. The Pacific Northwest Laboratory (PNL) Report. This report¹³ concentrates on materials control and accounting and stresses the need for improvements in the sensitivity and timeliness of loss detection. It examines methods of increasing promptness in diversion detection and in determining probabilities of unit loss detection and of various rates of loss over extended periods of time. Tabular data are given on measurement errors for various plants, error sensitivity as a function of time, and the effect of frequent running inventories. Data on holdup for each process component including clean scrap, dirty scrap, and miscellaneous waste are shown. These data were derived from PNL's "Generic Mixed-Oxide Fuel Fabrication Plant-Decommissioning Study."¹⁴ Information concerning materials control and measurement errors for various inventory periods is also presented.

Some of the suggestions and recommendations made were:

- To incorporate a real-time dynamic materials control and accounting system,
- To designate the PuO_2 storage area as a material balance area with daily weight measurements, and
- To conduct a monthly formal plant inventory.

4. The Brookhaven National Laboratory (BNL) Report. The purpose of the report¹⁵ was to evaluate the effectiveness of incorporating small percentages of radioactive additives into special nuclear materials to increase the sensitivity for their detection by doorway monitors. Three basic sensors (metal, gamma, and neutron detectors) were evaluated for various spiking schemes and material shields. The increased cost of spiking and handling these materials was substantial and would result in an increase in the cost of generated electricity of more than 1¢. In general the effects of spiking on measurement methods were detrimental. As an alternative to spiking, a group working with BNL recommended attaching ^{60}Co sources to fuel rods and canisters during shipment.

5. The Los Alamos Report. The LASL report¹⁶ "Materials Measurement and Control for a Mixed-Oxide Recycle Fuel Fabrication Facility: A Preliminary Review," reviewed qualitatively the materials control and accounting aspects of the safeguards problem and identified the problem areas amenable to quantitative solution with existing, or reasonable extrapolations of existing, technology. In this way it served to define the scope of the present study and furnished an orderly outline for the work presented in this report, which supersedes the Preliminary Review.

C. Summary and Strategy

This report describes a coordinated safeguards system that will provide reliable and effective safeguards for a commercial MO_2 fuel fabrication facility without adversely affecting its production goals. The ground rules for this study and the design philosophy of the safeguards system are summarized below.

(1) The safeguards system philosophy should be one of permissive operation, rather than use denial. Accordingly, the process must be allowed to proceed normally so long as safeguards requirements are satisfied.

(2) The safeguards system must be unobtrusive. It should interact passively with the process, collecting information from process functions. All process-controlling decisions, except those requiring immediate shutdown for health and safety reasons (e.g., fire), must be subjected to human evaluation before they can be implemented.

(3) The safeguards system, like the plant itself, should be based on current demonstrated technology or minor extrapolations of existing operating systems. The use of developmental systems must be minimized.

(4) The safeguards system should be autonomous in that subversion of the system by plant personnel should be as difficult as possible.

(5) The safeguards system should be acceptable to a commercial operator, having minimal interference with a properly run production plant, high reliability, and a low-false alarm rate. Furthermore, the safeguards system should provide useful data for improving process operations.

The objectives have been satisfied in the following way (items are keyed to the above criteria).

(1) The basic system architecture is such that disruptions of the process are minimal. Most data are collected and processed automatically, and safeguards inquiries are coordinated through the process control coordination (PCC) unit.

(2) Process control is implemented with an automated data acquisition system that provides human-modulated control decision capability for adaptability and efficiency.

(3) Nearly all the technology used in the plant has been accepted for use by the nuclear industry and should result in increased reliability, easier maintenance, and lower costs. Some software development may be necessary before detailed design is made.

(4) The plant information system consists of a process information system and a safeguards information system, both of which are accessible to authorized users. The safeguards information system cannot be affected by plant personnel without prior approval of the Safeguards Officer.

(5) The safeguards system attains reliability by operating through three computers connected in a triple-modular redundancy (TMR) mode, each checking the other two by means of background processing. The system gains respectability, and the associated acceptability, because it is based on current technology and has been developed with the close cooperation of the designers of this nation's first large-scale MO_2 facility.

The feasibility and effectiveness of the system have been tested by applying efficient diversion detection algorithms to data from simulated plant operations. Typical threshold sensitivity levels that include unmeasured in-process and diverted special nuclear material (SNM) in major plant process areas are: 100-200 g Pu (about 2% of throughput) for a single material balance period during which ~ 8 kg Pu is processed; 200-400 g Pu (about 0.2% of throughput) for any 1-wk period during which ~ 160 kg Pu is processed; and 400-800 g Pu (about 0.1% of throughput) for any 4-wk period during which ~ 640 kg Pu is processed. These results indicate that materials control on a unit process basis can result in the effective safeguarding of nuclear materials in a MO_2 fuel fabrication facility.

The overall costs of the integrated safeguards systems described in this report are not well defined. However, we believe they are considerably lower than the 10% of capital investment previously estimated. The staff required to operate the safeguards system, exclusive of guard personnel, is less than 10% of the total plant staff.

D. Format and Contents

The baseline plant design, based on the Westinghouse RFP, is discussed in Chap. II. Processes, capacities, and flows are

described, as well as requirements for staff. Details of operations and equipment are given in Appendix A.

The safeguards system and its subsystems are described in Chap. III. Designs and operation of the materials measurement and accounting system (MMAS), the safeguards coordination system (SCS) and the safeguards computer network (SCN) are detailed. Safeguards operating procedures and staffing requirements are defined. Details of the plant information system are given in Appendix B. The NDA techniques employed for materials control and accounting management are described in Appendix C.

The performance of the conceptual system design is evaluated in Chap. IV. The modeling, simulation, diversion analysis, reliability, and costs are described. Details of MOXSIM, the baseline plant simulation code, are given in Appendix D, which includes a detailed description of the unit processes into which the plant operations are broken down for modeling, simulation, and performance evaluation. The algorithms developed for theft detection are described in Appendix E.

Conclusions, results, alternatives, and recommendations are presented in Chap. V.

II. THE BASELINE MIXED-OXIDE RECYCLE FUEL FABRICATION FACILITY

A. Major Features

The model facility for this study of MO_2 recycle fuel fabrication facilities is based on the Westinghouse-Anderson design, which has been used in several health, safety, and safeguards analyses. Westinghouse has repeatedly modified the design since its 1973 license application in an attempt to keep pace with changes in technological, economic, and regulatory factors. With few exceptions, some of which are described in the companion Sandia Corp. report,² the design used in this preliminary report is taken from the 1975 Science Applications Incorporated (SAI) version used in the NRC Special Studies report.¹⁰ This reference design has been further modified to incorporate improvements resulting from the joint LASL-Sandia effort to design an integrated safeguards system and has been updated to reflect current Westinghouse operating plans.⁴

The following are criteria for the baseline MO_2 facility.

- Annual operating capacity at 60% design capacity: 200 MT* MO_2 , 4 wt% PuO_2 , 96 wt% UO_2 ;
- Annual input: 253 pressurized PuO_2 containers (32 kg each), 740 55-gal drums UO_2 (260 kg each);
- Annual output: 100,000 fuel rods (2.0 kg MO_2 each), 20 million pellets (10 g each);
- Customer target enrichment specifications: within $\pm 0.1\%$ (absolute);
- Shift structure: three shifts per day, 1000 shifts per year, consisting of a 7-day cycle of 19 or 20 shifts followed by one or two cleanout shifts;

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*Metric tonnes.

- Batch structure: one 225-kg MOX sub-blend per production shift, 1 blend = 21 sub-blends (assume one reject subblend per blend);
- Scrap rates: 10% of throughput recycled as clean scrap; 1 to 2% dirty scrap;
- Total number of personnel: 400 individuals working inside the manufacturing area, 4,10

The normal operating capacity has ample margin to compensate for periodic shutdowns or to convert to two production shifts and one "hot stand-by" shift.¹⁰ Division of plant operations into shifts is not a processing constraint. Many processes are continuous across shift boundaries, and processes cannot always be synchronized with shifts. Shifts are useful mainly for personnel and discrete process scheduling.

Annual plutonium feed for the baseline plant is 8000 kg, or about two-thirds of the plutonium output of the proposed Allied General Nuclear Services (AGNS) facility for reprocessing the spent fuel generated annually by fifty 1000-MWe power reactors. For further comparison, annual throughput of either the MWMO or Kerr-McClellan facilities is ~ 450 kg plutonium (~ 2.2 MT PWR fuel), and a typical LWR fuel fabrication plant has a throughput in the range of 1000-2000 MT of total uranium fuel.

In the baseline design, high throughput of recycle plutonium is achieved without excessive radiation exposure by automating the main process stream and by locating it in canyons with shielding walls. Linear arrays of processing equipment in the canyons, as well as overhead cranes and other equipment for remote maintenance, are common to spent-fuel reprocessing facilities. The automation and material isolation of such arrangements are advantageous for in-plant safeguards and control of SAM and facilitate the integration of NDA and automatic data processing into a common process and safeguards control system. Of course, not all material handling operations are automatic--some are performed remotely with manipulators, or manually.

through gloves. In contrast, existing plutonium facilities rely heavily on manual operations.

The main process stream for the MO_2 facility comprises receipt and storage of feed materials, transfer of feed to the main process stream, blending PuO_2 and UO_2 , powder preparation, pellet pressing, pellet sintering and grinding, and fuel rod loading, storing, and shipping. Coupled to the main processes is a clean scrap recovery system (CSRS).

Essentially all recyclable scrap (10% of throughput) is recovered in the CSRS and recycled as MO_2 feed material. The CSRS conditions rejected pellets and powders by crushing the scrap and subjecting it to successive oxidation and reduction steps to produce a powder with characteristics suitable for blending, pressing, and sintering. The plant has no capability to recover dirty scrap and waste, which amount to $\sim 0.5\%$ of the throughput.

Support operations in the manufacturing area are the analytical services facility (ASF), miscellaneous waste treatment facility (MWT), liquid waste treatment (LWT), and decontamination and repair (D&R) cells.

The ASF is a complete analytical chemistry laboratory for analyzing small samples from the process line. Conventional analytical methods are used.

The MWT operations are essentially sorting and highgrading functions, similar to the head-end operations of a full scrap recovery plant, but without waste recovery capability. The products of MWT and LWT are disposable wastes that are shipped out in 55-gal drums, and recyclable material and concentrated scrap that are stored in 1-liter containers for future disposition. No acids are used in the plant, except to dissolve small samples in the ASF, and most operations involving liquids are performed with detergent or water which is subsequently filtered, as is done in decontamination. After volume reduction by evaporation, contaminated aqueous solutions are fixed in concrete, which is cast in 55-gal drums.

The D&R cells are of conventional design and provide both direct and remote maintenance capabilities for equipment located in the canyon processing line.

B. Process Description

The processes for the base line facility have been described by SAI.¹⁰ The following descriptions were derived from that document, and were updated and verified in discussions with Westinghouse.⁴ They are intended primarily to provide the design basis for our critique. Appendix A contains more detail on the main stream processes.

1. Process Streams. The feed, product, and clean scrap flows for the MO_2 plant are shown in Fig. II-1.^{4,10} Average material flows, including sidestreams, per 8-h shift are given in Table II-1, and capacities of containers and storages are presented in Table II-2.

Processes 1A to 4A: PuO_2 receiving, storage, unloading, and process storage. Shipping containers for PuO_2 feed contain shielding for personnel protection and can dissipate up to 20 W/kg of the heat generated by the plutonium. Typically, 32 kg PuO_2 is contained in four cans (primary containers) inside a secondary pressure vessel, which is centrally located in a shipping cask. The shipping container design, which differs from the L-10 configuration assumed by SAI, is described in the procedures for receipt and storage given by Sandia Corp.² The storage vault, located on the second floor of the manufacturing building, has a capacity for 40 shipping containers, corresponding to a 53-day feed supply. PuO_2 is unloaded from a shipping container into three isolation compartments in series to avoid contaminating the shipping container. The primary container for the PuO_2 is disposable as waste. In the original design the cans of PuO_2 are weighed, opened, and randomly sampled for chemical analysis. The contained powder is transferred pneumatically to one of three criticality-safe bulk storage vessels,

TABLE II-1

AVERAGE MATERIAL FLOWS PER 8-h SHIFT

Unit Process	PuO_2 Throughput (kg)	PuO_2 Sidestream Type	Sidestream (kg)
1A. PuO_2 receiving	8.09	Analytical samples	0.006 to ASF
3A. PuO_2 unloading	8.07	Analytical samples	0.002 to ASF
4A. PuO_2 blending and storage	8.08	Analytical samples Returns	0.002 to ASF -0.008 from MWT*
	MO_2 Throughput (kg)	MO_2 Sidestream Type	Sidestream (kg)
5. MO_2 blending	236	Waste Dirty scrap Analytical samples	0.1 to MWT 0.1 to MWT 0.024 to ASF
6. MO_2 powder storage	225	Reject sub-blend	11.2 to recycle MO_2
7. MO_2 pelletizing	223	Clean scrap Waste Dirty scrap	1.0 to CSRS 0.3 to MWT 0.3 to MWT
9. Pellet sintering	221	Clean scrap Dirty scrap	2.0 to CSRS 0.2 to MWT
11. Pellet grinding	203	Waste Dirty scrap Clean scrap Undamaged pellets Analytical samples	0.3 to MWT 0.3 to MWT 18.0 to CSRS -0.8 from rod repair* 0.033 to ASF
12. Pellet inspection	203	Dirty scrap	0.1 to MWT
13. Rod loading	202	Waste Clean scrap	0.1 to MWT 1.0 to rod repair
14. Rod inspection	200	Rejected rods Repaired rods	2.4 to rod repair -0.2 from rod repair*
17. Fuel rod repair	3.4	Waste	0.02 to MWT
18. CSRS	23.4	Waste Analytical samples	0.1 to MWT 0.001 to ASF

* Minus sign denotes return flow.

TABLE II-2

CAPACITIES OF CONTAINERS AND STORAGES
FOR THE MIXED-OXIDE FACILITY

Unit Process	Description	Number of Units	Unit Capacity
1A,2A	PuO ₂ shipping container	--	32 kg PuO ₂
2A	PuO ₂ storage vault	1	100 PuO ₂ shipping containers
3A	PuO ₂ can (4 per shipping container)	--	8 kg PuO ₂
4A	PuO ₂ blending and bulk storage	3	170 kg PuO ₂ (1 blend)
1B,2B	55-gal drum UO ₂	--	250 kg UO ₂
2B	UO ₂ storage vault	1	100 drums
4B	UO ₂ bulk storage	1	3000 kg UO ₂
4C	MO ₂ recycle storage	3	720 kg MO ₂
5	PuO ₂ feed hopper	1	~10 kg PuO ₂
5	PuO ₂ weigh hopper	1	~10 kg PuO ₂
5	Recycled MO ₂ feed hopper	1	~50 kg MO ₂
5	Recycled MO ₂ weigh hopper	1	~40 kg MO ₂
5	UO ₂ feed hopper	1	~230 kg UO ₂
5	UO ₂ weigh hopper	1	~200 kg UO ₂
6	MO ₂ blender	1	~280 kg MO ₂
6	MO ₂ storage silo	9	225 kg MO ₂
7	Compactor feed hopper	2	~20 kg MO ₂
7	Pellet press feed hopper	2	~50 kg MO ₂
7,8,9, 10,11	Pellet boat (5 in. x 12 in. x 12 in.)	--	1500 pellets, 15 kg MO ₂
8	Green-pellet belt conveyor storage	1	58 boats
10	Sintered-pellet storage (buffer)	1	135 boats
11,12	Pellet tray	--	900 pellets, 9 kg MO ₂
12	Sintered-pellet tray storage (buffer)	2	444 trays
13,14, 15,16	Fuel rod	--	200 pellets, 2 kg MO ₂
15	Fuel rod storage channel	--	50 rods, 100 kg MO ₂
15	Fuel rod storage	1	25,000 rods
15,16	Shipping box	--	200 rods, 400 kg MO ₂

each having a capacity of 170 kg--the amount required for one blend. The material in each storage vessel is blended pneumatically with dry air and then sampled for analysis.

Processes 1B to 4B: UO_2 receiving, storage, unloading, and process storage. The UO_2 is received in 55-gal drums and stored in a separate area. The contents of a drum are moved pneumatically to a transfer hopper located inside the main process building.

Process 4C: Recycle MO_2 blending and storage. Three blending and storage vessels, each having a capacity of 720 kg, receive MO_2 powder from the CSRS via pneumatic transfer. The MO_2 in each vessel is blended pneumatically (using nitrogen), sampled for characterization, and returned to the process stream in the course of preparing a sub-blend. Rejected MO_2 sub-blends are returned to recycle storage.

Processes 5 and 6: MO_2 blending and storage. A sub-blend of materials is made up from three different feed supplies: PuO_2 , UO_2 , and MO_2 recycled from the process stream. Each type of material is transferred from bulk storage to a feed hopper which then automatically meters out a programmed amount of material to a weigh hopper. Materials from the three weigh hoppers are then released to the blender. At the completion of the blending cycle, the sub-blend is transferred pneumatically through a reduction mill to one of the nine MO_2 storage silos reserved for a single sub-blend (225 kg MO_2).

Processes 7 and 8: Powder preparation, pellet pressing, and pellet storage. The incoming feed for the powder granulation and pellet-pressing steps is a 225-kg sub-blend from one of the MO_2 silos. The material is compacted, granulated, and mixed with lubricant. The granulated particles are fed to the pellet press. The resulting green pellets are loaded into boats that sit on a conveyor. The green pellets are inspected for density, and rejects are returned to the CSRS. The conveyor transfers the boats to the sintering furnaces and acts as a buffer storage.

Processes 9 and 10: Pellet sintering and storage. Boats of green pellets are selected from green-pellet storage and conveyed mechanically to the pellet sintering process. Five sintering furnaces operate in parallel. The density of selected pellets is determined, and any overfired pellets are returned to the CSRS. Underfired pellets are returned for more sintering. Boats of acceptable pellets are stored on the sintered-pellet conveyor pending their release to the pellet grinder.

Processes 11 and 12: Pellet grinding, inspection, and storage. These processes take sintered pellets from the boats, grind their surfaces to a specified diameter, inspect them for dimensions and nicks, and load the accepted pellets into trays. Two independent process lines (one operational, one stand-by) are available. Grinder sludge, chips, and off-specification pellets generated in these processes are returned to the CSRS. Trays are mechanically conveyed to one of two buffer storage/dryer units and stored by a stacker-retriever system. Pellet samples are taken from the storage/dryer after 4 h for moisture analysis.

Processes 13, 14 and 17: Fuel rod loading and inspection. A tray of pellets is retrieved from storage, and a row of pellets is aligned with the open end of a rod and fed into the rod. This is repeated until the specified number of pellets has been inserted. Each rod receives an end spring and a top-end plug, and is then decontaminated. The end plug is welded in a helium atmosphere, after which the rods are inspected visually, radiographically, and with a helium leak detector. There is also provision for x-ray inspection and a passive gamma-ray fuel rod scan to check the uniformity of the plutonium enrichment. Rejected rods are unloaded and the pellets are returned to the main process stream or to the CSRS. Minor rod repairs are made.

Processes 15 and 16: Fuel rod storage and inspection. Fuel rods are stored in channel carriers, which are placed in one of four shielded storage compartments by a stacker-retriever. The vault as described by Westinghouse can hold

25,000 rods or 500 channels. Boxes with a 200-rod capacity are used for shipping.

Process 18: Clean scrap recovery system. The CSRS conditions clean (high-purity) MO_2 scrap collected from pellet fabrication operations (process steps 7, 9, and 11) and from fuel rod repair and dismantling (process step 17), as shown in Fig. II-2. Batches of 20-30 kg are reduced in size in a crusher and are subsequently processed by multiple oxidation-reduction steps. A batch is processed through one of two oxidation-reduction reactors. The forming gas used for reduction is non-explosive 6% H_2 -94% N_2 . The recovered MO_2 powder is transferred to recycle storage.

Process 19. Analytical services facility. The ASF is a conventional analytical chemistry laboratory in which small samples from the main process stream and the LWT and MWT facilities are analyzed, as shown in Fig. II-3. Each of six criticality control zones maintained within the ASF has a plutonium limit of 290 g. All samples are transferred pneumatically from the source to the central material handling station (CMHS) of the ASF, where they are logged in, split, and distributed for different types of analysis. The estimated weekly load is 200-300 samples.

Processes 20 and 21: Miscellaneous waste treatment and dirty scrap. A block diagram of this sorting and high-grading operation is shown in Fig. II-4. The following typical materials are received.

Solid Wastes

- Combustibles--waste paper, clothing, rags,
- Plastic and rubber--gloves, bottles, tubing,
- Filter elements and cartridges, and
- Miscellaneous hardware.

Dirty Scrap

- Contaminated MO_2 pellets, chips, and sweepings,
- Excess analytical and quality control samples, and
- Filter elements from LWT.

Fig. II-2. Clean scrap recovery system.

Fig. II-3. Analytical services facility.

Fig. II-4. Miscellaneous waste treatment system.

Liquid Wastes

- Aqueous waste from the ASF, and
- Solvents and spent lubricants.

The solids are sorted into recoverable and disposable categories by using NDA instrumentation. Approximately four 55-gal drums per week are packaged and shipped off-site. Plastics with recoverable amounts of plutonium are shredded, washed with water, and discharged to the disposable-waste line. Combustibles with recoverable amounts of plutonium are reduced to ashes in a roasting furnace, and the ashes are combined with dirty MO_2 powder in a blending/sieving operation. The powdered dirty scrap from this process is packaged in 1-liter containers, assayed, tamper-safed, and stored in a special vault with a capacity for 1000 containers. If the dirty scrap fraction is 0.5% of throughput, the output of the highgrading operation should be ~ 3 kg MO_2 per day, or one to three 1-liter containers per day.

The MWT system will also be used to dismantle and clean small components, to treat and dispose of organic liquids, and to precipitate and filter MO_2 from aqueous solutions.

We believe that the miscellaneous waste volumes for many commercial nuclear facilities have been greatly underestimated. Recent studies confirm that commercial estimates of waste volumes for MO_2 facilities are as much as 40 times lower than ORNL^{17,18} estimates which are based on on actual ERDA operating experience. These studies state:

It appears from the magnitude of this discrepancy that industry may presently be underestimating the future TRU* waste problem. Such an underestimation results mainly from a tendency by some companies to ignore room-generated and auxiliary-system waste as potential TRU waste. The inability to accurately

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*Transuranic.

assay waste at the 10-nCi/g level presently requires much of the room-generated waste and auxiliary-systems waste to be classified as TRU waste. The misconception regarding the definition of TRU waste indicates a further need for cooperative discussions and investigations by government and industry in an attempt to obtain realistic TRU waste generation rates.¹⁹

These larger waste volumes can be handled by high-throughput NDA waste-sorting equipment being developed and evaluated by LASL.

Liquid Waste Treatment (LWT). The LWT concentrates and solidifies contaminated aqueous wastes from NMT and decontamination operations by mixing it with cement. The product is cast in 55-gal drums, which are shipped off-site. Expected input to the LWT facility is 2-1/2 gal of liquid per day, and 26 gal can be fixed in one 55-gal drum of concrete.

2. Holdup. Holdup is a significant materials control problem for both process operation and safeguards, particularly in the powder handling operations. Holdup is highly variable and difficult to measure reliably, even with state-of-the-art NDA techniques. It is clearly desirable to reduce holdup to a minimum. The main factors in minimizing holdup are process design and the selection of hardware. Effective procedures to control holdup can also be implemented during process operation. In the baseline plant, powder storage vessels and pneumatic transfer lines are run out to low levels of residual holdup at convenient times during process operation. Cleanup and collection of holdup where practicable during normal operation provide the opportunity for measurement and can minimize losses. A more thorough cleanup and runout of process equipment is scheduled in each process area between enrichment changes. These procedures are in addition to, and support, the plant cleanout and inventory cycle.

Table II-3 gives estimates of holdup for each process area of the baseline plant. At this time, holdup has not been estimated for the peripheral process areas, such as the ASF and MMT. In the table, holdup estimates are given for a single, identified equipment item. (See Table II-2 for the capacities of powder buffer storage vessels.) The number of similar hardware items in a process area is given as part of the identification. Two categories of holdup are specified: (1) holdup during processing is the amount of material that would remain if the process equipment were run dry, and (2) holdup after runout is the amount of residual material after normal runout operations that include vibrating powder storage vessels and pneumatic transfer lines, and a modest amount of cleanup.

The holdup estimates in Table II-3 are based on Westinghouse experience with UO_2 powder handling.⁴ Because a high throughput MO_2 facility has not been built, we believe that estimates of both waste volumes and holdup will be subject to large uncertainties (see quotation, page II-13). Powder holdup on interior metal surfaces of equipment is estimated to be 10 g/ft^2 after runout, and larger by a factor of 3 for in-process holdup. Holdup in pneumatic transfer lines is estimated to be 10 g/ft^2 after runout, and larger by a factor of 5 during processing. Holdup in filters is estimated to be 50 g/ft^2 for filter surfaces during normal operation, with no runout or cleanup capability. Modifications and improvements in process design could significantly alter the holdup estimates. Experimental R&D studies are required to verify them for actual plant operation.

C. Process Control

The primary requirement of process control is optimal operation of the process line. This requirement has three important aspects: (1) economical operation, (2) health and safety considerations, and (3) effective safeguarding of SNM.

The economic factor must obviously be emphasized in a privately operated commercial facility. Economy of operation is

TABLE II-3

HOLDUP IN THE BASELINE MIXED-OXIDE PLANT

Unit Process	Equipment ID (number of items)	Holdup After Runout (kg)	Holdup During Processing (kg)
3A. PuO_2 unloading	Glovebox filters, walls	0.2 PuO_2	0.4-0.8 PuO_2
	Pneumatic transfer line to PuO_2 storage (1)	0.1 PuO_2	0.5 PuO_2
4A. PuO_2 blending and bulk storage	Slab storage vessels (3)	0.6 PuO_2	1.8 PuO_2
	Vessel filters (3)	--	1.5 PuO_2
	Pneumatic transfer to blending (1)	0.1 PuO_2	0.5 PuO_2
5. MO_2 powder blending	PuO_2 feed hopper (1)	0.04 PuO_2	0.12 PuO_2
	PuO_2 weigh hopper (1)	0.04 PuO_2	0.12 PuO_2
	Recycle MO_2 feed hopper (1)	0.12 MO_2	0.36 MO_2
	Recycle MO_2 weigh hopper (1)	0.08 MO_2	0.24 MO_2
	Slab blending vessel (1)	0.7 MO_2	2.1 MO_2
	Blending vessel filters, reduction mill, feeders	2 MO_2	4-6 MO_2
	Pneumatic transfer line to MO_2 powder storage (1)	0.5 MO_2	2.5 MO_2
	MO_2 powder storage Silo (9)	0.7 MO_2	2.1 MO_2
6. MO_2 powder storage	Silo filters (9)	--	1.5 MO_2
	Pneumatic transfer line to pelletizing (1)	0.5 MO_2	2.5 MO_2
	Pneumatic transfer line to recycle MO_2 storage (1)	0.7 MO_2	3.5 MO_2

TABLE 11-3 (cont)

Unit Process	Equipment ID (number of items)	Holdup After Runout (kg)	Holdup During Processing (kg)
46. Recycle MO_2 blending and storage	Slab storage vessel (3)	2.0 MO_2	6.0 MO_2
	Vessel filters (3)	--	1.5 MO_2
	Pneumatic transfer line to blending (1)	0.2 MO_2	1.0 MO_2
7. Pelleting	Compactor feed hopper (2)	0.04 MO_2	0.12 MO_2
	Press feed hopper (2)	0.02 MO_2	0.06 MO_2
	Filters, compactor, granulator, separator, feeders, pellet press (2)	2-6 MO_2	8-12 MO_2
11. Pellet grinding	Filters, grinder, sludge separator (2)	2-3 MO_2	3-6 MO_2
17. Rod repair	Rod repair glovebox (1)	0.1-0.5 MO_2	0.5-1.5 MO_2
18. Clean scrap recovery system	Filters, walls	2-3 MO_2	3-4 MO_2
	Process heel in clean scrap reactor vessel (2)	--	10-15 MO_2
	Pneumatic transfer line to recycle MO_2 storage (1)	0.15 MO_2	0.75 MO_2

accomplished by designing the process control to maximize throughput while consuming minimum resources. For the MO_2 fuel plant this requires that PuO_2 be converted to fuel rod assemblies at the design rate with as few interruptions as possible and with a minimum rejection rate.

Health and safety are important in such a facility because of the radiological hazard of multiple recycle plutonium. As much material handling as possible must be done remotely; consequently, some customary process line techniques are inapplicable. For example, most on-line equipment repair must be done primarily with manipulators, not directly by hand.

The adequate safeguarding of SNM could have an adverse impact on the economical operation of the plant. Consider the case of a small amount of plutonium lost from the process at some intermediate point. Normal process control would probably ignore this event; indeed, it would probably be unaware of it. However, the safeguards system, through its MMAS, is expected to detect the loss and ask for an investigation, and some interruption of operations may be necessary while the source of the problem is determined. If the loss is the result of malicious, purposeful diversion of SNM, or is a false alarm, the process control function tends to regard the interruption as a nuisance. On the other hand, if the loss is benign (e.g., equipment malfunction or powder leak), process control receives useful and otherwise unavailable information from the safeguards system. This is also true during normal operations because the MMAS monitors the material flows in greater detail and with more accuracy than the process control system. The material flow data are accessible by the process control function through the adaptive data link to the MMAS (Fig. II-5).

These considerations result in a slightly different concept of process control than that normally followed. The process control function must be willing and able to interact with the health and safety and safeguards functions so that all three operational requirements are satisfied. Economical plant

Fig. II-5. Process control hierarchy.

operation alone is not sufficient. It is our opinion that, with proper design, economical operation can be achieved with minimum disruption and maximum benefit from the health and safety and safeguards systems.

1. Control Hierarchy. The process line is divided into a number of unit processes, each having its own unit process controller (UPC) which reports to one of the control subsystems (Fig. II-5). In addition to the control subsystems, the process control coordination (PCC) system also contains other subsystems not directly concerned with process control.

The PCC unit is responsible for the coherent operation of the entire process line -- it performs a supervisory function. It determines operating levels and operational sequences for each UPC so that they all work together. This form of hierarchical control is called setpoint control and is the traditional method of controlling complex systems.²⁰ It has been proven effective, and is well understood in the process control field.

This hierarchy allows each UPC to be devoted to one relatively simple unit process, thereby simplifying the UPC design because interactions with other unit processes are handled by PCC. A general UPC functional diagram is shown in Fig. II-6. The control may be manual, automatic with manual override, or a combination of these. The primary information transferred from PCC to the UPC is the desired setpoint of the unit process. However, PCC is also capable of retrieving UPC operating histories that have been compiled from past data.

The instrumentation required for process control of some unit processes is also useful for materials accounting. The resulting measurement data are sent in parallel to NMAS.

2. PCC Subsystems. The 10 PCC subsystems and their primary functions are listed below (refer to Fig. II-1). Some are self-explanatory.

a. Executive

- Overall process control and monitoring,
- Production planning and scheduling, authorized by the plant manager,

Fig. II-6. Unit process controller.

- Process data management, including report compilation and summarization, and
- Interface with safeguards systems.
- b. Receiving and Storage (1A, B; 2A, B)*
  - Control and monitor PuO_2 and UO_2 powder receiving and storage.
- c. Bulk MO_2 Operations (3A, B; 4A, B, C; 5; 6; 25)
  - Control and monitor MO_2 powder blending and storage.
- d. Clean Scrap Recovery (18)
- e. Pelleting (7, 8, 9, 10, 11, 12)
  - Control and monitor pelletizing, sintering, storage, grinding, and inspection.
- f. Fuel Rod Operations (13, 14, 17)
- g. Fuel Rod Storage and Shipping (15, 16)
- h. Miscellaneous Waste Treatment (20, 21, 22, 23, 24)
- i. Analytical Services (19)
  - Perform assay on various samples from the process line,
  - Perform quality control for the process line, and
  - Maintain instrument calibration.
- j. Health and Safety
  - Continuously monitor all safety requirements throughout the plant, and
  - Perform criticality control.

3. Operating Procedures. Details of the operating procedures are contained in Appendix A. They can be grouped into five modes: (1) normal, (2) maintenance and inventory, (3) emergency, (4) standby, and (5) shutdown. All modes can be activated on command from plant management. The only mode that can be activated by other than management is the emergency mode, which may be commanded by the health and safety and safeguards

*The numbers in parentheses designate unit processes in the baseline plant definition, see Sec. II-B.

functions. All other modes require at least the concurrence of management for activation.

a. Normal Mode. The normal mode exists when plant operations are proceeding as expected.

b. Maintenance and Inventory Mode. The maintenance and inventory mode is in effect whenever repair or special materials accounting procedures are required. Runouts and cleanouts are also performed during this time. Any part of the plant can be in this mode, while the remainder can be in normal, standby, or shutdown modes. In other words, the entire plant is not always expected to be in the maintenance and inventory mode. Maintenance and inventory are usually done in a stepwise fashion, one or a few unit processes at a time, except as NRC regulations require otherwise.

c. Emergency Mode. There are several types of emergencies, classified according to the systems that are directly concerned with them.

(1) Health and safety: criticality, radioactive material release, personnel injury accident, etc.

(2) Process control: for example, catastrophic failure of process line equipment resulting in severe economic damage; this may also cause a Type 1 and/or Type 3 emergency.

(3) Safeguards: this involves

- Personnel control -- a breach in physical security,
- Item operations control, or
- Materials measurement and accounting.

The first two items under safeguards emergencies are treated in the Sandia Corp. report.² The last item is discussed in detail in the section on the MMAS.

From the viewpoint of process control, the response to the emergency mode is that PCC will control the process to a relatively secure state. This can be done by moving SNM to areas of the process line that are less accessible to personnel, for example.

d. Standby Mode. The standby mode is used for relatively short (less than 1 wk) interruptions in plant operations where production is expected to resume without the more extensive shutdown procedures. It can be applied to all or any part of the plant. The portions on standby are operationally ready and need only a command from PCC to resume operations.

e. Shutdown Mode. When the plant goes into the shutdown mode, it is expected to be idle for some time (longer than 1 wk). All process lines are cleaned out and SNM is measured and stored in sealed containers, which are locked in vaults.

4. Software Functions. The main burden of the process control software functions lies in PCC and its subsystems. Almost no control-related calculations are made by the UPCs but are performed by the associated PCC control subsystems. The three nonstandard subsystems are:

Executive

- Overall control coordination, including responses to the five operation modes,
- Production planning and scheduling; an information service provided to plant management including report compilation and summarization,
- Process data transfer to the safeguards system,
- Overall process operating history compilation, and
- NMAS data transfer to PCC for possible improved control;

Health and Safety

- Personnel exposure compilation, contamination surveys, and
- Criticality calculations for all process areas;

Analytical Services Facility

- Quality control calculations,
- Material flow data processing,
- Detailed operating history compilation,
- Operating sequence definition, and
- Material analysis calculations.

The other seven PCC subsystems (see Sec. II-C-2) generally perform three software functions: (1) material flow data processing, (2) operating sequence definition, and (3) detailed operating history compilation. Another function is the calculation of MO_2 powder blends in the bulk MO_2 operations subsystem.

The main software burden is that of data management. The control algorithms required in the operating sequence definitions are very simple, in some cases nonexistent. Most of the sequences are determined off-line, compiled in a manual of operating procedures, and perhaps stored in memory for machine accessibility. Because the plant has been designed to be inherently criticality-safe, any required on-line criticality calculations are straightforward. They are necessary primarily for gloveboxes and storage areas where the amount of SNM can vary greatly.

5. Hardware Implementation. The process control functions described in the preceding sections can be implemented in many ways, but to be effective, the implementation must be chosen on the basis of trade-offs between several competing factors. The hardware must be simple, reliable, and as inexpensive as possible. It must be capable of communicating bidirectionally with the safeguards systems, the process operators, and the plant management. Because of unexpected events, it must provide for close human-machine interaction. Finally, it should lend itself to upgrading as the technology improves, while making unauthorized modifications difficult.

Use of the hardware configuration shown in Fig. II-7 is one way to accomplish these goals. Most of the hardware is a multi-input data acquisition system that collects all the process data at the executive processor. These data are stored in the process information system and selected portions are available to the operator at the command/display console. The unit process control level also has access to operating history data stored in the process information system, as well as a small amount of computational capability in the subsystem.

Fig. II-7. Process control hardware configuration.

processors (e.g., for blend ratio calculations). The operator generates setpoint commands using process data, management input, and safeguards information. The setpoint commands are then transmitted directly to the UPCs over hardwired communications links.

The UPC data concentrators are located in the process line area, close to the unit processes they serve. There is one concentrator for each PCC subsystem. This is possible because the UPC data rates are low; furthermore, cabling costs and I/O (input/output) port requirements for the subsystem processors are reduced.

This configuration allows efficient data gathering for making decisions that are difficult to circumvent by machine fault. Even if the data acquisition system fails completely, effective control can be maintained through the hardwired communications links. The same is true for the failure of any subsystem. Such failure has minimal impact on the remainder of the process.

Hardware components and their characteristics are listed below.

a. Control Instrumentation. The control instrumentation, which interfaces directly with the UPCs and the process line, is shown in Fig. II-6; at least initially, it is conventional in design except that outputs are interfaced to the data acquisition system. This may be done directly or through an operator who records the instrument reading and later enters it into the machine data stream through a terminal. We recommend that this interface be direct to eliminate human error and unnecessary delays.

Eight types of instrumentation are used in the baseline plant for process control: (1) material level sensors, (2) radiation monitors for alpha particles, gamma rays, and neutrons, (3) pressure sensors, (4) load cells and balances for weight measurement, (5) flowmeters, (6) mechanical gauging, (7) analytical measurements required for material assay, and (8) temperature sensors. For most measurements (except for

weights), 1% of full scale resolution is sufficient; this results in an instrument data word length requirement after A/D (analog/digital) conversion of eight bits (seven bits plus sign). The required weight measurement resolution is 0.01%, and it can be satisfied by linking two 8-bit words together. We recommend that the fundamental instrument data word size be eight bits with double-precision capability available.

Insofar as possible, the A/D conversion interface for each type of measurement instrument should be modular and standardized to facilitate replacement and repair and decrease the spare-part inventory. For those measurements used by both the process control system and the safeguards systems, the A/D conversion interface must be capable of driving both systems. This can be easily achieved if the digital outputs are buffered.

b. UPC Local Displays. The instrument readings are displayed locally in conventional fashion. The volume of data from the process information system and the subsystem processors that is useful to the UPCs on a short time scale is very small and specific to each UPC. It can be output at the local display through hardwired devices. More voluminous process operating histories, infrequently needed, are sent to the UPC in hardcopy form, thereby eliminating the need for keyboard terminals at most UPCs. Terminals can be added if the data flows warrant the added expense, or if manual data entry is desired. If terminals are used, they are the recommended communications devices between the UPCs and the PCC operator.

c. UPC Data Concentrators. Each UPC data concentrator compresses onto one line (or one set of parallel lines) the data from the unit processors that are under the control of a single PCC subsystem. Each also routes data from its subsystem processor to the correct UPC. The maximum number of data channels from any of the UPCs to its PCC subsystem is 63 for the pelleting subsystem. This does not include channels for data flowing from the subsystem processor to the UPCs. We recommend that 128-channel concentrators be used for all subsystems to

allow some room for expansion and to make the concentrators interchangeable.

d. Subsystem Processors. The subsystem processors can be relatively simple because they have a small computational burden. They are primarily I/O interfaces that act as buffers between the executive processor and the UPC data concentrators. They should have excess capability so that other functions may be added later.

The subsystem processors can be implemented with 8-bit microprocessors having 4 kilowords of ROM (read-only memory), 4 kilowords of RAM (random-access memory), and 2 bidirectional I/O ports. The RAM is used to buffer-store the data and the ROM contains the necessary software. Reliability can be greatly increased by adding buffer memory in the form of a cassette tape unit. The processors are thus interchangeable from subsystem to subsystem with only a ROM replacement.

e. Executive Processor. The executive processor is more complicated than the subsystem processors because it must manage a large volume of data, select and process information for the command/display console, and interface with the process information system and safeguards systems. A good choice for the executive processor is a minicomputer with 16-bit word length and 32 kilowords of memory. This size will allow direct control of the command/display console and the process information system. In addition, the executive processor can drive the peripherals, such as a printer, used to generate reports.

f. Command/Display Console. The display part of the console can be implemented with a CRT (cathode-ray tube), graphics terminal and printer. The executive processor controls the CRT using the graphics software and drives the printer for hardcopy output. The command links are hardwired to the UPCs by voice and/or signal lines.

g. Interface/Data Links. Any convenient interface/data links compatible with the hardware may be used, but they should be designed according to existing standards. The link

to safeguards must be designed so that a failure in one system does not disrupt the other.

The foregoing discussion suggests the type of equipment that might be used; specification should be done in consultation with equipment manufacturers.

D. Process Information System

Process data storage, manipulation, and distribution within the facility are accomplished by the process information system. Sources of information are made available for those control decisions that require automated data processing to augment manual functions. Data base access from remote locations allows information to be made available to safeguards and plant management. Process data fall into these categories.

- Routine automatic or manual functions essentially invisible to the production flow;
- Process parameters having a direct influence on the output product; and
- Measurements of the input and output products.

The last two categories are emphasized.

Multidimensional information spaces available to the user are not bounded by individual computer or device hardware, but are part of a distributed multicomponent system. This virtual single data store contains backup and redundancy not readily apparent to the user. Details of the information system architecture are specified in Sec. III-F. The full range of data input methods can be provided, from direct reading instruments interfaced to a computer to terminal access for manual entries.

Storage is allocated for each of the major process areas, including quality control (QC) and health and safety, and is divided into blocks and data fields. All but the field size are adjustable for the particular entry. Data format is standardized for interchangeability among users, and a uniform set of pointer conventions is established for data searches.

Archival transfer from disc to tape is projected for a 2-month interval or less, as the planned 30-million character random access disc storage is filled.

Categories of information common to all process steps are work orders, shop orders, material availability, process specifications, workload management, plans and schedules, manufacturing instructions, process operating management, process set-point, operating sequence, overall product routing and flow, equipment maintenance and down time, overall plant diagnostics, product traceability, process history, and process efficiency. Classes of information in the digital store are readily accessible for direct examination, individually conceived custom sorts or searches, and extraction for standard reports. Higher levels of information processing provide summary production and process status reports for management, with bilateral interaction in production planning for scheduling of personnel and material resources. The summary data store has room for ~ 1 million characters.

E. Plant Management

The plant management structure is straightforward and similar to traditional configuration. The major difference is the presence of the safeguards system (discussed in detail in Chap. III) with the requirement that the plant and its management be responsive to safeguards considerations. A block diagram of the management structure and of the authorization, information, and control data paths is shown in Fig. 11-8.

Management activities consist of the following steps.

- (1) The general manager makes a decision on a fuel contract and issues authorization to proceed with processing.
- (2) The general manager's fuel projects staff defines the scope of the work and issues a work order to the plant manager.
- (3) The plant manager and his staff, using the process information system, plan and schedule the work load.

(4) The plant manager combines the work plan with any safeguards constraints and issues authorization to start work. A shop order describes the technical requirements and scheduling. The same information is transmitted to the safeguards system.

(5) The plant manager continually reviews the shop order status and safeguards system inputs and initiates any necessary action.

(6) Line management, with the help of PCC, organizes the work load and executes process operations on the basis of feedback from the process line, QC (ASF), and health and safety, and on data from the process information system.

(7) QC releases and maintains surveillance on product quality, analytical instrumentation calibration and inspections, and analytical data.

(8) Health and Safety continually monitors all safety requirements for the plant, including criticality-related material transfers.

(9) The safeguards system continually assesses the safeguards status of the plant and makes action recommendations to the general manager and plant manager in case of possible safeguards breaches.

F. Plant Layout

The physical layout of the plant, with locations of the various process stages, is shown in Figs. II-9 and II-10.⁴ The UO_2 receiving and storage operations are located in a separate area because of the negligible strategic value and low toxicity of this material. Equipment for the main stream processes is shown in more detail in the sections shown in Figs. II-11 to II-15. Receiving, storage, batch makeup, and blending facilities are on the second floor of the building; the remainder of the main stream processes, beginning with the preparation of MO_2 powder for pelletizing, are on the first floor. Much of the building is dedicated to air filtering, because the use of

FIRST-FLOOR PLAN

NOTE: See succeeding drawings for section details. Only the canyons and limited access areas are shown.

SCALE: 1/16" = 1'-0"

Fig. II-9. First-floor plan of the Westinghouse RFP.

SECOND-FLOOR PLAN

LEGEND

- ☐ HEPA FILTER
- 1 CLEAN SCRAP STORAGE AREA
- 2 CONVEYOR REMOVAL HATCHES (3)
- 3 DIRTY SCRAP STORAGE AREA
- 4 DETACH HATCH
- 5 BAG-OUT HATCH
- 6 EQUIPMENT & SCRAP REMOVAL HATCH
- 7 P.G. STORAGE TANKS (3)

- 8 RECYCLED MO₂ STORAGE TANKS (3)
- 9 MO₂ STORAGE TANKS (9)
- 10 CLEAN SCRAP CRUSHERS (2)
- 11 CLEAN SCRAP REACTORS (2)

NOTE: Only the canyons and limited access areas are shown.

SCALE: 1/16" = 1'-0"

Fig. II-10. Second-floor plan of the Westinghouse RFP.

POWDER COMPACTION COMPLEX
SECTION "A-A"

Fig. II-11. Powder compaction system section.

Fig. II-12. Storage vessel section.

*TRANSFER SECTION THRU CANYON
SECTION "C-C"*

SCALE: 1/8" = 1'-0"

Fig. II-13. Canyon section.

CHARGE WEIGHING & BLENDING COMPLEX
SECTION D-D

Fig. II-14. Charge weighing and blending system, side view.

CHARGE WEIGHING & BLENDING SYSTEM
SECTION: E-E"

SCALE: 1/2" = 1'-0"

Fig. II-15. Charge weighing and blending system, face view.

pneumatic systems for transfer of powders requires an extensive air filtering system.

C. Material Handling and Personnel

All process, recycle, recovery, and chemical analysis (CA) operations involving plutonium and NO_2 are performed inside sealed, negative pressure canyons or in gloveboxes. These areas are designated restricted access areas (RAA). Areas adjacent to RAAs, where sampling, maintenance, control, and monitoring occur, are called limited access areas (LAA). Areas adjacent to LAAs are called normal access areas (NAA). The RAA, LAA, and NAA are comparable to ventilation confinement areas denoted by Zones 1, 2, 3, respectively, in AEC Regulatory Guide 3.12. Material handling lines, e.g., pneumatic transfer systems, mechanical conveyors, or pipes for liquids, connect the main process area to the ASF, MKT, LWT, and storage.

The estimated number of necessary staff people and their functions are given in Table II-4. Entries for 200-MT/yr production capacity show the total personnel required for four-shift operation. For functions involving large amounts of uranium or plutonium, ~ 97 people have direct access to the material. Table II-4 does not include personnel required to man the safeguards system. Safeguards staffing is discussed in more detail in Chap. III and in the Sandia Corp. report.²

TABLE II-4

STAFFING FOR THE
MIXED-OXIDE FUEL FABRICATION PLANT

<u>Process Operation</u>	<u>Personnel Required</u>	<u>Personnel with Access to Large Amounts of SNM</u>
Chemical makeup	2	
Receiving	4	3
PuO ₂ unload	4	5
Store, blend, sample		
U-Pu blend	4	4
MO ₂ storage		
Slag, granulate, press	20	13
Sintering	20	15
Grind, inspect, store	32	21
Receive, clean first welding	16	
Fuel rod loading		
Repair, dismantling	16	11
Rod inspection and storage	36	25
Clean scrap recovery system	4	
Analytical services	47	
Dirty scrap, recovery system	32	
Waste treatment	16	
Line supervision	24	
Subtotal	181	97
<u>Process Support</u>		
Custodians	9	
Pipe fitters	8	
Computer staff	12	
Electricians	11	
Process control instrumentation		
technicians	9	
Instrument repair and calibration	4	
Sheet metal and welding	5	
Painters and carpenters	3	
Machinists	5	
Tool crib	4	
Line support supervisors	2	
Health physics	39	
Subtotal	117	
TOTAL	398	

III. THE SAFEGUARDS SYSTEM

A. Introduction

Traditionally, facility safeguards systems have evolved in two separate areas: (1) physical protection and (2) materials control and accounting. Physical protection has followed the conventional industrial security strategy of exclusion, that is, protecting a secure operating area against unauthorized entry. Materials accountability within a plant and the detection of losses or unauthorized removals have relied heavily on material-balance accounting following periodic shutdown, clean-out, and physical inventory. During periods of routine production, control of materials in facilities is vested largely in administrative and process controls, augmented by secure storage for discrete items. Because of the limited capacity for prompt detection of unauthorized removals or losses, especially those involving small quantities of material, there has been increasing emphasis on development of automated systems for real-time measurement and control. One such system is the DYMAC (Dynamic Materials Control) system. ^{21,22}

A comprehensive safeguards strategy includes three functions: (1) exclusion of all unauthorized persons from the facility, with further selective exclusion of others from sensitive areas within the plant; (2) control of all activities involving materials so that each such activity is specifically authorized; and (3) confirmation that all materials are contained in their proper locations. The system for implementing that strategy must operate without unnecessary disruption of plant operations, compromise of safety requirements, or infringements on employee working conditions. The first function--exclusion and entry control--is the traditional function of the security force. It is, in effect, a personnel control function; it involves prevention of forcible entry, identification of those authorized

to enter, and enforcement of security regulations governing those who are admitted. The third function - quantitative confirmation of material possession and flows - is accomplished by the materials accounting system.

The function of controlling activities involving materials within the facility is not covered directly by either of the traditional safeguards elements. The concept of item operations control (IOC) provides direct protection of materials at those parts of the material flow stream where material is in the form of discrete items and where smooth material flow has less impact on the process line. In particular, operations such as unloading incoming shipments of feed material, handling of containers for weighing and assay, moving containers from the unloading dock to the storage vault and from storage to the container unloading station, and handling operations involved in the storage, packaging, and loading of product items are not closely coupled to process operations, and transients introduced into the material stream at those points should be manageable.

Where bulk materials are in process, particularly in automated operations, the MMAS, acting through the PDC, is the means for detecting and intercepting unauthorized material flows.

This report describes the MMAS, SCS, and the MMAS. The personnel control (PC) and IOC functions are discussed in detail in the Sandia Corporation.

Structure of the Integrated

The general block diagram of the facility shown in Fig. 1-1 is a simplified representation of the plant process itself, which is divided into unit processes. Each unit process has an associated control area (CA) for control purposes. Each unit process has an associated setpoint for that setpoint. The setpoint, which is a condition of the process, is specified by the authorizations, original and revised, and is a function of the process.

Fig. 11-1. Structure of the integrated system.

Each ICA is under the direct supervision of the IOC function. This arrangement provides more effective protection through remote, overriding control of discrete material items in handling and storage. The concept is applied only to those portions of the plant outside the closely coupled process line where material flow is not critical to smooth process operations.

The PCC unit is capable of using data from the MMAS in an adaptive fashion to help improve process operations. It also defines operational procedures to be followed when the SCS modifies the operational authorization, as would be the case for overt diversion detection, for example. Normally, all actions that might affect process operations are executed through PCC. An exception is safety-related emergency responses that require direct action.

The remainder of the block diagram consists primarily of the safeguards system. The SCS recommends modifications to the work authorization from management according to its assessment of the safeguards status of the plant. For example, if the safeguards status is satisfactory, the management work authorization is unmodified. However, if overt diversion has been detected or if an attack is imminent, SCS recommends that PCC control the process to a relatively secure state to further restrict the accessibility of materials. The SCS also transmits continuously the safeguards status to the MMAS for information only, and to the PCS so that the security force's status and deployment are appropriate.

The MMAS combines conventional CA, piece counting, and weighing with the real-time measurement and surveillance capabilities provided by NDA instrumentation. The MMAS is configured to provide rapid and accurate assessment of the location and amount of material in a plant, as described in reports on MMAS.

C. The Safeguards Coordination System (SCS)

The SCS is the heart of the safeguards system. Its function is to supervise the MMAS, IOCS, and PCS, and to interact with plant management and PCC so that effective safeguards measures are assured. It is the focal point for decisions affecting the safeguarding of SNM for the entire plant.

The SCS, as well as the complete safeguards system, must be as simple, reliable, and inexpensive as possible. Furthermore, the SCS decision making function must be well designed. Decision criteria that cause a high false-alarm rate cause unnecessary process disruptions. On the other hand, decision criteria must be such that the probability of effective response to any credible safeguards violation is sufficiently high.

1. Structure of the SCS. As the central component of the safeguards system, the SCS has three primary functions: (1) data collection and processing, which is required for (2) safeguards condition assessment, which in turn is the basis for (3) the response determination decision. A structural diagram of the SCS is shown in Fig. III-2.

To make good decisions, the SCS must have access to all pertinent safeguards data, management inputs, and process control information. Current safeguards data are available from the PCS, IOCS, and MMAS, and the safeguards operating history is stored in the data base of the safeguards information system. All management authorizations are sent in parallel to the SCS and to their primary destinations, and the process control data summary can be acquired from the process information system through the PCC executive.

Much of the information available to the SCS is not in a form suitable for decision making. The data processing block summarizes and formats the data for output at the display console. In addition, it generates the variety of safeguards reports required for management and the regulatory authority.

The Safeguards Officer uses the data processing information output at the display console to perform the condition

Fig. 111-2. Structure of the safeguard coordination system.

assessment function. The result of the condition assessment is the plant's status with respect to safeguards requirements. Many of the minor condition assessments can be automated with manual override, but most require direct action from the Safeguards Officer. Incoming SCS data are machine-monitored for possible indications of status changes (for example, by observing material imbalances or machine failures), and a response to each possible change is requested from the Safeguards Officer. He then evaluates the plant safeguards status and determines appropriate responses for the PCS, IOCS, and MMAS, taking into account process operations. These responses are transmitted to management and PCC, along with recommendations for modified process authorizations.

As many status/response situations as possible are standardized in a manual of operating procedures. This manual (or appropriate portions thereof) is available to plant personnel on a need-to-know basis. Of course, standard procedures may not have been written up for many situations, and that is the main reason for the Safeguards Officer. This scheme combines the efficiency of a machine in data handling with the adaptability of a human supervisor in making decisions.

2. Operational Procedures. The procedures carried out by the SCS are closely linked to the process operations, which are detailed in Appendix A. A typical sequence might be as follows:

(a) The general manager issues an authorization to proceed with processing on a fuel contract.

(b) The SCS receives the authorization and alerts the safeguards system that material processing is about to begin.

(c) The Safeguards Officer assesses the status of the safeguards system and informs plant management and PCC. If the safeguards system is not ready, he recommends a delay.

(d) After processing starts, the Safeguards Officer monitors the condition of the safeguards system and the safeguards status of the plant.

(e) If a safeguards system malfunction occurs, the Safeguards Officer assesses the extent of the impact, initiates (or confirms) remedial action, and makes appropriate recommendations to plant management and PCC.

(f) If a clear safeguards violation occurs or is impending, the Safeguards Officer alerts the safeguards system, plant management, and PCC, assesses the impact and recommends a course of action to all.

(g) If a possible safeguards violation is detected, the Safeguards Officer alerts the safeguards system, plant management, and PCC and, in consultation with the plant management and PCC, determines a response.

(h) The SCS (and MMAS) may supply PCC with details of material flows (adaption data) to aid PCC in improving the process behavior.

(i) During and after processing of a fuel contract, the SCS stands ready to supply any reports required for plant management and the regulatory authority.

The safeguards system has the same five operating modes as process control (see Sec. II-C-3): (1) normal, (2) maintenance and inventory, (3) emergency, (4) standby, and (5) shutdown. The main difference is that when SNM is moving, the safeguards system must be in the normal mode if at all possible. Otherwise, special arrangements for recording material transfers must be made.

In assessing the condition of the plant, the Safeguards Officer uses status reports from various parts of the plant. Taken together, these status reports constitute the plant status, which is stored in great detail in the safeguards and process information systems. However, the information normally displayed to the Safeguards Officer is condensed for quick assessment, with nonstandard situations flagged to indicate areas that should be investigated. The Safeguards Officer can ask for more detail, either in response to a flag or of his own volition. The standard report might be organized as follows:

Process Status

Management processing authorization

Process operating mode

Contract details

Identification

Specifications

Schedule

Equipment status

Safeguards System Status

Safeguards coordination system

Safeguards operation mode

Equipment status

Materials measurement and accounting system

Materials status

Current materials unbalances

Cusum* charts

Equipment status

Item operations control system

Item status

Equipment status

Personnel control system

Personnel on duty

Visitors/transients

Equipment status

Much other information could be included, but these data and the flags on possible problem areas are probably most suitable for efficient assessment of the plant condition.

After a new plant status report is available, the Safeguards Officer quantifies the situation by declaring that the plant condition is at one of four levels. These levels give a gross indication of the probability of SNM diversion or of danger to personnel.

*Cumulative sum of materials balances. See Chap. IV and Appendix E.

Level A is the normal operating level.

Level B is in effect whenever the possibility of diversion of a small amount of SNM exists or whenever there may be some hazard to personnel.

Level C indicates that substantial SNM diversion has probably occurred (or is impending) or there is significant probability of harm to plant personnel.

Level D is the level of catastrophe. The diversion of SNM is a virtual certainty, and/or human lives are in imminent danger. The three nonnormal levels may be further described by giving details of the problem, such as locations or SNM amounts. The details included must be sufficient for appropriate plant personnel to know what their responsibilities are.

Insofar as possible, the various situations encompassed by the four levels are described in a manual of operating procedures, along with suitable responses. This relieves the Safeguards Officer's decision-making burden somewhat, and helps ensure that the plant responds coherently to abnormal situations. After appropriate responses have been determined, the Safeguards Officer transmits them to the MMAS, LOCS, and PCS, and makes recommendations to plant management and PCC.

The SCS recommendations can range from no recommendation to the extremes of process shutdown and plant evacuation. If the safeguards system is successful, there will most frequently be no recommendation at all. In any case, the course of action in abnormal situations is chosen by agreement among the Safeguards Officer, plant management, and PCC, although some responses may be dictated by regulation. A detailed description of situations and responses is beyond the scope of this report.

The safeguards system status is available only to those plant personnel who are directly concerned, i.e., the safeguards staff, general manager, and plant manager. This helps prevent a potential SNM diverter from taking advantage of SCS malfunctions. Furthermore, safeguards functions are backed up by voice

command to prompt appropriate action when discrepancies are detected.

3. Software Functions. The first software function of the SCS is data management in support of the Safeguards Officer's decision function, and report generation for plant management and the regulatory authority. It is not a difficult task, and normally involves very little computational burden.

The second SCS software function consists mostly of a comparison of the latest materials data in the safeguards and process information systems. The computations required are simple and straightforward. PCC data are compared with the MMAS data to ensure that they agree on material transfers and locations. The probability of legitimate disagreement is small because almost all material monitors used for process control are also used for the MMAS. This scheme provides both a materials check and a systems integrity check. If significant disagreement is detected, an immediate investigation must be launched.

The third function of the SCS software is to spotcheck the integrity of the MMAS and the PCS/IOCS computing systems. This is done in the background of the SCS computer so that normal processing is not disrupted. Abnormal results cause load switching among the computers to maintain system effectiveness. Details of this arrangement are given in Sec. III-1.

D. Safeguards Information System

The safeguards information system provides a data management structure for coordinating and supervising activity relative to SNM control. Available sources of information are compared and contrasted using automated data processing and manual interpretation in searching for anomalous discrete events, trends, and tendencies toward possible theft or diversion. All files within the information store are available for use together with data from real-time function monitors, control consoles, and other forms of written and oral communication.

The primary facility interface to NRC is provided in terms of safeguards plans, compliance with regulatory policy, final preparation and distribution of reports, and scheduling of on-site inspections. Through accumulated data analysis and simulation, areas for measurement improvement are identified and development tests on new sensors and techniques are conducted continually to reduce material balance uncertainties. Data base privacy is enforced for selected information such as MMAS data and diversion detection thresholds. An initial list of safeguards information system files is given in Appendix B-II.

The basis for plant condition assessment can be partially automated through data processing and programmed decision logic. Discriminating factors include agreement with historical operating data and standard procedures, personnel present, interlock conditions, direct reading sensors for real-time monitoring, and oral communication. Similar decision processes are used in false-alarm analysis (see Sec. IV-A and Appendix E) and in evaluating the potential impact of other anomalous data.

Unauthorized and/or malicious changes to software and data bases can have a serious impact on decisions that are augmented by automated data processing. Integrity is initially verified by code-listing parity checks, and subsequently through line-by-line code comparisons with vault-secured master software tapes. Data base integrity is confirmed through comparisons with randomly distributed, known data entries. All user interactions with the system are logged and records are maintained of major computational functions performed. This is currently within the capability of existing minicomputer operating systems. An additional altering factor is that of repeated log-in attempts with incorrect employee payroll number, password, and/or access credentials. Only a small fraction of available minicomputer capacity is required to execute computer programs associated with these tasks.

The safeguards coordination system staff supervises SNM reporting procedures described in 10 CFR 70 and Regulatory Guide

10.1 for normal and unusual occurrences. These reports are listed in Sec. III-F, materials measurement and accounting system. Information from these and process line reports is summarized for plant management cognizance of SNM status. The summary can be placed on-line for interactive terminal access or can be put into hardcopy format. Further file access for custom searches and data processing by authorized personnel is available through the information store. Reports showing how the more comprehensive and precise safeguards information can benefit the process line are generated and made available through data base access.

The safeguards coordination system assists production control in its interactions with reprocessing plants in resolving shipper-receiver differences, tracing shipments, and negotiating equivalent fissile content material exchanges with nuclear power companies. SCS responsibilities also include supervising changes in SNM measurement techniques, revising and updating the SNM control plan, and obtaining corresponding approvals from NRC.

E. Materials Measurement and Accounting System (MMAS)

The MMAS design selected for the recycle NO_2 plant is an extension of DYMAL. This system takes full advantage of recently developed NDA methods and supportive computer and data base management technology to provide timely assessment of the location and amount of material within a plant. Conventional safeguards inventory control consists of major inventories conducted during periodic plant shutdowns and numerous accounting and administrative procedures for interim plant operating periods. The classical material balance associated with this system may not be sufficiently sensitive to detect a trigger quantity of SNM when plant throughput is large. Conventional inventory methods are not fast enough to deter SNM diversion effectively, and furthermore, economic penalties of more frequent plant-wide shutdowns for tighter control are severe.

Systems similar to DYNAC that address these problems have been described. 8-13,23

To implement the DYNAC approach, the baseline facility is first partitioned into discrete accounting envelopes, referred to as unit process accounting areas that can be one or more chemical or physical processes or a storage area. In contrast, storage vaults and buffer storages for discrete containers of material are conventionally referred to as item control areas (ICAs); material balance areas (MBAs) are defined on the basis of geography, function, custodianship, and regulatory requirements. By partitioning a facility into unit processes and measuring all material flows, quantities of material much smaller than the total plant inventory can be controlled on a timely basis. Computer-generated control charts derived from measurements and process operating characteristics can be used to indicate thefts, losses, or excessive holdup (see Chap. IV and Appendix E). This detailed control forces a potential diverter to steal SNM in sufficiently small quantities that his individual removals will be masked by measurement uncertainties. Thus, to obtain a sizable quantity of material, the diverter must commit many thefts with the concomitant high risk of detection by the accounting system, surveillance instruments, doorway monitors, and physical protection system.

The concept of timely material balances must be flexible to be practicable; its application should be graded according to the safeguards strategic value and vulnerability of the material. Often these timely material balances are only approximately closed, the reasons for which are best illustrated by comparison with the traditional periodic plant inventory and material balances. During an inventory, stocks of SNM and residual holdup in each MBA are measured. A balance is drawn using the equation

$$\text{Material Balance} = \text{Last Inventory} + \text{Receipts} - \text{Shipments} \\ - \text{Current Inventory,}$$

and a limit of error is calculated. If all SNM in each category has been measured (no unmeasured sidestreams or holdup), the balance should be zero within the limit of error; if some material is unmeasured, the balance closure is only approximate.

The DYNAC system complements, but does not replace, the cleanout and physical inventory cycle. Material balances drawn around unit processes are referred to as dynamic material balances to distinguish them from balances drawn around each MBA after a cleanout and physical inventory. A dynamic material balance is based on measurements of significant material transfers into and out of the unit process during its material balance period. Whether in-process material and holdup are measured depends primarily on the variability in the level of these materials during the balance period. If the variability is sufficiently small, the effect on individual balances may be negligible. Furthermore, the added control obtained by measuring small sidestreams of material may not justify the difficulty and expense of making the measurements.

Although the immediate consequence of unmeasured sidestreams and holdup may be negligible, the long-term effect will be similar to that produced by repeated small thefts. Two complementary methods are used to distinguish unmeasured process material from the diversion of small amounts of SNM. Small sidestreams may be accumulated at a convenient location and then measured, i.e., the accumulated material will be measured less often than the larger material transfers. The measured amount of sidestream material is subtracted from the cumulative sum of dynamic material balances. In the same way, if holdup slowly accumulates in the process area, a portion of it will be cleaned up and measured periodically. The time between sidestream and holdup measurements depends on the size and variability of the amounts of SNM involved. For example, much residual holdup in the plant, that is, holdup remaining after a cleanout campaign, would be measured only at physical inventories.

In the second method, historical data are used to estimate the level of unmeasured material during process operation. Several analytical techniques have been proposed that compare predicted results of process operation with incomplete measurement data (see Appendix E). All of these use (or generate) historical data to make estimates. Such estimates can be included directly in the dynamic material balances or used to interpret trends observed in measurement data. In either case, the uncertainty in the estimates can be combined with the measurement errors to determine system sensitivity to long-term diversion.

The key points concerning unmeasured sidestreams, holdup, and dynamic balances are:

- If a material stream causes significant variability in individual dynamic balances for a unit process, it should be measured.
- Estimates of unmeasured material can be used with measured dynamic balance data to detect trends caused by repeated small thefts. These estimates must be updated or replaced by data from measurements that are made less frequently than the dynamic balance requirements, the ultimate update being the traditional cleanout and inventory procedure.
- The unmeasured SNM must be either in a form that is unattractive for diversion or that is physically inaccessible between measurements.

Two factors influencing the selection of measurement and material balance strategies for the MMAS are the concept of graded materials safeguards and the requirement for minimum process disruption. Much design effort has been spent on material controls for PuO_2 powder handling operations, as this is the most desirable form of SNM for diversion in the baseline plant. Less stringent material controls are placed on unit processes that handle MO_2 powder and pellets because the plutonium is diluted by a factor of 25 by the powder blending operation. Process areas where the SNM is well controlled by physical means, e.g., the areas containing assembled fuel rods, also

receive less emphasis. The compatibility of the fabricated MO_2 fuel forms with the graded safeguards concept is illustrated qualitatively by Table III-1, which shows the number of pellets, rods, fuel elements, etc., that would have to be diverted in order to obtain 10 kg of plutonium. The increasing attractiveness of the larger assemblies is offset by their size and weight; a single fuel assembly will probably weigh over 1 MT and is about 4 m long. Diversion of smaller, more manageable units, such as a few pellets or some feed powder, would require repeated efforts to obtain the same quantity of plutonium, thereby enhancing the probability of detection.

TABLE III-1

PLUTONIUM CONTENT OF MIXED-OXIDE COMPONENTS

<u>Unit</u>	<u>Number of Pellets</u>	<u>Pu (g) Per Unit</u>	<u>Units Per 10 kg Pu</u>
Pellets	1	0.353	28,347
Pellet boats/trays	900	317	31.5
Fuel rods	200	70.6	142
Shipping boxes	40,000	14,111	<1
Fuel elements	45,000	15,875	<1

NOTE: A single pellet is assumed to weigh 10.0 g.

The principal goal of the MMAS is to draw dynamic material balances at least once per processing increment, which typically requires one or two 8-h shifts to complete. The system has been defined and evaluated with the aid of detailed computer models and simulation of the processes and measurements (see Sec. IV-A and Appendixes D and E).

1. Measurements and Inventory Control. The measurement system for inventory control is a combination of weighing and CA, nuclear NDA, and item identification (ID) and counting. The recommended system, although similar to the original Westinghouse design, includes the upgrading of some existing instruments and the inclusion of a small number of additional instruments to permit material balances to be drawn around each unit process. For the main process stream, which includes the CSRS, simple neutron and gamma-ray instruments and weighing devices were added to provide timely data on process materials and hold-up. The instruments and, to a large extent, the measuring and calibration procedures, are automated so that data are fed directly to the materials accounting computer with minimal operator interaction. Sophisticated NDA devices were added to the ASF to provide rapid analysis of process samples for verification and for the calibration of process-line NDA instrumentation for current process materials. These instruments may in some cases eliminate the need for further CA measurement in the ASF. NDA instrumentation in the MWT and LWT facilities provides essentially all the data needed for material balances in these areas and for their principal functions of waste and scrap management.

Weighing and nuclear NDA instruments selected for the MMAS are described in Appendix C. Typical measurement uncertainties needed for the essential description of the MMAS are given below. Specific subsets of these measurements and their associated uncertainties used for the performance evaluation of dynamic material balances with the MMAS are given in Secs. IV-5 through IV-9. A more extensive review of the uncertainties of both CA and NDA methods for materials of the fuel cycle has been made by Reilly and Evans.²⁴

Main Process Stream. The measurement system for inventory control of materials in the main process stream is presented in Tables III-2, III-3, and III-4. The only measurements shown for the UO_2 receiving and storage operations are those required for

TABLE III-2

MEASUREMENT SYSTEM FOR MAIN PROCESS STREAM

Unit Process	Instrument Type	Change in Baseline RFP	Number	Measurement
1A, 2A. PuO ₂ receiving and storage	ID and seal NDA (n)	I ^a	1	Shipping container
		A	1	Shipping container verification
3A. PuO ₂ unloading	ID and seal Weighing (10 kg) Sample/CA & NDA ^c NDA (γ) ^d	I	1	Shipping container, canisters
			1	Canisters
		I	1	Pu, Pu isotopic, H ₂ O, etc. Holdup in box, empty canisters
3B, 4B. UO ₂ unloading, storage	Sampling/CA & NDA		-	U, ²³⁵ U, H ₂ O, etc.
4A. PuO ₂ blending and bulk storage	Weighing (10 kg)	A	3	3 weigh hoppers
	Weighing (170 kg)		3	Storage vessels
	NDA (γ)	I	1	Holdup in weigh hopper
	Sample/CA & NDA		-	Pu, Pu isotopic, H ₂ O, etc.
	NDA (γ)	I	2	Holdup in transfer line
	NDA (γ)	I	3	Storage router valve
4C. Recycled MO ₂ blending and storage	NDA (γ)	I	3	3 blending vessel filters
	Weighing (50 kg)	A	3	3 weigh hoppers
	Weighing (720 kg)		3	3 storage vessels
	Sample/CA & NDA		-	Pu, U, isotopes, H ₂ O
	NDA (n)	I	3	3 storage vessels
	NDA (γ)	I	1	Holdup in transfer line
	NDA (γ)	I	1	1 representative vessel filter

^aAdditions and improvements are denoted by A and I, respectively.

^bNDA (n) - nondestructive analysis by neutron detection.

^cSample/CA & NDA denotes samples taken from the process line to the ASF where they are analyzed by chemical analysis (CA) and NDA.

^dNDA (γ) - nondestructive analysis by gamma-ray detection.

TABLE III-3

MEASUREMENT SYSTEM FOR MAIN PROCESS STREAM^a

Unit Process	Instrument Type	Change in Baseline RFP	Number	Measurement
5, 6. MO ₂ blending, milling and storage	Weighing (15 kg)	A	1	PuO ₂ feed hopper
	Weighing (300 kg)	A	1	Recycled MO ₂ feed hopper
	Weighing (10 kg)		1	PuO ₂ weigh hopper
	Weighing (250 kg)		1	MO ₂ weigh hopper
	Weighing (250 kg)		1	Recycled MO ₂ weigh hopper
	NDA (n)	I	1	Recycled PuO ₂ feed hopper
	NDA (γ)	I	1	Recycled PuO ₂ weigh hopper
	Sample/CA & NDA		-	Pu, U, isotopics, H ₂ O
	NDA (n)	I	1	Blending vessel
	NDA (γ)	I	1	Blending vessel filter
	NDA (n)	I	1	Powder mill
	NDA (γ)	I	3	Powder transfer line
	NDA (γ)	I	3	3 representative storage routings
	Weighing (250 kg)		9	9 storage silos
	NDA (n)	I	9	9 storage silos
	NDA (γ)	I	3	3 representative silo filters
7, 8. MO ₂ pelleting	NDA (n)	I	2 ^b	2 compactor feed hoppers
	NDA (n)	I	2	2 pellet press hoppers
	NDA (γ)	I	6	Holdup
	Counter	A	2	Green pellets loaded into boat
	ID, weighing (20 kg)	A	2	Green pellet boats
	ID, weighing (35 kg)	A	2	Scrap containers
9, 10. Pellet sintering and storage	ID, weighing (20 kg)	A	2	Boats after sintering
	Sample/CA & NDA		-	Pu, U, isotopics, etc.
	ID, weighing (35 kg)	A	2	Scrap containers
	ID,	I	2	Item control - stacker/retriever storage for sintered pellet boats

^a See footnotes a-d for Table III-2.

^b The Westinghouse RFP design incorporates dual process lines for pelleting through fuel rod loading operations. The number of instruments shown for these processes is for two lines.

TABLE III-4

MEASUREMENT SYSTEM FOR MAIN PROCESS STREAM^a

Unit Process	Instrument Type	Change in Baseline RFD	Number	Measurement
11, 12 Pellet grinding and storage	ID, counter	A	2	Sintered pellet boat unloading
	Counter	A	2	Pellets loaded into tray
	ID, weighing (20 kg)	I	2	Pellet trays
	ID	I	2	Item control - stacker/retriever
	ID, weighing (35 kg)	A	2	Storage for trays
	NDA (n)	A	2	Scrap containers
	Sample/CA & NDA		2	Grinder, sludge holdup
	Weighing (35 kg)		-	Pu, U, isotopes, etc.
	ID	I	-	Finished pellet reservoir
	Counter		2	Pellet trays
13, 14, 17. Fuel rod loading, inspection and repair	NDA		2	Pellets loaded into rods
	ID, weighing (3 kg)	I	1	Fuel rod analyzer for total fissile and pellet-to-pellet uniformity
	NDA (γ)	I	1	Fuel rod
	ID, weighing (35 kg)	A	1	Holdup in rod repair box
	ID, seal	I	1	Scrap containers
	ID	I	1	Fuel rod channels
15, 16. Fuel rod storage and shipping	ID, seal	I	1	Item control - stacker/retriever
	ID	I	1	Storage for fuel channels
	ID, seal	I	1	Shipping boxes of rods
18. Clean scrap recovery	ID, weighing (35 kg)	I	1	Clean scrap containers
	NDA (n)	I	1	Clean scrap containers
	NDA (n)	I	2	2 crushers
	NDA (n)	I	2	Hoels in two R-O-R reactors
	NDA (γ)	I	2	Filters on R-O-R reactors
	NDA (γ)	I	1	Holdup in product powder transfer line

^aSee footnotes a-d for Table III-2.

safeguards management of materials in the main process stream. The total numbers of instruments of each type used in the main process stream were not always specified in the original RFP design and their function was usually threshold indication instead of quantitative analysis. Similarly, the recommended ID system uses an automatic label reader, whereas the RFP ID design uses manual readings. Thus, many of the changes reflect advances in technology since the original design of the RFP.

Most of the instruments used in the main process stream are weighing devices and nuclear NDA neutron and gamma-ray detection systems for measuring holdup and process materials. Digital balances with measurement standard deviations between 0.01 and 0.02% of full scale are specified for the PuO_2 unloading operation. For load cells, which are used for all other weighing operations, the standard deviation of a measurement lies in the range of 0.1-0.5% of full scale, depending on process line constraints. Uncertainties in the holdup measurements currently specified are considerably lower than those achieved with portable instruments. Typically, the relative standard deviation of a nuclear NDA measurement of holdup or process material is expected to be in the 5-25% range. These projections are based on holdup measurements performed under less than ideal conditions at LASL, K-25 (the Oak Ridge gaseous diffusion plant), and at the Kerr-McGee plutonium facility.²⁵⁻²⁷ The technique used to verify the nuclear contents of shipping containers of PuO_2 in the receiving area is similar to that used for holdup evaluation by neutron detection and is expected to have a relative uncertainty of ~ 5% (1 σ).

For the operation of the MMAS, the most important measurements of samples sent to the ASF are plutonium and uranium weight fractions and isotopic compositions, specific neutron yields, and moisture content. The weight fractions and the moisture measurement affect the weighing of bulk materials in the main process stream, while the isotopic compositions and neutron yields are needed for the calibration and interpretation

of the nuclear NDA measurements in the process line. The uncertainty of the plutonium fraction derived from CA ranges from $\sim 0.1\%$ for PuO_2 feed material to 0.3% for clean scrap.²⁸ Uncertainties in isotopic analysis depend on the abundance of the isotope and the form of the material, as discussed in Appendix C.

Pellet counters supplement weight measurements in the process line, from the loading of green-pellet boats to the loading of fuel rods. Counting (item control) provides better control and eliminates the need to weigh rods between welding and inspection operations. Pellet counters with rates of $\sim 6/\text{s}$ have been designed for the High Performance Fuel Laboratory (HPFL) to be constructed at the Hanford Engineering Development Laboratory (HEDL).²⁹

The NDA fuel rod analysis system for the fuel inspection operations (unit process 14), is a key nuclear NDA system for safeguards, as well as for product quality assurance. A device similar to that designed by Nenlove et al.,³⁰ for analysis of FFTF fuel rods can analyze all rods produced, at a rate of about 13/h. Total fissile content of the rod and pellet-to-pellet uniformity are measured. The relative precision for analysis of the fissile content of a single rod is 0.5% (1 σ), and the uncertainty of the measured fissile content of a large number of rods may be as small as 0.1% , depending on factors such as the quality of calibration standards.³⁰⁻³² Pellets with enrichments that are out of specification by 5% (relative) or more can be detected with almost 100% efficiency and a false rejection rate of less than 2% . Additional straightforward development is required to adapt the FFTF fuel rod analyzer design for LWR recycle fuel rods.

Miscellaneous Waste Treatment. The instrumentation needed for MWT scrap and waste sorting and concentration operations is almost identical to that used routinely in the LASL plutonium scrap recovery facility.³³ Materials received at MWT include high-concentration fuel scrap, low-concentration combustibles, hardware, and glass, and plutonium-rich solutions. Containers

for these materials range in size up to 20 liters. As shown in Figs. II-3 and II-4, the products of the MWT are: (1) small containers of highly concentrated solid scrap to be stored for future recovery, (2) drums of treated organic solvents and dense waste destined for waste disposal, and (3) contaminated filtrates and wash solutions for return to LWT. The following instruments should suffice for the accounting and management of materials in MWT with minimal need for sample analysis at the ASF:

- Two ID and weighing systems for receipts and products,
- One large neutron coincidence unit^{34,35} for analysis of receipts and products and for sorting,
- One multi-energy gamma assay system (MEGAS),³⁶ with a metal detector, for sorting combustible waste at the 10-nCi/g fiducial,
- One Ge(Li) gamma-ray analysis system with segmented scanning and selected isotopic analysis capabilities for analysis of solids and liquids,
- One on-line solution analyzer at the solution receiving tank,
- One in-line neutron coincidence counter³³ and NaI detector in the glovebox for shredding, washing, and filtering, and
- One portable NaI gamma-ray system³⁷ for holdup measurements.

The fixed instruments listed above will be interfaced with the MMAS computing system, and for accounting purposes MWT is treated as a single unit process. With the above instruments, the measurement uncertainty of the product containers of dirty scrap, which contain the bulk of the MWT plutonium throughput, is expected to be less than 5% (1 σ).

Liquid Waste Treatment. Because the function of LWT is to receive and solidify aqueous wastes that do not contain recoverable quantities of plutonium, the only measurement required is that of the solution plutonium concentration after filtration.

Any of the following three options for this measurement should be satisfactory:

- Sample and analyze with NDA measurements at MWT,
- Sample and analyze with CA or NDA measurements at the ASF, or
- Use a local in-line, low-level, gamma-ray solution analyzer.

The last option may be preferable if a simple instrument can be used to obtain semiquantitative data for concentrations below a fiducial. In MMAS, LWT is treated as a single unit process.

Analytical Services Facility. The ASF described in the Westinghouse RFP design comprises a central material handling station and the following laboratory areas:

- Chemical analysis,
- Emission spectrography,
- Low-level alpha measurements,
- Mass spectrometry,
- Radiochemistry, and
- Metallography.

The functions of this facility include the preparation and calibration of control standards for SNM and development of analytical programs for quality assurance, as well as routine analytical support for the entire plant. The daily sample load for the ASF is ~ 70 samples. Turn-around times for sample analyses vary from 4-24 h. Westinghouse estimates of SNM quantities per shift from the various points of origin are presented in Table III-5. The NDA capabilities recommended for MWT and LWT in the present conceptual design eliminate the need for samples from these facilities.

In this conceptual design, an NDA station is added to the ASF at the CMHS, where samples are received, logged, weighed, and split for various analyses. The NDA instruments permit rapid analysis of process samples for verification and calibration of process line NDA instrumentation. Considering the success of well-designed NDA instrumentation operated in a controlled, low-background environment, it is likely that these

TABLE III-5

ANALYTICAL SERVICES FACILITY SAMPLES

<u>Point of Origin</u>	<u>SNM Measurements</u>	<u>Quantity of Material (g/8-h shift)</u>
PuO ₂ receiving (vendor samples)	plutonium, plutonium isotopes, trace uranium	7.1
PuO ₂ unloading	plutonium, plutonium isotopes, moisture	2.3
PuO ₂ slab storage and blending	plutonium, plutonium isotopes	1.4
UO ₂ receiving	uranium, uranium isotopes	7.1
UO ₂ blending	uranium, uranium isotopes, moisture	3.8
Recycle MO ₂ slab storage and blending	plutonium, plutonium isotopes, uranium, moisture	1.2
MO ₂ storage	plutonium, plutonium isotopes, uranium	23.8
MO ₂ pellets (after sintering)	N.A. ^a	40.0
MO ₂ pellets (after sintering)	plutonium, plutonium isotopes, uranium, uranium isotopes	33.3
MO ₂ pellets (after drying)	N.A.	4.8
LWT feed tank	plutonium	<0.1
Decon cell, liquid hold tank	plutonium	<0.1
ASF liquid waste pretreatment	plutonium	2
MWT, treated scrap (MO ₂)	plutonium, plutonium isotopes, uranium	2.8
MWT, organic waste	plutonium	nil
MWT filtrates	plutonium	nil

^aNot applicable.

Instruments will frequently reduce or eliminate the need for further CAs.

The NDA station consists of two instruments: (1) a polyethylene-moderated neutron coincidence well detector, and (2) a high resolution Ge(Li) gamma-ray spectrometer. These instruments and the digital balance used for weighing the samples can be serviced with one small minicomputer, which can also do the ASF accounting and report to the MMAS computer.

The neutron coincidence detector measures a combination of the ^{240}Pu and ^{242}Pu content of the sample, and conversely, if these isotopic abundances are known, the total plutonium content can be obtained. Such detectors are now well developed, ³⁸⁻⁴³ and measurement uncertainties of less than 0.5% (1c) should be obtained for samples with more than 10 g plutonium. This detector can also measure the specific neutron yield of PuO_2 and MO_2 materials drawn from key points in the process line, thereby providing a calibration for in-line neutron detectors that are used for dynamic material balances.

The Ge(Li) gamma-ray spectrometer can be used to measure the ^{239}Pu , ^{241}Pu , and ^{238}Pu relative abundances, and plutonium and uranium contents. The ^{235}U isotopic abundance of UO_2 feed material can also be readily obtained. The optimum detector for this wide range of applications has a resolution better than 0.8 keV at 122 keV and an efficiency of about 10% (relative to NaI) for ^{60}Co gamma rays. Detectors with these characteristics are commercially available, although at premium prices.

It may also be necessary to add a high-efficiency NaI gamma-ray analysis system to the above systems for the analysis of small samples such as individual pellets. Such a detector is fully compatible with the NDA station design, and should not increase the cost much. Another available option is a calorimeter, which, together with the mass spectrometer, could be used for verification of plutonium assay and as a part of the standards and measurements control program for the nuclear NDA systems. The use of calorimetry for plutonium analysis is well

documented, and some aspects that relate to NO_2 analysis are discussed in Appendix C.

The ASF is treated as a single unit process in the MMAS design.

2. Standards and Measurements Control. A format program of calibration and quality control of all NDA and CA instruments used for SNM material inventory control is required. System calibrations and reliabilities are of paramount importance to process control, safety, and product quality assurance, as well as to safeguards.

Standards and measurement controls for traditional chemical methods are well developed and rely on periodic calibration with standards traceable to the National Bureau of Standards. Inter-laboratory exchange programs also provide data on measurement performance.

The status of programs for standards and measurement controls for NDA systems is not as good as for traditional chemical methods, but progress has been recently accelerated by developers, users, and groups working to develop consensus standards, e.g., American National Standards Institute Subcommittee INMM-9.4. Several studies of measurement uncertainties have been reported. 24,44-47

The first step in developing such a program for NDA measurements is to characterize plant materials as to type, matrix, containers, administrative controls, etc., so that measurement methods and construction or selection of representative working standards may be optimized. Detailed analysis should be performed for each instrument, quantifying identifiable sources of error such as geometry, matrix, isotopic mix, spatial distribution. Results of these analyses form the basis for assessment of measurement errors, a task essential to the determination of limits of error for material balances. As part of the error analyses, NDA measurements are compared with CA and recovery data. Operating manuals must be available for each NDA instrument and chemical method, documenting details of operation, stability checks, calibration, limitations, data reduction, and

error analysis. For most instruments, calibrations can be made automatically and, if required, randomly to deter tampering.

The review of NDA and CA measurement uncertainties that is to be presented in a separate document²⁴ should be useful for evaluating the performance of measurement systems for nuclear facilities.

3. Surveillance Instrumentation. Consistent with the safeguards architecture described in this chapter, surveillance systems logically fall under the plant physical protection system being described in the companion paper,² and will not be discussed here. Many reports on developments and evaluations of surveillance instruments are available.⁴⁸⁻⁵²

4. Materials Inventory Accounting. Conventional materials accounting techniques are compatible with the safeguards design. In particular, material transfer records are readily available, either on-line or from 5-yr archival storage. MBA accounting is still done as required by regulation, and all necessary reports are generated in a timely fashion. Furthermore, unit process accounting data, which are more detailed than MBA accounting data, are available, and material transactions are electronically recorded to decrease the volume of daily paper work. The double-entry materials accounting system is computerized for efficient data management.

F. Safeguards Computer Network (SCN)

We have emphasized repeatedly that the SCN must be as reliable and inexpensive as possible. The reliability of the SCN and the entire safeguards system is particularly important for two reasons. First, of course, is the protection of SNM. Clearly, diversion of SNM cannot be detected or prevented in a timely manner without reliable, effective SCN implementation. Second, the SCN affects process operations through Safeguards Officer recommendations to plant management and PCC that are based on information provided to the Safeguards Officer by the SCN. Erroneous or unavailable SCN data degrade recommendation quality and can cause unnecessary process disruptions. Thus,

SCN reliability directly affects economical operation of the plant.

Many implementations of a reliable safeguards computer network are possible. However, economic and performance constraints dictate that the SCN design be used on well-known, proven technology that is readily available. The SCN, as well as the entire plant, is a production-oriented system, not a developmental one. Although valuable experience will be gained, production of fuel rod assemblies is the prime objective. New concepts can of course be tried if their impact on the process is carefully considered beforehand.

The use of proven technology has several advantages in addition to reliability. Most important is that much of the equipment, both hardware and software, is stocked by manufacturers as off-the-shelf items. Capital costs for proven systems are generally lower than for untried systems, and developmental and testing programs are less extensive and costly. Furthermore, maintenance and repair capabilities already exist.

Security of the SCN, which is related to its reliability, severely constrains the SCN design. The main security threats are sabotage and data misappropriation. Sabotage can range from destruction, which results in immediately apparent catastrophic failure of some portion of the system, to functional subversion, which covertly compromises system integrity. Physical security, controlling access to the SCN, is the first line of defense against sabotage, but it is vulnerable to attack by an insider. Equipment and functional redundancy, also required for reliability, are important threat deterrents at all levels, and self-checking capabilities can effectively eliminate the possibility of undetected subversion.

Physical security also helps prevent data misappropriation, and includes not only personnel movement control, but control and monitoring of man-machine interfaces. The personal magnetic card for terminal activation exemplifies this approach. Restricted access file structures are an integral part of software

security measures, and can take the form of passwords and access mode permits (e.g., read, write, and/or purge).

Reliability and security techniques are necessary for the safeguards system, but they can also be useful in process control. For example, the commercial plant operator may wish to protect proprietary process information. These kinds of decisions are left to plant management and are not discussed further here.

1. General Structure of the SCN. One possible configuration for the SCN is shown in Fig. III-3. Both SCS and MMAS have their own mainframe computers, and an additional one, the physical security computer, serves both the PCS and IOCS. The MMAS data are collected at I/O ports and sent through data concentrators to the MMAS buffer memory; physical security data for the PCS and IOCS are gathered similarly. As for process control (Sec. II-C), the data concentrators, located in the process areas, help reduce cabling costs and I/O requirements for the buffer memories. Redundant trunk lines from data concentrators to buffer memories help to prevent common-cause failures and to deter sabotage. The buffer memories can store as much as one shift of raw data, thus preventing loss of safeguards information if the rest of the SCN crashes.

The three computer mainframes are separate but highly interactive. Each is connected to both buffer memories, and all have access to the safeguards information system. Furthermore, process control data is available through PCC from the process information system. The functions of the safeguards coordination computer (SCC) and the materials accounting computer (MAC) are discussed in Secs. III-C and III-E, respectively; physical security computer (PSC) functions are given in the Sandia Corp. report.²

Each computer has foreground (FG) and background (BG) processing domains. The currently high-priority functions are done in the FG; for example, MMAS calculations are done in the MAC FG. The BG of each computer is used to sample and check the results of the other two computers. Thus, the SCC and MAC

Fig. III-3. Safeguards computer network architecture.

BG check PSC FG results, and so forth. Because of the sampling feature, the computational burden on each computer increases only 10-20% under normal conditions. However, each is capable of assuming the most important tasks of the other two in the event of a failure. In that case, all absolutely necessary work can still be done, although with some increase in processing delays. This means that a factor-of-3 increase in each main-frame's capability is not required if speed and unnecessary tasks can be sacrificed.

This scheme uses available computer power much more effectively than, for example, fully redundant backups for each computer, or even one backup for all three. Furthermore, the system described above is fault-correcting, whereas single backup (a duplex configuration) only gives fault detection; the faulty machine must be identified by other means.

Fault correction can be done with the voter array shown in Fig. III-4. Voters V1-V3 compare the results of the three computers, one FG to two BGs, for each safeguards subsystem. On the basis of these three comparisons, voter V4 decides which machine, if any, is faulty and switches the load of that machine to the other two. The extra load can be apportioned to the two remaining computers according to their current workloads. If one machine fails, the SCN becomes a duplex system with fault-detection, but not fault-correction, capability.

The simplest voter implementation is human supervision whereby results are compared by hand. This is a very useful method (and a good one to start with), although it is slow and susceptible to errors. The voting function can be shared among the machines themselves, but questions of voter reliability in the face of machine failure are unresolved. A third, more costly, alternative is a microprocessor-based voter array requiring a 16-bit microprocessor with some computational ability. In any case, voter-array reliability is important, and careful design is imperative.

The SCN event sequences during times of machine failure must be studied in detail. In particular, machine

Fig. III-4. Safeguards computer network voter array.

resynchronization following failure repair is necessary (see Refs. 53 and 54). The paper by Torin⁵⁵ discusses various types of faults and their consequences, as well as several redundancy techniques.

This three-machine SCN configuration is a form of triple-modular redundancy (TMR) applied to the processed data level of the network. The TMR concept was first discussed by von Neumann⁵⁶ in 1956 and subsequently expanded by others (see Refs. 57-61). Technology for TMR implementation is well developed,⁶²⁻⁶⁵ and minicomputer systems compatible with this form of TMR are readily available.

2. SCN Hardware. Suitable choices for the computer mainframes are 16-bit minicomputers with 64 kilowords (expandable to 128 kilowords) of memory for each. They must be compatible with the TMR concept and be of a design that has been extensively tested. The machines should be similar to facilitate maintenance and repair.

Each computer should have its own set of central I/O peripherals. These can consist of a keyboard CRT graphics terminal, line printer, magnetic tape drive, and disc drive. Magnetic tapes store operating systems, permanent programs, and archival data; i.e., tapes are used for long-term storage. Magnetic discs hold transient data and programs; portions of the disc contents can be transferred to tape as desired.

The PCS/IOCS and MMAS buffer memories should be nonvolatile because they are backups in case of machine failure. Two floppy discs or small cassette tape units with 8 kilowords of memory each are adequate for storing all raw data for one shift. Redundant buffer memories are unnecessary because the mainframe computer memories provide short-term backup.

Data concentrators are the same type as that used for process control (Sec. II-C), but have only 64-channel capacity. To eliminate common-cause failures in which a process control fault disrupts the safeguards system, data concentrators should not be common to both systems. This also allows special

security precautions, such as accessibility barriers, for the safeguards data concentrators.

Cabling between the buffer memories and data concentrators is redundant for improved reliability and security. Redundancy techniques are common, for example, in the nuclear reactor field, and a number of equipment standards exist.⁶⁶⁻⁶⁸

As with process control (Sec. II-C) and the MMAS (Sec. III-E), we recommend that data I/O ports be directly connected to process line instrumentation wherever possible. Human errors are minimized and hardware costs are lower because fewer computer terminals are required.

The SCN must have an uninterruptible power supply; for example, commercial power with battery backup. This is a standard item for most computer installations and is readily available.

3. SCN Software. Software functions for the SCC (Sec. III-C) and MMAS (Sec. III-E) have already been discussed; the Sandia Corp. report² describes the PCS/IOCS software functions. The computer should have a high-level (e.g., FORTRAN) compiler for ease of programming and to decrease development and modification costs. Commercially available operating systems that have already been field-tested are preferable. Custom software development should be minimized.

Operating systems must have provisions for secure information processing to prevent misuse of data and sabotage of programs. Government agencies, military installations, and many commercial companies have years of experience with secure operating systems that are available to systems designers.

4. Physical Layout. Techniques for attaining secure physical layout are available in several standards,^{69,70} particularly for nuclear power plants. Standards primarily attempt to prevent common-cause failures by specifying separations and barriers between redundant devices. For example, the PSC, SCC, and MAC should be separated by fire-retardant walls. The Sandia Corp. report² discusses physical layouts in more detail.

G. Item Operations Control and Personnel Control Systems

Basic concepts of the IOCS and PCS are presented in Sec. III-B. Techniques developed for the SCN apply because the PCS and IOCS implementations are an integral part of the SCN. The Sandia Corp. report² describes the PCS and IOCS in greater detail.

H. Safeguards Staffing

Table III-6 lists the staffing requirements for the MO₂ plant safeguards systems. The safeguards force can be relatively small because of the automated nature of the system. Furthermore, many support functions for the baseline plant can also support the safeguards system with only a small increase in personnel, particularly if standard equipment is used throughout.

TABLE III-6

STAFFING FOR THE MIXED-OXIDE PLANT SAFEGUARDS SYSTEM (Total for four shifts)

Safeguards Officer	4
Safeguards assistant	4
Computer staff	12
Instrumentation technician	4
Safeguards line inspector	<u>8</u>
TOTAL	32

The safeguards staff is about 8% of the total plant staff; however, this does not include guards required for the PSC. The Sandia Corp. report² provides details on the guard force.

IV. SAFEGUARDS EVALUATION

Chapter III and Appendixes B-E define the safeguards system and its operation in some detail. Because a high-throughput MO_2 fuel refabrication facility has not been built, evaluation of a coordinated safeguards system for such a facility must be based on detailed models and computer simulations.

The safeguards system is evaluated from three viewpoints: (1) SNM diversion sensitivity, (2) safeguards reliability, and (3) cost. The results that follow indicate that SNM in a MO_2 fuel refabrication facility can be safeguarded in a timely, effective, reliable manner at a reasonable cost.

A. Evaluation of the Materials Measurement and Accounting System

In this section, the sensitivity of the generic MMAS is evaluated. The data and results reported here are based on material presented elsewhere in the report. In particular, the reader is directed to the description of the baseline MO_2 fuel fabrication plant in Chap. II and Appendix A, the description of MMAS measurements and instrumentation in Chap. III and Appendix C, the baseline plant model, MOXSIM, in Appendix D, and the diversion detection algorithms in Appendix E. Before the results are presented, the philosophy and technical approach are reviewed, followed by a discussion of the models of plant process operation and materials measurements from which the data were derived. Relationships of the parameters in the diversion detection algorithms to the measurement data are given. Finally, these relationships are used to make quantitative estimates of the sensitivity obtained in major plant process areas with the generic MMAS.

1. Philosophy and Technical Approach. The DYMAC approach complements the traditional cycle of periodic plant cleanouts

and physical inventories (see Sec. III-E). In the DYNAC concept, the baseline plant is divided into unit processes, and SNM flowing through each unit process are controlled using timely dynamic material balances. Often these dynamic balances are closed only approximately because some in-process holdup and minor material sidestreams may be measured less frequently than major material transfers.⁷¹ Dynamic material balance data are updated when holdup and sidestream measurements are made. During the interim, historical data can be used to interpret trends in the material balance data.

The concept of graded safeguards and the economic requirement for minimum process disruption are important factors in the generic MMAS design. For example, the most stringent controls are applied to PuO_2 powder handling operations; less control is maintained on operations involving MO_2 powder where the plutonium is diluted by a factor of 25. For SNM that is well controlled by physical barriers (security vaults, fuel rods, etc.), verification measurements that support item control are incorporated.

The generic MMAS includes a minimal set of measurements that provide dynamic balances at least once per major process step for each unit process.* Most measurements included in the original Westinghouse plant design are incorporated in the generic MMAS. In particular, most of the original weight measurements (some of which have been upgraded) and traditional CAs are used by the MMAS.

To identify required SNM measurements and control problems, a detailed model of plant operation was constructed (see Appendix D), and modifications of process operations that enhance materials control were used in the model. Process data generated from simulated plant operation are input to a corresponding model of SNM measurements. This measurement model generates material balance data by applying measurements to the process

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*A major process step usually corresponds to the processing of one sub-blend, ~ 8 kg Pu.

data. Separation of the process models from the measurement models enhances flexibility in simulating both process operations and MMAS measurements.

Detection algorithms for single theft and long-term diversion were developed in parallel with the baseline plant and measurement models (see Appendix E). The MMAS design has been evaluated and revised on the basis of the sensitivity obtained from various measurement strategies.

2. Modeling and Simulation of the Baseline Plant. Appendix D describes a Monte Carlo simulation model of process operations based on the plant definition given in Chap. II and Appendix A. The plant is divided into 11 unit process areas and 2 peripheral process areas. Each unit process is modeled separately, which permits a detailed description of process operations that are specific to each. Because process variability, particularly in the levels of in-process holdup and material sidestreams, can have a significant effect on materials control, a very detailed baseline plant model is required for making quantitative estimates of MMAS sensitivity.

In the model, a schedule of material flow events is specified for each unit process. The schedule includes an initial event in which beginning inventories are set, a minimum of one type of process event, and a final event in which runouts and cleanups are performed. The process descriptions and the unit process event schedules are incorporated in a computer program called MOXSIM that simulates baseline plant operation 1 wk at a time. MOXSIM uses the executive of the GASP IV simulation language⁷² to schedule the individual unit process events in proper sequence. The GASP IV controller provides added flexibility. In addition to timed events, it can schedule conditional events that arise during process operation; for example, stopping the flow of material when a tank has been filled.

The simulated process operation is defined in terms of true material flow data from each event. These data are saved for

use by the measurement simulation computer program, MACSIM, which applies simulated measurements to flow data to produce measured material balance data.

3. Measurement and Accounting Modeling and Simulation.

Operation of the MMAS was evaluated using the Monte Carlo computer code MACSIM (Material Accounting and Control Simulation). This code simulates measurement of the true material flow data generated in MOXSIM (see Sec. IV-A-2 above and Appendix D), and computes material balances and sums of material balances appropriate to each of the unit processes considered.^{73,74}

MACSIM incorporates a generic measurement model that provides for both proportional and constant random error components and for a constant bias term.* The measured value M of a true quantity μ is given by

$$M = \mu(1 + \eta) + \epsilon + \beta, \quad (1)$$

where η and ϵ are the proportional and constant random errors respectively, and β is the bias. The variance σ_M^2 of M is given by

$$\sigma_M^2 = \mu^2 \sigma_\eta^2 + \sigma_\epsilon^2, \quad (2)$$

where σ_η^2 and σ_ϵ^2 are the variances of η and ϵ respectively. Each of the random errors η and ϵ is assumed to be normally distributed with mean zero. Individual measurement results are assumed to be independent.

Standard deviations σ_η and σ_ϵ are specified for each measurement situation. Because measurement uncertainty in a weighing operation is relatively constant over the range of the instrument, only σ_ϵ is given a nonzero value for mass determinations using either balances or load cells. In contrast, the

*Statistical terms are used in accordance with American National Standard ANSI Z39-18-1972, Statistical Terminology and Notation for Nuclear Materials Management.

uncertainty of a NDA measurement tends to be proportional to the quantity of material being measured, and only σ_n is assigned a nonzero value for this type of measurement. Furthermore, because the plant is expected to have an effective, operating measurement control program (designed to eliminate sources of measurement bias, or to estimate the effects of potential sources of bias and correct measurement data as needed), the bias term B in Eq. (1) is set to zero for all measurements.

NDA measurements are assumed to produce directly a value for the quantity of plutonium element present. The uncertainties in the plutonium isotopic composition and instrument calibration are incorporated into the imprecision (σ_n) specified for each NDA measurement. In the case of a weighing operation, the measured weight is multiplied by an element factor (g Pu/g sample) to obtain the plutonium mass. The element factor is determined by chemical analysis of samples taken during plant operation. In MACSIM, the element factor is obtained by simulated measurement, using the uncertainty appropriate to the CA of PuO_2 or MO_2 . The assigned uncertainty includes both analysis errors and sampling errors. The frequency with which the element factor is determined corresponds to the sampling schedule anticipated by Westinghouse.

The precisions assigned to the measurements are based on estimates obtained from the literature^{24,27,46} for similar instrumentation. In general, 0.25% of full scale is taken as the relative precision for a typical load cell in normal operation, and 0.02% of full scale as the relative precision for a digital balance. The relative precision of the plutonium element factor is assumed to be 0.1% for PuO_2 and 0.2% for MO_2 , in most cases. For NDA measurement, a special effort was made to assign conservative values of measurement precisions.

Each material balance computed in MACSIM is a linear combination of measured quantities of plutonium. The uncertainty in the computed value of the material balance is produced by the combined effects of uncertainties in the contributing measured values. In MACSIM, the measurement results are assumed to be

independent, and the variance associated with each material balance is the sum of the variances of the terms in the material balance equation.

A cusum is computed by MACSIM after each material balance period. It is the sum of all material balances for the unit process since the beginning of the accounting period. The cusum variance is a complex combination of the variances of individual material balances, as these balances usually are not independent. Most unit processes will have one or more variables for which a single measurement value appears as output in one material balance period (i.e., this value has a negative sign in the material balance equation) and as input in the next. For example, this can be the result of accumulating material in a tank or scrap container and measuring the contents during each balance period. In such cases, only the first and last measurements of the container contents appear in the cusum, and only the corresponding variances appear in the cusum variance.

The design of the generic MMAS is based on studies using MACSIM. The code is sufficiently versatile to permit independent investigation of materials control sensitivity as a function of process variability, measurement variability, and instrument configuration. Fixed sets of measurements have been applied to different sets of material flow data, and a variety of measurement strategies applied to fixed sets of flow data. Design choices were based on the dual criteria of satisfactory sensitivity to both single theft and long-term diversion and minimal perturbation of process operation. Results of the evaluation of the MMAS are described in Secs. IV-A-5 to IV-A-10.

4. MMAS Diversion Sensitivity. Sensitivity of the MMAS is determined quantitatively from relationships between parameters in the diversion detection algorithms and the dynamic material balance data. Algorithms for the detection of short-term and long-term diversion of materials are discussed in Appendix E.

Short-term diversion refers to the single theft of a relatively large amount of material. The sensitivity of the MMAS

to short-term diversion depends on the measurement uncertainty (standard deviation, σ) associated with individual material balances. If unmeasured holdup or material sidestreams significantly affect the individual balances, that is, if an average positive bias on the order of 1σ is introduced by not making the measurements, the material probably should be measured and included in each dynamic balance.

If B is the measured value of a material balance (i.e., an estimate of the unmeasured material), the ratio B/σ is used with the design curves (Appendix E, Figs. E-1 - E-3) to detect single thefts. A reasonable threshold sensitivity is $B = 3\sigma$ for which the detection probability is 0.5 if the false-alarm probability is set at approximately 1 in 1000. A useful format for presentation of the material balance data is the so-called Shewhart chart⁷⁵ on which the data are plotted with 1σ error bars, and lines are drawn at the average 2 and 3σ levels so that outliers are readily apparent.

Long-term diversion refers to repeated thefts of nuclear material on a scale too small to be detected in a single material balance because of measurement uncertainties. Repeated small thefts of SNM are indicated by the trend (positive slope) they induce in the cusum chart of material balances. Detection of trends due to small thefts is complicated by unmeasured holdup and small sidestreams of material that introduce similar trends in the cusum data. Analysis of trends is complicated by correlations between the cusum data and the variability of measurement errors in a sequence of material balances.

A technique for detecting trends is the cusum chart and V-mask⁷⁶ method of control discussed in Appendix E. By this approach, levels of sensitivity are set for small theft detection based on cusum uncertainties.

Implementation of this technique is still under development, and in its present form is rigorous only for independent material balances of constant and equal variance. It is applicable to the case in which the cusum variance grows linearly

with the sequence length L of material balances. In this case, the average positive bias B that can be detected over a sequence of material balances of length L is proportional to σ_C/L , where σ_C is one standard deviation of the cusum. A reasonable estimate of the threshold sensitivity to small amounts of unmeasured material is $B = 2 \sigma_C/L$, corresponding to a detection probability of 0.84 and a false-alarm probability of about 1 in 6.

Patterns in the cusum associated with unmeasured holdup and material sidestreams can be identified by the cusum chart and V-mask method. For example, in many instances in the baseline plant, holdup is cleaned up and measured, and accumulated sidestreams of material are measured, on a weekly cycle. This cycle produces a sawtooth pattern in the cusum, i.e., the cusum has a positive trend between the weekly measurements, then returns near zero at the end of the week when the measurements are made. The V-mask detects these trends as short sequences of material balances, each with an average positive bias. If historical data indicate that the cleanups are reasonably effective, e.g., the level of holdup is restored near a residual (irreducible) level, then the V-mask will detect only these weekly trends. If longer trends are detected as operation continues beyond 1 wk small thefts are indicated.

In the following sections, sensitivity levels will be given for the major unit process areas in the baseline plant on the basis of the generic MMAS design. The sensitivity to large thefts is given as 3σ , where σ is the average standard deviation of the dynamic material balances. The sensitivity to small thefts is given as $2\sigma_C/L$, where the cusum standard deviation, σ_C , is evaluated at the end of 1 wk and at the end of 4 wk of operation. It is assumed that the cusum is rezeroed periodically, perhaps after a cleanout and physical inventory. The expected amount of unmeasured material in normal process operations, based on the plant process model (see Appendix D), is also given.

The sensitivities to small-scale diversions are not necessarily indicative of the amount of SNM that a single person might steal. They are detectability limits for average amounts of missing material per material balance period. For a single diverter to steal SNM at a rate equal to the average detectable amount, each theft would be larger by a factor of 3 or 4, with a corresponding increase in probability of detection.

5. PuO₂ Powder Unloading. In this unit process, one shipping container containing four canisters of PuO₂ powder is received during each unloading shift. One canister is opened, sampled, and unloaded to bulk storage during a nominal 2-h period. Normal process operation is one shift per day for five consecutive days per week, followed by a cleanup.

Three material control strategies were investigated for this unit process.

a. Strategy 1. A dynamic material balance is drawn around the unloading of each canister to bulk storage and around the cleanup operation. The measured variables are:

- BI PuO₂ contents of each canister.
- EWM Residual PuO₂ in emptied canisters; canisters are accumulated and sent to MWT for measurement and disposal at weekly cleanup.
- HU Holdup in the routing valve after runout of the pneumatic transfer line, measured after unloading each canister.
- AS Sample sent to the ASF.
- ΔDV The portion of unmeasured holdup in filters and the glovebox recovered and measured at cleanup.
- XM Inventory in the PuO₂ storage tank.
- PuF Plutonium element factor.

The measurements and associated precisions (σ_n and σ_e) are given in Table IV-1.

TABLE IV-1

MEASUREMENT STRATEGY 1 APPLIED TO
PuO₂ POWDER UNLOADING

Variable	Measurement Type ^a	σ_n (%)	σ_ϵ (kg)
BI	PuO ₂ net weight; digital balance	0	0.003
ΣWM	NDA; neutron well counter	2	0
HU	NDA; gamma	5	0
AS	NDA; small-sample counter	2	0
ΔDV	NDA; neutron well counter	5	0
XM	PuO ₂ weight; load cell	0	0.500
PuF	Chemical analysis	0.1	0

^aSee Appendix C for a detailed discussion of typical instrumentation.

The n^{th} material balance is given by

$$MB_n = XM_{n-1} + HU_{n-1} + BI_n - XM_n - HU_n - AS_n.$$

The material balance at cleanup is given by

$$MB_c = XM_{c-1} + HU_{c-1} - XM_c - HU_c - AS_c - \Delta DV - \Sigma WM.$$

b. Strategy 2. A weigh hopper is inserted in front of the PuO₂ bulk storage tank. The material balance is now closed around the unloading of each canister to this weigh hopper; i.e., the bulk storage area is separated from the unloading process. The additional measured variable is

BO PuO₂ content of the weigh hopper.

The measurements and associated precisions for this material control strategy are given in Table IV-2.

TABLE IV-2
MEASUREMENT STRATEGY 2 APPLIED TO
PuO₂ POWDER UNLOADING

Variable	Measurement Type ^a	σ_n (%)	σ_e (kg)
BI	PuO ₂ net weight; digital balance	0	0.003
BO	PuO ₂ net weight; load cell	0	0.035
ΣWM	NDA; neutron well counter	2	0
HU	NDA; gamma	5	0
AS	NDA; small-sample counter	2	0
ΔDV	NDA; neutron well counter	5	0
PuF	Chemical analysis	0.1	0

^aSee footnote to Table IV-1.

The n^{th} material balance is given by

$$MB_n = BI_n - BO_n + HU_{n-1} - HU_n - AS_n$$

The material balance at cleanup is given by

$$MB_c = HU_{c-1} - HU_c - BO_c - \Sigma WM - \Delta DV,$$

where BO_c represents material that is obtained during cleanup and runout of the pneumatic conveyor and router valve and is sent to the weigh hopper.

c. Strategy 3. The material balances are closed as in strategy 2; however, a room monitor has been installed to permit measurement of holdup in filters and glovebox once each

shift, and the empty canisters are sent to MWT for measurement once each shift. An additional measured variable is introduced:

DV Holdup in filters and glovebox.

The measurements and associated precisions are given in Table IV-3.

TABLE IV-3
MEASUREMENT STRATEGY 3 APPLIED TO
PuO₂ POWDER UNLOADING

Variable	Measurement Type ^a	σ_n (%)	σ_E (kg)
BI	PuO ₂ net weight; digital balance	0	0.003
BO	PuO ₂ net weight; load cell	0	0.035
ΣWM	NDA; neutron well counter	2	0
HU	NDA; gamma	5	0
AS	NDA; small-sample counter	2	0
DV	NDA; neutron	25	0
ΔDV	NDA; neutron well counter	5	0
PuF	Chemical analysis	0.1	0

^aSee footnote to Table IV-1.

The n^{th} material balance is given by

$$MB_n = BI_n - BO_n + HU_{n-1} - HU_n - AS_n.$$

The end-of-shift material balance is given by

$$MB_E = BI_E - BO_E + HU_{E-1} - HU_E - AS_E + DV_{E-4} - DV_E - \Sigma WM.$$

The material balance at cleanup is given by

$$MR_c = HU_{c-1} - HU_c - BO_c + DV_{c-1} - DV_c - \Sigma WM - \Delta DV.$$

Material balance and cusum plots corresponding to the three material control strategies are given in Figs. IV-1 to IV-3, respectively. For purposes of comparison, each plot represents the same 4 wk of typical unloading operations. The uncertainty in each material balance is significantly reduced by inserting a weigh hopper in front of the PuO_2 powder bulk storage vessel. (Compare Figs. IV-1 and IV-2). This isolates the bulk powder storage area from the unloading operation. The positive trends in the cusum data that occur weekly for strategy 2 (Fig. IV-2) are produced by unmeasured waste and holdup in the unloading station. These trends are also present in strategy 1, but are obscured by the large uncertainty in the cusum. The weekly measurements of accumulated waste and the amount of holdup that is cleaned up from the unloading station produce the four large negative material balance data points in Fig. IV-2. The PuO_2 powder that is cleaned up is particularly vulnerable to diversion under strategy 2 and added security precautions would be taken during cleanup.

No significant trends are apparent in the cusum for strategy 3 (Fig. IV-3) because measurements of holdup and waste in the unloading station are included in the cusum at the end of each shift. Note that the PuO_2 powder from weekly cleanup is better controlled under strategy 3 because the residual level of holdup in the unloading station is measured after cleanup.

Estimates of the sensitivity for each strategy are given in Table IV-4.

6. MO_2 Blending. The blender is charged with sufficient material for a single sub-blend from PuO_2 , UO_2 , and recycle MO_2 weigh hoppers. At the completion of the blending cycle, the sub-blend is transferred to one of the MO_2 storage silos. Normal operation involves 20 sub-blends per week followed by a cleanup operation.

Fig. IV-1. Material balance and cusum data from 4 wk of typical PuO_2 powder unloading using measurement strategy 1.

Fig. IV-2. Material balance and cusum data from 4 wk of typical PuO_2 powder unloading using measurement strategy 2.

Fig. IV-3. Material balance and cusum data from 4 wk of typical PuO_2 powder unloading using measurement strategy 3.

TABLE IV-4

SENSITIVITY OF THE NMAS APPLIED TO PuO_2 POWDER UNLOADING

	Single Theft, ^a (g Pu)	Long-Term Diversion ^b		Expected Unmeasured Material ^c (g Pu)
		(1-wk average, g Pu)	(4-wk average, g Pu)	
Strategy 1	1900	61	31	18 ^d
Strategy 2	110	14(330)	7(650)	18 ^d
Strategy 3	110	16(350)	8(700)	18 ^e

^a Amount (3σ) of unmeasured material that can be detected in a single balance period with a probability of 50% at a false-alarm rate of approximately 1 in 1000.

^b The average amount ($2\sigma_c/L$) of unmeasured material per balance period that can be detected during 1-wk and 4-wk periods with a probability of $\sim 85\%$ at a false-alarm rate of about 1 in 6. The total amount ($2\sigma_c$) is given in parentheses.

^c Average amount of unmeasured material expected per balance period during normal process operation taken from the baseline plant model (Appendix D). The actual amount typically ranges from zero to twice the average value.

^d Accumulated and measured each week.

^e Accumulated and measured each shift.

A material balance is drawn around each sub-blend, from the weigh hoppers that feed the blender, through the MO_2 storage silo. A material balance is also computed at cleanup. The measured variables are:

BI(1) PuO_2 weigh hopper.
 BI(2) MO_2 recycle weigh hopper.
 BO Storage silo contents.
 ESM Accumulated scrap sent to MWT once per week.
 EWM Accumulated waste sent to MWT at cleanup.
 AS Sample sent to the ASE.
 PuF Plutonium element factor.

The measurements and associated precision (σ_n and σ_e) are given in Table IV-5.

TABLE IV-5

MEASUREMENT STRATEGY APPLIED TO MIXED OXIDE BLENDING

Variable	Measurement Type ^a	σ_n (%)	σ_e (kg)
BI(1)	PuO_2 net weight; load cell	0	0.014
BI(2)	MO_2 net weight; load cell	0	0.354
BO	MO_2 net weight; load cell	0	0.884
ESM	NDA; neutron well counter	2	0
EWM	NDA; neutron well counter	5	0
AS	NDA; small-sample counter	2	0
PuF	Chemical analysis	0.2	0

^a See footnote to Table IV-1.

The n^{th} dynamic material balance is given by

$$NB_n = BI(1)_n + BI(2)_n - BO_n - AS_n.$$

The material balance at cleanup is given by

$$NB_c = -\Sigma SM - \Sigma WM.$$

Material balance and cusum data for 4 wk of typical blending operations are plotted in Fig. IV-4. Weekly positive trends in the cusum data are produced by unmeasured holdup, waste, and dirty scrap. At the end of each week, the accumulated waste and dirty scrap are measured, and a portion of the holdup is cleaned up and measured. These weekly measurements produce the distinctive negative material balance data points in Fig. IV-4. Material obtained from weekly cleanup is not well controlled by the MMAS. Increased physical security and estimates from historical data should be applied at cleanup times. Note that a few kilograms of MO_2 powder are cleaned up from the blending area each week in the baseline plant model.

The individual material balance measurements have an uncertainty (1 σ) of about 42 g of plutonium, which is reflected in the error shown in the cusum data. The silo weight measurement accounts for 35 g of the 42-g uncertainty; the rest is a combination of errors in the PuO_2 and recycle MO_2 weigh hopper weights. Significant improvement in the precision of individual material balances (and thus in the cusums) requires improved precision of the silo weight measurement. The variability in the present measurement strategy is indicated in Fig. IV-5 where cusum data from two different 4-wk periods of blending operation are compared.

The sensitivity of the generic MMAS applied to the blending operation is estimated in Table IV-6. The level of control may be acceptable for this process because the material, MO_2 powder, is contained in the blending vessel, transfer pipes, and storage silo.

Fig. IV-4. Material balance and cusum data from 4 wk of typical NO_2 powder blending.

Fig. IV-5. Comparison of cusum data from two different 4-wk periods of MO₂ powder blending.

TABLE IV-6

SENSITIVITY OF THE MMAS APPLIED TO MO₂ BLENDING^a

Single Theft (g Pu)	Long-Term Diversion		Expected Unmeasured Material (g Pu)
	(1-wk average, g Pu)	(4-wk average, g Pu)	
130	20(400)	10(800)	15 ^b

^aSee footnotes a-c in Table IV-4.

^bAccumulated and measured each week.

7. Pelleting. The MO₂ powder is transferred from a bulk storage silo to the compactor feed hopper. From the compactor, the prepared powder is fed to the pellet press via the press feed hopper, and the resulting green pellets are loaded onto boats. Approximately 15 boats can be made from one sub-blend of MO₂ (~ 225 kg). Normal operation is 19 sub-blends per week, followed by runout and cleanup.

A material balance is drawn around each sub-blend, from the silo through loaded green-pellet boats. One is also computed at cleanup. The measured variables are:

- BI(1) MO₂ content of silo.
- BI(2) Compactor feed hopper inventory.
- EBO Sum of green-pellet boats.
- SM Accumulated clean scrap.
- WM(1) Accumulated dirty scrap sent to MWT and measured at cleanup.
- WM(2) Accumulated waste sent to MWT and measured at cleanup.
- HU Press feed hopper inventory.
- PuF Plutonium element factor.

The measurements and associated precisions (σ_r and σ_e) are given in Table IV-7.

TABLE IV-7

MEASUREMENT STRATEGY APPLIED TO PELLETING

Variable	Measurement Type ^a	σ_r (%)	σ_e (kg)
BI(1)	MO ₂ net weight; load cell	0	0.884
BI(2)	NDA; neutron	5	0
BO	MO ₂ weight; load cell	0	0.100
SM	MO ₂ weight; load cell	0	0.125
WM(1)	NDA; neutron well counter	5	0
WM(2)	NDA; neutron well counter	5	0
HU	NDA; neutron	5	0
PuF	Chemical analysis	0.2	0

^aSee footnote to Table IV-1.

The n^{th} dynamic material balance is given by

$$MB_n = BI(1)_n + BI(2)_{n-1} + HU_{n-1} + SM_{n-1} - \Sigma BO - BI(2)_n - HU_n - SM_n.$$

The dynamic material balance after runout and cleanup is given by

$$MB_c = BI(2)_{c-1} + HU_{c-1} + SM_{c-1} - \Sigma BO_c - SM_c - WM(1) - WM(2).$$

Material balance and cusum data are plotted in Fig. IV-6 for 4 wk of pelleting operation. Variability in the cusum data is produced by a combination of measurement errors and process variability in the amount of holdup that is cleaned up and measured weekly. The uncertainty in individual material balances

Fig. IV-6. Material balance and cusum data from 4 wk of typical pelleting operations.

is 45-50 g Pu (1σ). About 5-15 kg MO₂ holdup per week are accumulated in the pelleting process area.

Design studies indicate that measurement errors are the main source of variability in the cusum data. This variability is indicated by the comparison in Fig. IV-7 of two different sets of cusum data for the same 4 wk of pelleting operation.

Of the approximately 50-g Pu uncertainty in the dynamic balances, about 40 g comes from a combination of the silo and green-pellet boat weight measurements. Thus, to improve the controls on material flowing through the pelleting process, one must first improve the precision in the silo and green-pellet boat measurements. For example, we have tried a measurement strategy that includes a 2%, rather than a 5%, NDA measurement of material in the compactor and press feed hoppers. The lower limit of 40-g Pu uncertainty was attained by this strategy, but with little reduction in variability of the cusum data.

The sensitivity of the generic MMAS for the pelleting operation is given in Table IV-8.

TABLE IV-8

SENSITIVITY OF THE MMAS APPLIED TO THE PELLETING PROCESS^a

Single Theft (g Pu)	Long-Term Diversion		Expected Unmeasured Material (g Pu)
	(1-wk average, g Pu)	(4-wk average, g Pu)	
150	20(400)	10(800)	33 ^b

^a See footnotes a-c in Table IV-4.

^b Accumulated and measured each week.

Fig. IV-7. Comparison of cusum data from different measurements for the same 4-wk period of pelleting operations.

8. Pellet Grinding. Sintered pellets are unloaded from boats, ground, and stacked in trays. The pellet feeder and grinder are run out at the end of each sub-blend (after about 15 sintered-pellet boats have been processed). Normal operation is 19 sub-blends per week, followed by a cleanup operation.

A material balance is drawn around each sub-blend, from sintered-pellet boats through finished-pellet trays. One is also computed at cleanup. The measured variables are:

- BI Sintered-pellet boat unloaded to the pellet feeder.
- BO Loaded tray to storage.
- SM Accumulated clean scrap from dried grinder sludge; the container is removed when full.
- WM(1) Accumulated dirty scrap sent to MWT and measured once per week.
- WM(2) Accumulated waste sent to MWT and measured once per week.
- AS Pellet samples.
- PuF Plutonium element factor.

The measurements and associated precisions (σ_n and σ_e) are given in Table IV-9.

The n^{th} dynamic material balance is given by

$$MB_n = \Sigma BI + SM_{n-1} - \Sigma BO - SM_n - AS_n.$$

The dynamic material balance computed after cleanup is given by

$$MB_c = SM_{c-1} - SM_c - WM(1) - WM(2).$$

Figure IV-8 contains the material balance and cusum data for 4 wk of pellet grinding. The weekly positive trends represent the accumulation of dirty scrap and waste and holdup that is cleaned up and measured weekly. A few kilograms of MO_2 powder and broken pellets are cleaned up each week.

Fig. IV-8. Material balance and cusum data from 4 wk of typical pellet grinding operations.

TABLE IV-9

MEASUREMENT STRATEGY APPLIED TO PELLET GRINDING

Variable	Measurement Type ^a	σ_n (%)	σ_e (kg)
Bl	MO ₂ weight; load cell	0	0.100
BO	MO ₂ weight; load cell	0	0.100
SM	MO ₂ weight; load cell	0	0.125
WM(1)	NDA; neutron well counter	5	0
WM(2)	NDA; neutron well counter	5	0
AS	NDA; small-sample counter	2	0
PuF	Chemical analysis	0.3	0

^aSee footnote to Table IV-1.

The weight measurements of boats, trays, and clean scrap produce an uncertainty (1 σ) of only 25 g Pu in the individual material balances. Reliable historical data probably can be gathered on holdup in the grinding operation. The combination of small measurement uncertainty and reliable historical data can provide satisfactory control. Sensitivity estimates for the grinding operation are given in Table IV-10.

TABLE IV-10

SENSITIVITY OF THE MMAS APPLIED TO PELLET GRINDING^a

Single Theft (g Pu)	Long-Term Diversion (1-wk average, g Pu) (4-wk average, g Pu)		Expected Unmeasured Material (g Pu)
80	12(250)	6(500)	22 ^b

^aSee footnotes a-c in Table IV-4.

^bAccumulated and measured each week.

9. Clean Scrap Recovery System (CSRS). The oxidation-reduction reactor is charged with a batch of clean scrap from storage. The scrap is processed to usable MO_2 powder and sent to recycle MO_2 storage. If a sub-blend has been rejected from a silo to recycle MO_2 storage, no scrap is processed during that shift. If the inventory in clean scrap storage is less than 35 kg of MO_2 , no batch is processed at the CSRS. If the inventory in the recycle MO_2 tank being filled exceeds 700 kg MO_2 , CSRS operation is suspended until the following week. Normal operation involves up to 20 shifts per week, followed by cleanup.

A material balance is drawn around each charge of the reactor, from the batch transferred from clean scrap storage through a weigh hopper inserted in front of the recycle MO_2 storage tank. This weigh hopper separates the bulk storage vessel from the recovery process. A material balance is also computed at cleanup. The measured variables are:

- BI Batch (container) of MO_2 from clean scrap storage.
- BO Output batch from reactor to weigh hopper.
- WM Accumulated waste sent to MWT and measured at cleanup.
- HU Holdup (heel) in reactor after discharge.
- PuF Plutonium element factor.

The measurements and associated precisions (σ_n and σ_c) are given in Table IV-11.

The n^{th} dynamic material balance is given by

$$\text{MB}_n = \text{BI}_n + \text{HU}_{n-1} - \text{BO}_n - \text{HU}_n.$$

The dynamic material balance computed at cleanup is given by

$$\text{MB}_c = \text{HU}_{c-1} - \text{WM} - \text{HU}_c.$$

Figure IV-9 contains material balance and cusum data for 4 wk of CSRS operation. The uncertainty in the individual

Fig. IV-9. Material balance and cusum data from 4 wk of typical clean scrap recovery operations using a 15% NDA measurement of the reactor process heel.

TABLE IV-11

MEASUREMENT STRATEGY APPLIED TO CLEAN SCRAP RECOVERY SYSTEM

Variable	Measurement Type ^a	σ_p (%)	c (kg)
BI	MO ₂ weight; load cell	0	0.125
RO	MO ₂ weight; load cell	0	0.125
RV	NDA; neutron well counter	5	0
RU	NDA; neutron	15	0
Pu	chemical analysis	0.3	0

^a See footnote to Table IV-1.

material balances ($c = 90-100$ g Pu) is dominated by the 15% NDA measurement of the process heel in the clean scrap reactor. Two of these measurements appear in each dynamic balance. For comparison, the same process data and measurements were run with a 5% NDA chemical reactor measurement. These results are plotted in Fig. IV-10. The 1c material balance uncertainty in this case is ~ 30 g Pu. The uncertainty in each material balance is essentially equal to the NDA measurement uncertainty.

The uncertainty in the cusum also reflects the fact that two NDA reactor measurements appear in each cusum value. The cusum uncertainty has a large initial value close to the NDA measurement uncertainty. As balances are added, the cusum error slowly grows because of errors in the weight measurements.

The sensitivity of the generic MMAS for CSRS operations is given in Table IV-12.

10. Long Term Diversion in PuO₂ Powder Unloading. For detection of long term diversion, cusum data trends due to unmeasured material from normal process operations must be separated from trends due to theft. This is a kind of pattern recognition problem for which the χ^2 mask technique (see Appendix I-11)

Fig. IV-10. Material balance and cusum data from 4 wk of typical clean scrap recovery operations using a 5% NDA measurement of the reactor process heel.

TABLE IV-12

SENSITIVITY OF THE MMAS APPLIED TO CLEAN SCRAP RECOVERY SYSTEM^a

Single Theft (g Pu)	Long-Term Diversion		Expected Unmeasured Material (g Pu)
	(1-wk average, g Pu)	(4-wk average, g Pu)	
290 ^b	12(250)	6(500)	5 ^d
100 ^c	5(130)	3(250)	5 ^d

^aSee footnotes a-c in Table IV-4.

^b15% NDA measurement on process heel.

^c5% NDA measurement on process heel.

^dAccumulated and measured each week.

appears to be a promising tool. With the V-mask, the analyst can detect significant positive trends in the cusum data and record the sequence lengths in each trend. In addition, the average value of material balances in each trend can be calculated, giving an estimate of the average positive bias. An estimate of the total bias is found by multiplying the average balance by the sequence length.

The diversion detection probability is estimated from the average bias, sequence length, and cusum standard deviation, and trends are classified according to their estimated detection probability. The classification scheme currently in use is given in Table IV-13.

Examples of the V-mask method as applied to the PuO₂ unloading process are given here. Two patterns of small theft, one random and the other uniform, were applied to measurement strategy 2 (sidestreams measured each week) and to strategy 3 (sidestreams and holdup measured each shift, see Sec. IV-A-5).

TABLE IV-13

CLASSIFICATION OF TRENDS DETECTED BY THE CUSUM
AND V-MASK METHOD

Classification	Detection Probability Range (%)	False-Alarm Probability Range (%) ^a
A	70-80	30-20
B	80-85	20-15
C	85-90	15-10
D	90-95	10-5
E	95-98	5-2
F	98-99	2-1
G	>99	<1

^aProbability of detecting an apparent trend when no trend exists. The probability of missing a real trend has been set equal to the false-alarm probability (see Appendix E).

The diversion patterns are unrealistic because a theft usually occurs each shift, a situation which would require collusion among several people. However, the examples illustrate the implementation of the V-mask method.

Only the results from measurement strategy 2 are presented here; these cusum data exhibit the weekly positive trends caused by unmeasured holdup and sidestreams that are typical of data from most unit processes. The only historical information assumed is that the cleanups are reasonably effective, viz., at least half the in-process holdup, on the average, is cleaned up and measured each week.

In Fig. IV-11, cusum data from 4 wk of normal powder unloading operation are compared with data from the same 4 wk with a random series of small thefts applied. In the diversion scheme, 60 to 70 g of PuO_2 powder could be removed from the contents (~ 8 kg PuO_2) of a single canister, with only one theft

Fig. IV-11. Comparison of cusum data from 4 wk of normal PuO_2 powder unloading operation (upper) with that for a random diversion scheme applied (lower).

during each unloading shift. The amount actually stolen is given in Table IV-14.

TABLE IV-14

RANDOM DIVERSION SCHEME

Week No.	Total per Week (g PuO ₂)	Cumulative Amount Stolen (g PuO ₂)	Fraction of Total Throughput (%)
1	196	196	0.12
2	268	464	0.15
3	331	795	0.17
4	193	988	0.15

From the cusum data in Fig. IV-11 (lower plot), one would suspect an abnormal condition during the second week of operation, and after cleanup at the end of the second week one would probably conclude that material was being diverted. Evidence based on the cusum data alone is somewhat ambiguous during the second week because of the trending due to normal operation.

Figure IV-12 shows trends detected by the V-mask for normal operation (upper plot) and with random thefts (lower plot). The letter symbols correspond to the classifications given in Table IV-13. The trends are plotted according to the initial and final sequence numbers (L_1 and L_2 , respectively) of the material balances in a trend. Note that any sequence of length one (a single material balance) would fall on a 45° line through the origin. All other sequences fall below this line, i.e., in the lower right half of the plot.

During normal operation, the symbols representing detected trends cluster in groups near the 45° line. Each cluster of trends corresponds to in-process material that is not measured during the week. The symbols on the L_2 -axis in the lower plot

Fig. IV-12. V-mask chart of trends detected in normal PuO₂ powder unloading operations (upper) and with a random diversion scheme applied (lower).

of Fig. IV-12 correspond to longer trends. By the middle of the second week ($L_2 \sim 30$), these trends have become so persistent that an abnormal condition is indicated. Thus, combining the V-mask with cusum data to detect patterns of trends as well as the trends themselves, appears to improve sensitivity to long-term diversion. We note that the average theft per balance period in this case was ~ 9 g Pu during the first week, and ~ 10.4 g Pu during the 4 wk. The corresponding detection limits given in Table IV-4 are 16 and 8, respectively.

To test further the sensitivity of the V-mask and cusum method, we imposed a uniform (but unrealistic) diversion scheme of very small thefts (4 g PuO_2) from each canister. The total amount diverted during the 4 wk was 320 g PuO_2 (282 g Pu) in 80 thefts, which is to be compared with the 700-g detection limit quoted in Table IV-4. Figures IV-13 and IV-14 are the cusum and V-mask plots for this scheme. The cusum gives little evidence of diversion; it is apparently within the limits of normal operation. The V-mask plot (Fig. IV-14, lower plot) also does not contain conclusive evidence of theft, but the persistence of long trends along the L_2 -axis ($L_2 > 20$) should be of concern. This result is gratifying because the level of theft is smaller by a factor of 2.5 than the quoted detection limit and is consistent with our intent to make conservative sensitivity estimates for long-term diversion pending further study of the cusum and V-mask method.

B. Safeguards Reliability

Safeguards reliability is an important consideration because, as discussed in Chap. III, it affects SNM safeguards and economical plant operation. This section examines the comparative reliability of the safeguards system (see Chap. III) and several alternatives.

The treatment here is intended only to give a rough idea of expected results. Actual reliability depends on a number of factors: local equipment environment, computer workloads, and

Fig. IV-13. Comparison of cusum data from 4 wk of normal PuO_2 powder unloading operations (upper) with that for a uniform diversion scheme applied (lower).

Fig. IV-14. V-mask chart of trends detected in normal PuO_2 powder unloading operations (upper) and with 2 a uniform diversion scheme applied (lower).

preventive maintenance, for example. We disregard these factors and assume that unit (device) reliabilities are constant in time and from unit to unit.

1. Safeguards Computer Network (SCN) Reliability. This section considers reliability of the SCN core, i.e., the PSC, SCC, and MAC, and their associated peripherals. Data concentrator and safeguards instrumentation reliabilities are discussed in Secs. IV-B-2 and 3.

For these calculations, SCN failure is said to occur whenever the SCN is losing safeguards data. Under this criterion, the SCN may not be performing safeguards calculations, merely storing the raw data while some SCN component is being repaired. If the component can be repaired before the data storage device is filled, then a failure is deemed not to have occurred. The implicit assumption is that all PCS/LOCS and MMAS calculations and computerized functions can be delayed for a short time (e.g., 8 h), and that plant operation can continue with reduced safeguards capability. However, in general, SCC functions cannot be delayed. Therefore, if the SCC functions are disrupted, the SCN has failed. After SCN repair, its calculations and functions are updated.

To calculate network reliabilities, component reliabilities are necessary. We assume that any component is subject only to failures that occur at random intervals, and the expected number of failures is constant for long operating periods. Therefore, the component reliability, or probability of survival, is^{77,78}

$$P_s = e^{-fT},$$

where f is the average failure rate, and T is an arbitrary operating time. A T of 1000 h is roughly equivalent to the length of a processing campaign in the baseline MO_2 plant. By the same method, the probability of repairing a component in time t is

$$P_r = 1 - e^{-rt},$$

where r is the average repair rate. For example, if the failure rate of a component is $1/1000$ h and its repair rate is $1/2$ h, then the probability of one failure in 1000 h is 0.368 and the probability that it will be repaired in 8 h is 0.982.

For these calculations, four probabilities are necessary:

P , the reliability of the PSC, SCC, and MAC,

P_b , the reliability of any associated buffer memory,

P_8 , the probability that the PSC, SCC, or MAC can be repaired within 8 h after a failure, and

P_d , the probability that after repair the PSC, SCC, or MAC will operate long enough to empty a buffer memory.

The fundamental reliability, P , of each main computer is not controllable (except through choice of equipment or operating conditions), but it strongly affects network reliability. The same is true for buffer memory reliability, P_b . The probability P_d is fixed by selection of P ; they are related through a change of time scale. The 8-h fix probability (P_8) is determined by a number of factors including effectiveness of maintenance personnel and availability of spare parts.

Reliabilities for six possible SCN configurations are calculated. The configurations are representative of those which might logically be chosen, and they include that given in Chap. III.

The simplex (S) configuration consists of the PSC, SCC, and MAC in series, with no redundancy or buffer memory. Its reliability is

$$P_1 = P^3.$$

That is, the SCN fails if any portion fails.

The simplex with buffer memory (SBM) adds memory backups to the PSC and MAC to prevent loss of data when either fails. The reliability is the probability that PSC and/or its buffer memory is working, and that SCC is working, and that MAC and/or its buffer memory is working, i.e.,

$$P_2 = P \left[P P_b + P(1-P_b) + P_b(1-P)P_8P_d \right]^2 = P \left[P + (1-P)P_bP_8P_d \right]^2$$

In this case, the reliabilities of the PSC and MAC have been increased by the term $(1-P)P_bP_8P_d$, which is the probability that the PSC or MAC has failed $(1-P)$, but the buffer memory has not (P_b) and the PSC or MAC can be repaired within 8 h (P_8) and will work long enough to empty the buffer memory (P_d) .

For the duplex system with buffer memory and single backup (DBM1B), the spare computer can back up the PSC, SCC, or the MAC, but only one at a time. The network reliability is

$$P_3 = P' \left[P' + (1-P')P_bP_8P_d \right]^2,$$

where $P' = P + P^3 - P^4$.

This has the same form as P_2 , but the reliability P has been increased to P' by the single backup.

The duplex system with buffer memory and triple backup (DBM3B) is the same as DBM1B except that the PSC, SCC, and MAC can be backed up simultaneously. The reliability is

$$P_4 = P'' \left[P'' + (1-P'')P_bP_8P_d \right]^2,$$

where $P'' = 2P - P^2$.

The three backups can be three separate machines or one big machine with equivalent capability.

The triple-modular redundant (TMR) network with buffer memory is discussed in Sec. III-F and is the safeguards design. It effectively links the PSC, SCC, and MAC into one large module with reliability^{79,80}

$$P_T = P^3 + 3P^2(1-P),$$

so that the total network reliability is

$$P_5 = P_T P_b^2 + (1-P_T) P_b^2 P_8 P_d P + 2P_T P_b (1-P_b) + P_T (1-P_b)^2.$$

The P in the second term of P_5 reflects the fact that the buffer memories cannot back up the SCC; that is, if the TMR module fails, the SCN also fails whenever the SCC is one of the failed machines, regardless of the buffer memories.

The last configuration is the triple-modular redundant network with one backup (TMR1B) and buffer memories. We assume the backup is not dermant, so that the reliabilities of all four computers are equal to P . The module (TMR core plus backup) reliability is

$$P_T' = 1 - (1-P)^3(1+3P),$$

and the total network reliability is

$$P_6 = P_T' P_b^2 + (1-P_T') P_b^2 P_8 P_d P + 2P_T' P_b (1-P_b) + P_T' (1-P_b)^2.$$

The behavior of these network reliabilities with varying fundamental computer reliability, P , can now be investigated. Assume that the buffer memory average failure rate is one every 6 months, and that the average repair time for the PSC, SCC, or MAC is 2 h. Then $P_b = 0.793$, $P_8 = 0.982$, and P_d can be calculated from

$$P_d = \exp[\ln(P)t_d/T],$$

where t_d is the average time required to empty a buffer memory; t_d is less than 0.5 h. With $T = 1000$ h, P_d is very close to unity for P greater than 0.01 and is neglected.

Reliability curves are shown in Fig. IV-15 and labeled A, B, C, X, Y, Z for the six probabilities, P_1 - P_6 , respectively. It is clear from these curves that the TMR1B network has the best reliability, the DBM3B and TMR networks the next best, etc.

Fig. IV-15. Reliability of various SCN configurations as functions of the fundamental reliability of the PSC, SCC, or MAC.

It is also true that the TMR network (or TMR1B, depending on available equipment) makes most efficient use of the machines.

If a value for P can be obtained, the network reliabilities for each configuration can be read off the curves. For the types of computing systems discussed here, a typical failure rate for the PSC, SCC, or MAC is about one failure every 3 months, so that $P = 0.629$. Table IV-15 summarizes the network reliabilities for this case.

TABLE IV-15

RELIABILITIES FOR VARIOUS SCN CONFIGURATIONS

<u>Configuration</u>	<u>Reliability at 1000 h</u>	<u>MTBF^a (h)</u>
S	0.249	719
SBN	0.530	1,575
DBM1B	0.635	2,203
DBM3B	0.811	4,773
TMR	0.810	4,746
TMR1B	0.910	10,615

^aMean time between failures.

Thus, SCN failure rate can be improved by a factor of more than 6 by using a TMR configuration rather than a simplex. Furthermore, TMR reliability is about the same as for DBM3B, but uses half as many machines. This comparison is not quite fair because about the same total computer power is necessary for either TMR or DBM3B. However, if the PSC, SCC, and MAC are chosen so that each can handle all necessary SCN functions, the TMR configuration gives better reliability and hardware utilization than DBM3B.

For TMR, the module is assumed to fail when any two machines fail, i.e., when one machine fails there is no

procedure for choosing between the other two, a necessity for any duplex system. If such a procedure is available for TMR, then the TMR module reliability is

$$P_T = P^3 + 3P^2(1-P) + 3P(1-P)^2$$

For $P = 0.629$, $P_T = 0.949$ and the network reliability is 0.969 at 1000 h for a 31,667-h (about 3.7-yr) MTBF.

One advantage of the TMR network is its self-checking and correcting capability through the voter array (see Sec. III-F). For the duplex networks, this function must be done either by an operator or by a checking routine that is executed by a machine that may be failing, with concomitant possibility of error. For these calculations, changeover reliabilities and times for the redundant networks are assumed to have no effect.

These results should be viewed with caution because they provide only rough guidelines to SCN reliability. Quantitative answers will require more detailed calculations.

2. Data Concentrator Reliability. Four data concentrators form the interface between the safeguards instrumentation and the SCN. For reliability calculations, the concentrators can be considered to be in series because if any one fails the SCN loses data. Therefore, the reliability of the data concentrator network is

$$P_{dcn} = P_{dc}^4$$

where P_{dc} is the reliability of any single data concentrator.

The data concentrators are relatively simple and highly reliable. If the failure rate for one unit is one every 3 yr, then $P_{dc} = 0.9622$ and $P_{dcn} = 0.858$ at 1000 h; the network MTBF is about 6530 h, or a little more than 9 months.

Standby-spare data concentrators probably cannot be switched into the network fast enough; to increase reliability, any spares must be fully redundant (operating in parallel).

This added redundancy may not be necessary, but it is an inexpensive improvement. Local buffer memories at the process line could increase the allowable changeover time for standby spares (and thus the reliability), but at higher cost.

3. Safeguards Instrumentation Reliability. The safeguards instrumentation (see Chap. III) that has been added to the baseline plant design consists of 14 weighing devices, 4 pellet counters, a 35-head automatic label-reading system and 66 nuclear NDA measurement devices. These are the numbers of each of the instrument types that are in use simultaneously, some instruments are duplicated to service both sides of the split process line. For reliability calculations, all these instruments are connected in series.

Weighing devices are usually very reliable, having typical failure rates of one every 5 yr; this corresponds to a unit reliability of $P_{wd} = 0.9771$. Furthermore, repair of all but two of the weighing devices can consume 4 h without undue process disruption. Therefore, if the MTTR* for one unit is 2 h, the total reliability of all 14 devices is

$$P_w = P_{wd}^2 [P_{wd} + (1 - P_{wd})P_{wr}]^{12},$$

where P_{wr} is the probability of repair of one unit within 4 h, $P_{wr} = 0.865$. In this case, $P_w = 0.920$, and the MTBF is 11,974 h.

A pellet counter also can be expected to fail about once every 5 yr. Therefore, the total pellet counter reliability is $P_{pc} = (0.9771)^4 = 0.911$ for a MTBF of 10,792 h.

The automatic label-reader reliability is arbitrarily taken to be $P_{lr} = 0.945$ (about a 2-yr MTBF).

Of the 66 nuclear NDA devices, 58 are simple holdup measuring devices that can be replaced by standby spares in 0.5 h. Their measurements usually can be delayed for 4 h without

*Mean time to repair.

process disruption. The failure rate of gamma-ray instruments is about one per year and that for neutron counters about one every 2 yr, so that the holdup measurement reliability is

$$P_h = [P_\gamma + (1-P_\gamma)P_a]^{32} [P_n + (1-P_n)P_a]^{26},$$

where P_a is the probability of repair within 4 h at a 2/h repair rate. Then $P_a = 0.9997$, $P_\gamma = 0.891$, $P_n = 0.944$ and $P_h = 0.9985$.

The other 8 devices are more complicated (many use a mini-computer for control and calibration) and can be expected to fail about once every 6 months. However, standby spares provide a 0.5-h repair time, and down time can be 4 h. Therefore, the reliability for these eight units is

$$P_C = [P_c + (1P_c)P_a]^8,$$

so that $P_C = 0.999$. Thus, the total safeguards instrumentation reliability is $P_{si} = P_w P_{ps} P_{lr} P_h P_C = 0.79$.

4. Total Safeguards Reliability. The total safeguards reliability is the product of the reliabilities of the SCN, data concentrators, and instrumentation. Thus,

$$P_S = P_{TMR} P_{dcn} P_{si} = 0.55 \text{ at } 1000 \text{ h},$$

and the total MTBF is ~ 2.3 months, i.e., plant management can expect a safeguards-related failure about every 2 months, on the average.

Note that these calculations do not take into account secondary backup systems, for example, manually implemented safeguards functions that are normally present. As a result, many failures will not significantly disrupt process operations; moreover, the seemingly high failure rate is due partly to the restrictive definition of failure. The intent of the calculations is to give a rough idea of the system reliability and to pinpoint areas where improvement might be needed.

C. Safeguards Costs

The safeguards costs are estimates of the differences between the costs for the safeguards system described in this report and the safeguards costs for the proposed Westinghouse RFP design. The cost data listed in Table IV-16 include hardware, floor space, engineering planning (architectural engineering), installation, equipment engineering design and procurement, and contingency.

TABLE IV-16

INCREMENTAL SAFEGUARDS COSTS

Item	Unit Cost (\$k)	Number	Extension (\$k)
PSC, MAC, and SCC minicomputers	200	3	600
SCN voter array	20	1	20
Data concentrators	12	4	48
Cabling	-	-	20
Buffer memories	5	2	10
Memory backups:			
disc	20	1	20
tape drives	10	2	20
controller	10	1	10
Spare SCN parts (at 20%)	-	-	150
Software development	75/man-yr	5 man-yr	375
Weigh hoppers, PuO ₂ blending and storage	6	3	18
Weigh hoppers, MO ₂ blending and storage	6	3	18
Weigh system, PuO ₂ feed hopper to MO ₂ blending	8	1	8

TABLE IV-16 (cont)

Item	Unit Cost (\$k)	Number	Extension (\$k)
Weigh system, MO ₂ feed hopper to MO ₂ blending	30	1	30
Pellet boat weigh system	10	4	40
Scrap can weigh system	14.5	8	116
Pellet counters (with two spares)	10	10	100
NDA (γ) holdup analysis units (with eight spares)	11.5	40	460
NDA (n) holdup analysis units (with four spares)	9	30	270
NDA (n) verification sta- tion for PuO ₂ shipping	45	1	45
Automatic ID reader with 40 heads	250	1	250
Large neutron coincidence detector	90	1	90
Ge(Li) gamma-ray analysis system with segmented scanning option	85	1	85
MEGAS: Ge(Li) system with NaI backup	60	1	60
On-line solution analyzer	35	2	70
ASF NDA station; includes a neutron coincidence de- tector, Ge(Li) gamma-ray spectrometer, NaI well counter, assay cell and minicomputer for data reduction and CMHS manage- ment	200	1	200
Spare electronics	-	-	80
Spare Ge(Li) detector	15	1	15

TABLE IV-16 (cont)

Item	Unit Cost (\$k)	Number	Extension (\$k)
Spare ^3He , BF_3 , and NaI detectors	-	-	10
Spare minicomputer with peripherals (the four minicomputers in the ASF and MWT are identical for interchangeability)	20	1	20
SUBTOTAL			3258
Equipment engineering design and procurement (at 15%)			489
Contingency (at 30%)			1124
TOTAL			4871

Therefore, the safeguards incremental capital cost is less than ~ 5% of the total plant cost. Safeguards staffing costs are assumed to be \$20k/man-yr with 100% overhead, for a total (see Table III-6) of \$1280k.

V. RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

A. Results

The major result of this study is the conceptual design of an effective safeguards materials management system for generic MO_2 facilities that provides minimal interference with fuel production goals at a reasonable cost. Details of this design are given in Chaps. II and III and Appendixes B-E. Other results include the development of the control logic, management strategy, systems architecture, and the methodology necessary to evaluate the system in a form largely transferable to safeguards studies of other nuclear fuel cycle facilities.

1. Design Features of the NMAS. The major features of the NMAS are listed below.

(a) Conventional process control is implemented by an automated data acquisition system that supports human-modulated control decisions. This approach combines human adaptability with machine efficiency.

(b) The plant information system comprises the process and safeguards information systems, and is accessible to both process and safeguards personnel on a need-to-know basis. However, the safeguards information system cannot be affected by process personnel without prior approval by the Safeguards Officer.

(c) The plant management structure is conventional, except that the safeguards system can affect the process through Safeguards Officer's recommendations to the plant manager.

(d) The safeguarded plant architecture allows the plant to operate in accord with good industrial practice and introduces minimal process disruptions.

(e) The safeguards system can be made reliable enough to have a minimal impact on the process by connecting the three main safeguards computers in a TMR configuration, each

checking the other two by background processing. Buffer memories provide reliable data acquisition, and spare units increase safeguards instrumentation reliability.

(f) Almost all the safeguards system technology is already used extensively. Experimental or developmental systems are avoided where possible, resulting in higher maintainability and reliability and lower capital and developmental costs.

(g) Materials accounting can be significantly improved by relatively minor changes in the process line, for example, by separating large powder storage vessels by weigh hoppers.

(h) The concept of graded materials safeguards and the economic requirement for minimum process disruption are important factors in the generic MNAS design. Thus, the most stringent controls are applied to PuO_2 powder handling operations. Less control is maintained on operations involving NO_2 powder because the plutonium in this form is diluted by a factor of 25. For SNM that is well controlled by physical barriers (security vaults, fuel rods, etc.), verification measurements that support item control are used.

(i) Dynamic material balances are drawn around unit processes that include the primary flows of material through the unit process. These dynamic balances provide effective control of SNM even though measurements of some in-process holdup and small material sidestreams are not included in each balance.

2. Performance Evaluation Tools. Because the baseline plant has not yet been built, evaluation of the safeguards system depends on process and measurement simulation models. To quantify safeguards effectiveness, detailed models, including holdup and sidestream estimates, are used. Separation of materials flow simulation from materials measurement simulation gives greater flexibility in investigating various process and measurement techniques and SNM diversion schemes.

The GASP IV simulation language has been very useful for the simulations. A schedule of material flow events is supplied

for each unit process, and the GASP IV controller properly sequences the events.

3. Diversiion Detection Algorithms. The MMAS sensitivity to short-term diversion (single theft) depends on the measurement uncertainty (standard deviation, σ) associated with individual material balances. A useful format for graphical presentation of the material balance data is the Shewhart chart on which the data are plotted with 1σ error bars, and lines are drawn at the average 2 and 3σ levels so that outliers are apparent.

Long-term diversion (repeated small thefts of SNM) is indicated by the trend it induces into the cusum chart of material balances. Such trends can be detected by applying the V-mask technique to the cusum chart. This combination is a promising tool for separating trends caused by unmeasured sidestreams and holdup from those caused by long-term diversion. In addition, historical data on holdup and minor sidestreams can be used effectively in interpreting trends.

4. Diversiion Sensitivity. Diversiion sensitivities for five major unit processes are given in Table V-1. For comparison, the throughput of plutonium oxide is 168 kg/wk.

5. Reliability. With proper safeguards computer network configuration (TMR with buffer memories) and spare safeguards instrumentation, the safeguards failure rate can be reduced to less than one every 2 months. Furthermore, the use of well-developed technology minimizes down time when a failure does occur.

6. Cost. The capital cost of the safeguards system (not including a large part of the physical protection system) is less than 5% of the total cost. The safeguard staff (excluding guards) constitutes about 8% of the total plant staff.

B. Conclusions

The primary conclusion from this study is that current technology provides a means for safeguarding strategic quantities of SNM in MO_2 facilities at an acceptable cost and with

TABLE V-1

ESTIMATED SENSITIVITY OF THE GENERIC MMAS
FOR SELECTED UNIT PROCESSES IN THE BASELINE PLANT

Unit Process	Single Theft ^a (g Pu)	Long-Term Diversion ^b		Expected Unmeasured ^c Material (g Pu)
		(1-wk average, g Pu)	(4-wk average, g Pu)	
PuO ₂ unloading ²	110	16(350)	8(700)	18 ^d
MO ₂ blending	130	20(400)	10(800)	15 ^e
Pelleting	150	20(400)	10(800)	33 ^e
Grinding	80	12(250)	6(500)	22 ^e
Clean scrap recovery	200	10(200)	5(400)	5 ^e

^a Amount (3σ) of unmeasured material that can be detected in a single balance period with a probability of 50% at a false-alarm rate of approximately 1 in 1000.

^b The average amount ($2\sigma_C/L$) of unmeasured material per balance period that can be detected during 1-wk and 4-wk periods with a probability of approximately 85% at a false-alarm rate of about 1 in 6. The total amount ($2\sigma_C$) is given in parentheses.

^c Average amount of unmeasured material expected per balance period during normal process operation taken from the baseline plant model (Appendix D). The actual amount typically ranges from zero to twice the average value.

^d Accumulated and measured each shift.

^e Accumulated and measured each week.

minimal disruption of production processes. The need to evaluate the effectiveness of such materials control systems, without actually having the opportunity to operate them, leads to an extremely important secondary conclusion: while there may be generic solutions to safeguards problems, the concept of a generic facility design is of very limited usefulness.

To safeguard gram quantities of SNM throughout the entire process, including waste streams, sampling streams, and holdups, these flows and processes must be known in detail and with greater precision than can be described in any generic or prototypical facility. The need for quantitative performance evaluations therefore requires that a specific (or archtypical) nuclear facility be described in engineering detail, and as a result, a generic design rapidly becomes very much a detailed practical study of the effects of seemingly minor process, operational, and equipment features. The alternative is to provide a qualitative review, which largely ignores the problem. This has been done several times in the past, with predictable results.

Although the facilities themselves need to be analyzed in great detail, the generic approach can be used in the specification of the measurements, systems, and methodology that are needed to address specific problems, once they are identified. The features most common to all nuclear facilities, such as control logic, measurement requirements, management structure, safeguards strategies, and evaluation methodology, are subject to generic treatment and, accordingly, represent highly transferable technologies. Plant designs, flowsheets, and materials balances are not held in common by generic facilities and are not readily transferable. This consideration highlights the necessity for industrial participation in the systems design and the type of close cooperation between plant designers and safeguards systems designers that is reflected in this report.

Another important conclusion regards the practical effectiveness of process-coordinated materials controls integrated with physical security in a balanced safeguards system.

Both components provide essential incidental benefits; their omnipresence provides an important psychological deterrent and an immediate verification or denial of the classic blackmail or diversion threat. Above all, the existence of two interactive safeguards components has a valuable synergistic effect because the characteristics of the materials management system force the potential diverter to decide whether to attempt a series of relatively large, preplanned thefts, timed to evade the physical security system, or to launch an even longer campaign of smaller diversion below the detection threshold of the materials control system, hoping somehow to escape detection by the physical security system. The probability of either approach resulting in the successful diversion of strategic quantities of SNM seems remote.

C. Areas for Further Effort

Several items need more study to improve and verify the effectiveness of the safeguards system. The list includes:

- (1) Experimental verification of holdings, material side stream estimates, and measurement uncertainties in an operating facility;
- (2) Further study and evaluation of the cusum and V-mask method for detection of long-term diversion;
- (3) Evaluation of other filtering techniques (e.g., the Kalman filter) for data smoothing and/or detection of long-term diversion;
- (4) Study of specific measurement models with regard to inclusion of covariance terms and degraded calibration effects;
- (5) Evaluation of materials control for nonstandard or pathological processes (e.g., pilot blending), and for peripheral process areas such as the ASF and MBT;
- (6) Study of the relationship of dynamic materials control to the element and physical inventory cycle;
- (7) Scrutiny of the interface with the physical protection system;

(8) Definition of the details of the materials accounting software;

(9) Evaluation of the use of historical data in materials accounting;

(10) Further definition of the safeguards-process interaction;

(11) More detailed and accurate calculations of reliabilities and costs; and

(12) Refinement of measurement methods to reduce uncertainties.

In addition to addressing the above MO₂ considerations, the approach used in this study should be applied to other nuclear fuel cycle facilities to provide them with effective materials control safeguards as well as to test the general applicability of the concepts and techniques employed.

APPENDIX A

DETAILED DESCRIPTION OF PLUTONIUM PROCESSING

This appendix discusses in depth the main process stream, particularly with regard to plutonium flow. Relationships between the various processes are shown in Fig. II-1.

I. PuO_2 RECEIVING, BLENDING, AND STORAGE

The PuO_2 receiving, blending, and storage system receives and stores incoming shipping containers of PuO_2 powder, unloads the PuO_2 from the containers, verifies the contents, and transfers the powder to vessels for blending and storage.

System boundaries extend from the feed material receiving area through the PuO_2 storage vessel star feeders. Figures A-1 and A-2 are block diagrams of these processes.

A. General Description

PuO_2 powder in specialized shipping containers arrives at the site by secured truck. The truck with its contents enters the receiving area on the first floor of the feed material receiving building. Health and Safety Services surveys the incoming shipment for alpha contamination, and QC verifies the shipping documents. If contamination is detected on the exterior of a shipping container, decontamination is accomplished in a special area in the receiving building.

Samples of the PuO_2 from a truck shipment are received and analyzed before that truck shipment arrives. These samples go to the ASF.

Filled shipping containers are transported into the building and placed on an elevator for transfer to container storage on the second floor. Shipping containers are transported as

Fig. A-1. Feed material receiving and initial storage.

Fig. A-2. PuO₂ unloading from containers.

required to unloading operations, where a container is opened, and the contained PuO_2 powder is weighed, sampled, and transferred pneumatically to a blender-storage vessel. After a storage vessel is filled, the contents are blended, sampled for homogenization, and certified by QC before release as feed material for enrichment blending.

B. Subsystems and Components

1. PuO_2 Receiving and Decontamination Area. The truck dock can accommodate only a single truck shipment.

The area set aside for decontamination has the required supplies, including the appropriate decontamination solutions, wipes, plastic materials for bags, floor covering and tents, a drum for storing bagged contaminated wipes and plastics, and appropriate radiation monitoring and protection equipment.

2. Shipping Container Storage Area. This shielded storage area provides space for the PuO_2 shipping containers, as well as for the storage of shipping containers of dirty scrap and empty containers.

Area entry and exit must be through the same access point. An authorized person controls operation of the shielded door at the access point. Continuous radiation monitoring in the storage area is required.

3. Shipping Container and Contents. The filled shipping container comprises four major components.

(a) Four sealed canisters, each containing approximately 8 kg of PuO_2 ;

(b) A primary pressure vessel containing the four canisters; this has a double-seal closure with leak-checking and venting capability; and venting capability;

(c) A secondary pressure vessel containing the primary pressure vessel; it also has a double-seal closure with leak-checking and venting capability;

(d) An overpack containing the secondary pressure vessel and outer package; the outer package includes nuclear

shielding and thermal control features. The overpack cover with plug is sealed with a gasket.

4. Unloading Station. The PuO, unloading station is a four-compartment, shielded, glovebox enclosure. Filtered air is drawn through the enclosure and exhausted through absolute filters.

Compartment 1 contains

- A motorized monorail hoist that positions, lowers, and raises and which is operated by a hand switch.
- An impact wrench, which is air-actuated by hand switch; the impact wrench may be manually connected to the hoist hook and can remove bolts from the shipping container lid and the secondary pressure vessel lid.

Compartment 2 contains

- A drum jack on which a shipping container is secured; the drum jack, activated by hand switch, raises the shipping container until it is sealed to the entrance of Compartment 3; sensing devices at the sealing point indicate when a positive seal has been made.

Compartment 3 contains

- A motorized bridge crane, operated by hand switch, for canister unloading, canister storage, and canister removal from storage.
- An impact wrench, lid-lifting tool, and canister lifting tool, all air-actuated by hand switches and connected to the crane hook by remote control.
- A shielded and criticality-safe canister storage array for storing as many as four canisters; sensing devices indicate when the storage slot is occupied.

Compartment 4 contains

- A motor-driven conveyor, activated by hand switch, for transporting a single canister to each powder unloading operation; the conveyor is reversible.

- A weigh scale for remote readout of canister gross weight and final tare weight.
- A motorized canister opener activated by hand switch; the canister must be positioned properly for the opener motor to operate.
- An air-activated canister lid device, controlled by hand switch, for removing canister lids.
- A PuO_2 unloader inserted by remote control into powder canisters to transfer powder pneumatically to one of three PuO_2 storage vessels.
- A mechanical reversible conveyor.

5. PuO_2 Blender-Storage Vessels. These vessels provide the following functions:

- Receive and accumulate PuO_2 from the unloading station,
- Blend PuO_2 into a homogeneous powder,
- Store PuO_2 in large blends,
- Supply PuO_2 to the fabrication process, and
- Provide sampling capability.

Three criticality-safe slab vessels are provided. Vessel controls interface with the batching controls for enrichment blending. In normal operation, one vessel is supplying material to the fabrication process, one vessel is receiving material from the unloading station, and a third vessel is isolated and in the process of blending and certifying material for release to the process.

The vessel contents are blended pneumatically and each vessel contains a bank of porous filters. Reverse-flow blow-back is provided to the filters and operates intermittently during the blending operation. The off-gas from the vessel passes through a backup filter and a HEPA (high efficiency particulate air) filter before discharge into the plant off-gas system. A schematic of a pneumatic transfer operation is shown in Fig. A-3. Weigh cells are provided on each vessel for inventory purposes.

LEGEND:
 EQUIPMENT IDENTIFICATION (BY LETTER)
 INSTRUMENTATION (SEE CODE)

CODE:
 L - LEVEL
 R - RADIATION
 P - PRESSURE
 W - WEIGHT
 F - FLOW
 G - GAUGING
 A - ANALYTICAL
 T - TEMPERATURE

NOTE
 1) ONLY ONE OF THREE STORAGE TANKS SHOWN

ITEM	QTY	DESCRIPTION	REMARKS
1	1	PuO ₂ STORAGE TANK BLENDING COMP.	
2	1	OFF-GAS BLEND. PuO ₂ UNLOADING PTS	
3	1	HEAT FILTER. PuO ₂ UNLOADING PTS	
4	1	BURN-UP FILTER. PuO ₂ UNLOADING PTS	
5	1	PuO ₂ TANK DISCHARGE BLEND	
6	1	PuO ₂ TANK BLEND TANKS	

Fig. A-3. Flow diagram for PuO₂ storage and blending.

C. Instrumentation and Control

The presence of a shipping container is verified visually in the unloading box and by container identification input.

Confirmation of the container identification and an "occupied" indication activate the monorail hoist, permitting lid removal and opening of the secondary pressure vessel. Repositioning of the opened container to the drum jack for elevation to the second compartment is confirmed by a second position indicator. The primary pressure vessel closure is removed and the canisters are lifted out by the bridge crane.

Completion of the canister removal operation is verified visually at the safe array storage; the third compartment is then isolated by a remotely actuated air-lock door. After isolation of the safe array storage, the bridge crane and conveyor transfer the canisters to weighing and sampling areas.

Gross weight measurements are made and compared to shipper's values. Out-of-limit weight differences are reported and require management action before the operation may proceed. Individual net weight confirmations, completion of required canister operations, and acknowledgment of sample transfers are necessary before the unloading operation and PuO_2 transfer can continue.

Interface acknowledgments are also required before the transfer operations can begin. Confirmation of receiver vessel weight readout, inventory status, and transfer inputs must be acknowledged for each canister. The tare weight of each emptied canister must be confirmed before it can be transferred out of the unloading box.

PuO_2 is transferred to the blender-storage vessels by activating routing valves from keyed lock-out switches. Once a vessel has been valved to accept material, its contents cannot be discharged until another keyed lock-out has been switched by an authorized person.

Supervisory action is required to change material routing because the routing valves are operated from keyed actuators.

When the contents of a vessel have been discharged to the process, valving is switched to prevent further discharge and to permit filling; material is introduced into the transfer system until the vessel is filled, after which the vessel is isolated and a blending cycle is initiated. Samples of the blended product are extracted and transferred to the ASF. The vessel remains isolated until certified and released by QC. After release, the material routing valves can be switched and the PuO_2 discharged upon demand of the powder batching system.

D. Operation

The mode of operation for the PuO_2 receiving, blending, and storage system includes direct handling of full and empty shipping containers, gloved access for in-box operations, semi-remote material movement, and panel-controlled material transfers.

1. Introduction of Container. A shipping container is transferred from the secured storage area to a self-propelled dolly for introduction into the enclosure where container identification is verified. Access to the unloading box is controlled by keyed switches with remote status indication.

2. Container Opening and Canister Removal. The top lid of the shipping container is removed and alpha-surveyed; only negligible contamination is expected and detected areas are cleaned in place. The secondary pressure vessel is then opened and survey and cleanup performed as necessary.

The container is moved to a second position and is elevated to the seal opening of the second compartment. The seal establishes a negative pressure with respect to the first compartment. The repositioning is confirmed by a position sensor with local and remote readouts.

A bridge crane manipulator in the second compartment removes the top closure of the primary pressure vessel allowing access to the canisters. The canisters are lifted out and placed in a safe storage array in Compartment 3; after removal

of all four canisters, Compartment 3 is isolated from Compartment 2 to minimize back-contamination. The primary pressure vessel is closed, and the container is disengaged, surveyed, and returned to the first compartment position where closure of the secondary pressure vessel and the external container is completed. Return of the container to storage requires confirmation of canister contents as itemized below.

3. Canister Weighing and Sampling. The canisters are moved by the bridge crane through an air-lock closure onto a conveyor in Compartment 4 for transfer to a weighing area. Each canister is taken through all steps, including canister discard, before the next canister is introduced. A canister is moved by manipulator from the conveyor to the scale, which provides both local printout and remote input. The manipulator places the canister back on the conveyor for positioning at the next station for lid removal and sampling.

At that station, the canister is fixed in place and the lid removed by the remotely operated tool. A powder sample is remotely withdrawn to a sample container and transferred via pneumatic tube to the ASE. A second sampling system permits periodic extraction of larger quantities of powder as feed for pilot fabrication testing.

4. PuO₂ Transfer and Waste Discard. The canister is conveyed to the powder transfer system. The interface with the blend-storage module is consulted to confirm that the following conditions are satisfied to permit initiation of transfer:

- Confirmation of shipping container net weight,
- Confirmation of sampling,
- A canister is positioned in the transfer system,
- Pneumatic transfer system flows and pressures setpoints are satisfied,
- The selected storage vessel is below its high value setpoint, and
- The routing valve is positioned to the selected vessel.

When powder transfer is completed, the empty canister (with lid) is weighed to confirm the tare weight. Empty canisters are transferred into the canyon RAA for disposal via the MWI system.

An alternate route is available for introduction of PuO_2 powder directly to the PuO_2 feed hopper of the powder batching operation.

5. PuO_2 Blending and Storage. In normal operation, one vessel is supplying material to the fabrication process, one vessel is receiving material from the unloading station, and a third vessel is isolated and in the process of blending and having material certified for release to the process. Operator input is required to initiate the blending operation.

E. Maintenance

Minor equipment repair may be performed inside the unloading station, but contact maintenance, through gloves, is limited to Compartments 1 and 2. Provision is made for removal of waste and defective equipment by conveyor into the RAA canyon. Remote maintenance is required for equipment in Compartments 3 and 4. External viewing and crane manipulator operations are used.

Failed equipment is repaired in place within the canyon confinement whenever possible. Glove port access, where applicable, is provided to all equipment including disconnects, mounts, clamps, flanges, unions, and inspection/cleanout ports. When not in use, glove ports are closed with shielded covers.

II. POWDER PREPARATION AND STORAGE

The powder preparation and storage system receives, batches, homogenizes, deagglomerates, and stores certified UO_2 , PuO_2 , and recycled MO_2 powders. Following QC release, the blended MO_2 is available on demand as feed for pelleting operations. Rejected sub-blends are released only to the recycled MO_2 storage vessels. The boundaries of the system extend from the UO_2 , PuO_2 , and recycled MO_2 feed hoppers through the star

feeders for the blended MO_2 powder storage silos. A schematic of the MO_2 powder blending system is shown in Fig. A-4, and Fig. A-5 shows a block diagram of the system.

A. General Description

When a sub-blend of MO_2 is required for production, the three components-- UO_2 , PuO_2 , and the recycled MO_2 powder required for the batch--are calculated and programmed into the batch control system. Control logic activates the proper equipment to prepare the batch. This is accomplished by filling the feed hopper for each component to a predetermined powder level, then transferring the required weight of each powder component from the respective feed hopper to its weigh hopper. Predetermined quantities from each weigh hopper are transferred into the blender, and operation of the blender is initiated.

When a sub-blend of MO_2 powder is uniformly blended, it is discharged through a reduction mill, sampled, and pneumatically transferred to one of nine MO_2 storage silos. Sub-blends released by QC are fed to the pelleting operations. Reject sub-blends are pneumatically transferred to one of three CSRS storage vessels.

B. Subsystems and Components

1. Mixed-Oxide Batching. This subsystem interfaces with the PuO_2 , UO_2 , and recycle MO_2 feed material storage vessels and performs the following functions:

- (a) UO_2 , PuO_2 , and recycle MO_2 feed hopper charging,
- (b) UO_2 , PuO_2 , and recycle MO_2 weigh hopper charging,
- (c) UO_2 , PuO_2 , and recycle MO_2 weighing, and
- (d) MO_2 enrichment blender charging.

The batching system control logic activates and controls the appropriate equipment for each sub-blend as described below.

a. UO_2 , PuO_2 , and Recycle MO_2 Feed Hopper Charging. Powder is transferred from a storage hopper to the corresponding feed hopper as directed by the batch control system.

0	0	0.5% BLANKET FLOW CONTROL	
0	0	RECYCLE NO2 BLANKET	
0	0	0.5% RECYCLE NO2 BLANKET FTS	
0	0	RECYCLE NO2	
0	0	BLANKET NO2 BLANKET FTS	ONE TANK
0	0	RECYCLE NO2 BLANKET FTS	
0	0	RECYCLE NO2 BLANKET FTS	
0	0	RECYCLE NO2 BLANKET FTS	
0	0	RECYCLE NO2 BLANKET FTS	
0	0	RECYCLE NO2 BLANKET FTS	
0	0	RECYCLE NO2 BLANKET FTS	

0	0	0.5% BLANKET FLOW CONTROL	
0	0	RECYCLE NO2 BLANKET	
0	0	0.5% RECYCLE NO2 BLANKET FTS	
0	0	RECYCLE NO2	
0	0	BLANKET NO2 BLANKET FTS	ONE TANK
0	0	RECYCLE NO2 BLANKET FTS	
0	0	RECYCLE NO2 BLANKET FTS	
0	0	RECYCLE NO2 BLANKET FTS	
0	0	RECYCLE NO2 BLANKET FTS	
0	0	RECYCLE NO2 BLANKET FTS	
0	0	RECYCLE NO2 BLANKET FTS	

Fig. A-4. Flow diagram for MO_2 blending and storage.

Fig. A-5. MO₂ powder blending.

The following conditions and sequence of events are required for this transfer:

- The rate feeder is off,
- The weigh cells of the feed hopper indicate that the required powder weight has not been reached,
- The unit vacuum conveyor is actuated,
- The storage hopper discharge positive shut-off valve is open, and
- The storage hopper bin activator and rate feeder are actuated.

All devices are actuated by the batch control system when it receives the command to charge the feed hopper. Transfer continues until the powder weight in the feed hopper has been reached, at which time the batch control system shuts down the transfer of powder, restoring all intervening automatic devices to their passive mode. The feed hopper is charged to a larger quantity of powder than is required for one batch. This powder transfer may be performed with manual controls.

b. UO_2 , PuO_2 , and Recycle MO_2 Weigh Hopper Charging.

After the feed hoppers of all three component (UO_2 , PuO_2 , and MO_2) powders are fully charged, the batch control system interlocks will permit the charging of the UO_2 , PuO_2 , and MO_2 weigh hoppers if the following conditions exist:

- The enrichment blender has been discharged since the last fill-discharge cycle of the weigh hoppers (to prevent double charging of the blender),
- The positive shut-off discharge valve on each weigh hopper is closed,
- The UO_2 dual-sequencing isolation valve is closed (this valve allows transfer of UO_2 into the RAA between the weigh hopper and the blender), and
- The weigh hopper load cell calibration cycle has been completed.

When the signal to load the weigh hoppers is received, all screw feeders are started at full speed. As each weigh hopper weighing system indicates that its hopper has received most of

its scheduled material, the respective screw feeder switches to low speed and stops when the required amount of material has been received.

After charging of the weigh hoppers is completed, operator action is required before the batch control system will permit discharge into the blender. Moreover, blender charging can be initiated only if each of the three weigh hoppers possesses the weight of powder that had originally been programmed into the batch controller.

The contents of the UO_2 weigh hopper, located in the LAA, are discharged incrementally by gravity into the blender via a dual sequencing isolation valve. The blender discharge valve is in the off position, the positive discharge shut-off valve of the weigh hopper is opened, and the vibrator is actuated. When all of the UO_2 has been transferred to the blender, the hopper vibrator is deactivated, the hopper discharge and isolation valves are closed, and the weigh hopper is reweighed to assure complete transfer.

The contents of the PuO_2 and recycle MO_2 weigh hoppers are discharged by gravity into the blender. The blender discharge valve is in the off position, the positive discharge shut-off valve of each weigh hopper is opened, and the vibrators are actuated. When all of the PuO_2 and recycle MO_2 has been transferred to the blender, the hopper vibrators are deactivated, the hopper discharge valves are closed, and the weigh hoppers are recalibrated to assure complete transfer.

2. Enrichment Blending. This subsystem receives UO_2 , PuO_2 , and recycled MO_2 powders from the weigh hoppers, pneumatically blends the three powder components to a homogeneous mixture, and discharges the blended mixture to storage.

a. Enrichment Blender. The blender is a rectangular-shaped, criticality-safe, stainless steel slab vessel with a V-shaped bottom section. A timing device actuated at the control panel automatically initiates all powder blending events for a specific time interval. At the completion of the blending

cycle, the timer shuts off and the events previously described for powder discharge are automatically actuated.

Controls are programmed so that discharge valves to the weigh hoppers are opened only when powder transfer from the enrichment blender is complete and the blender discharge valve is in the off position. Powder discharge from the blender cannot occur until PuO_2 and UO_2 (or MO_2) powders are charged to the blender. This is to prevent undiluted PuO_2 from being charged to the storage silos. Manual overrides are provided for abnormal conditions.

A cyclic timer with a fixed on time and interval time provides control of pulsed air to the porous filters. Overrides permit the blender blow-back system to clean out and operate under emergency conditions. A pressure differential sensor located in parallel with the porous filter elements indicates filter blockage or breakage. A pressure relief device prevents vessel overpressurization, and off-gases from the blender are vented to the off-gas system.

Interlocks shut down upstream operations (weigh hopper discharge valves), blender operations, and downstream operations (rate feeder, reduction mill) if the discharge valve is not positioned properly. This valve has a manual override.

b. Rate Feeder. The rate feeder motor interlocks with the programmed controls in operations immediately upstream (previously described) and operations downstream so that the feeder will not operate if there is a malfunction to the equipment involved in those operations. If the rate feeder malfunctions, these interlocks shut down equipment immediately upstream and downstream of the feeder until corrective action is taken. The rate feeder has manual overrides.

3. Milling, Sampling and Storage. This subsystem mills, samples, and stores sub-blends of MO_2 powder from the enrichment blender. Nine storage silos provide sufficient storage for powder to be available at the rate required downstream. This subsystem interfaces with the pelleting operations compactor,

CSRS vessels, ASF transfer system, and the pneumatic transfer system.

When a sub-blend of MO_2 powder is uniformly blended and ready for release from the blender, one of nine MO_2 silos is selected for storage. Diverter valves in the pneumatic conveyor, which routes the powder from the powder reduction mill, are positioned to allow flow to the selected silo. The blender discharge valve is opened and the reduction mill drive and rate feeder drive are actuated for the interval required to completely empty the contents of the blender and mill. The discharged milled MO_2 powder is transferred to the silo via the pneumatic conveyor. A weigh cell system indicates the tare weight of the empty silo assembly and the gross weight of the silo and powder when the silo is full.

Samples of milled powder are extracted from each sub-blend at the discharge of the reduction mill by means of a preset periodic sampler. The sample containers are placed in a special conveyor container and dispatched via pneumatic transport conveyor to the ASF.

The results of the sample analysis determine the disposition of stored powder. If the sub-blend is within specification, it is released for pelleting operations; if not, the sub-blend is transferred to the clean scrap storage vessels.

a. Reduction Mill. The reduction mill is located immediately downstream from the rate feeder and interlocks with those upstream control functions described in the enrichment blender subsystem. The mill and pertinent upstream equipment are controlled on a specific time cycle; failure of any piece of equipment will result in the shutdown of the other equipment controlled by the same time cycle. This applies to downstream operations, i.e., pneumatic conveying, sampling, and diverter valve positioning on the silos. The mill has manual override.

b. Powder Sampler. The MO_2 powder sampling device is programmed to extract several samples from the discharge of the reduction mill. Samples are accumulated and placed in a

container, manually transferred to a sample pneumatic station, and pneumatically transported to the ASF.

The sampler is programmed on a time cycle. During powder discharge, the sampler extracts a single sample within a preset time, holds for a preset time, extracts the second sample, holds, etc. After powder discharge is completed, the sampler cycles for a preset time and then shuts off. Any malfunction in the immediate upstream operations will deactivate the sampler. Manual override is provided.

c. Storage Silos. The nine MO_2 powder storage silos are stainless steel slab vessels equipped with valved discharge ports, weigh cell systems, filtration system, air pads, and pneumatic vibrators.

Routing of sub-blends through diverter valves to the storage vessels is performed manually from keyed activators. This guarantees that an authorized person must take positive action to change a material routing path and to allow powder transfer to occur. The position of the diverter valves during operation is monitored by indicator lamp. The position of a diverter valve must mesh with the charging end of the selected silo or powder transfer is blocked. Once a silo is filled, a lock-out switch prevents further powder from being charged to that silo until the silo has been emptied.

A weighing system on each silo is provided for inventory purposes and to determine when powder discharge is complete. Hide-out detectors may be required to ensure that no significant quantities of powder remain in the silos.

C. Instrumentation and Control

Values input to the batch control system activate and control the proper equipment for preparing each sub-blend. The batch control system directs all activities upstream from the enrichment blender. The processing equipment (including the off-gas system) is controlled to stop under the following conditions:

- A seismic incident in excess of a preset value,
- A fire alarm in areas immediately adjacent to canyon LAA,
- A criticality alarm,
- A power interruption, or
- A loss of flow in the ventilation system or the absence of a pressure differential across the containment barrier.

D. Operation

The powder preparation and storage system operates by batch processing, with automatic sequencing of processing steps once a processing cycle has been initiated. Recovery from abnormal conditions and emergency stoppages is by manual restart, after inspection for damage and correction of the condition causing the stoppage. Immediate and constant operator attention is not required in this system except when a processing cycle is initiated. The controls are designed to fail-safe the operation and to provide an alarm to the operator when a processing cycle fails to reach completion because of an abnormal situation. The next step will not start until after the current step reaches completion.

E. Maintenance

Whenever possible, failed equipment is repaired in place. Glove port access, where applicable, is provided to all items including disconnects, mounts, clamps, flanges, unions, and inspection/cleanout ports.

III. PELLETING SYSTEM

The pelleting system transfers MO_2 powder, forms it into pellets with specific dimensions, and collects and stacks the pellets for transfer to the next station. System boundaries extend from the powder storage vessel star feeders through the

boat loader. The off-gas system is also included in this area of the plant.

The pelleting system consists of a compactor feed hopper, compactor, weight-sensing platforms, separator, powder lubricant feeder, rolling drum, bulk density check, press feed hopper, pellet press, ribbon conveyor, green density inspection apparatus, boat loader, backup filter, off-gas blower, and associated instrumentation and controls for each of these components. A schematic of this system is shown in Fig. A-6 and a block diagram is given in Fig. A-7.

A. General Description

The pelleting system receives blended MO_2 powder, precompacts it, granulates the precompacted material, and separates the fines from the granule stream for recycle. The granules are conditioned by rolling with lubricant, sampled for bulk density, and fed to a hopper. Process feed is dispensed to the pellet press. The pellets are conveyed away from the press, sampled for density, collected, and stacked into sintering boats.

B. Subsystems and Components

1. Compactor Feed Hopper. Rotating valves serving either side A or B are manually operated within the RAA through glove ports. A selector system, accessible only to authorized personnel, has position indicators which must match the valve position or the silos will not discharge to the vacuum transfer system.

The feed hopper has level sensors which control upstream and downstream equipment by means of the following signals and control functions:

- HI-HI limit--shuts off the discharge system from the powder storage silos to the vacuum transfer line and initiates an alarm;

- HI limit--provides visual warning that the system is approaching HI-HI shut-off;

Q	4	STAR FEEDER	
P	4	WEIGHT-SENSITIVE PLATFORM	
B	1	OFF-GAS BLOWER	
M	1	HEPA FILTER	
L	1	BACK-UP FILTER	
S	2	GREEN PELLET CENSITY MEASUREMENTS	
J	2	PELLET PRESS	
U	2	PRESS FEED HOPPER	
S	2	BULK CENSITY CHECK APPARATUS	

F	2	POWDER LUBRICANT FEEDER	
E	2	ROLLING DRUM	
D	2	SEPARATOR	
C	2	COMPACTOR	
B	2	COMPACTOR FEED HOPPER	
A	2	COMPACTOR FEED HOPPER	
ITEM	QTY	DESCRIPTION	REMARKS

NOTES
 1) QTY. QUANTITY SHOWN IS FOR BOTH SIDES OF SPLIT LINE.

Fig. A-6. Flow diagram for MO₂ pelleting.

Fig. A-7. MO₂ pelleting.

- Upper level--turns equipment on from LO-LO limit shut-off; powder lubricant is introduced after a time delay;

- Lower level--turns equipment on from HI-HI limit shut-off;

- LO limit--provides visual warning that the system is approaching LO-LO shut-off;

- LO-LO limit--shuts down the star feeder, the compactor, and powder lubricant feeder (after a time delay), and activates an alarm.

NOTE. The above limits are adjustable and may coincide.

2. Compactor. The compactor, star feeder, powder lubricant, granulator, separator, and feeder are all controlled as a single unit unless otherwise specified. Compactor pressures are manually controlled.

The compactor drive motor(s) have manual speed adjustments and are located in the LAA, driving through the containment wall by means of rotary seals. The system pressure and the power input to the process drive mechanisms are indicated on a panel or otherwise displayed.

To prevent powder leakage, ambient pressure within the compaction system is negative with respect to the RAA. Vacuum is introduced through the compactor feed hopper, which collects and recycles entrained dust. The vacuum system is designed to maintain a minimum of 1 in. water gauge vacuum in all of the equipment it serves.

The following equipment is internally connected to the vacuum system:

- Compactor,
- Granulator,
- Separator,
- Oversize particle container, and
- Rolling drum.

3. Material Sensor Between Compactor and Granulator. The material sensor detects excess material that may bridge the hopper and cause a jam. When it detects this condition, the

sensor shuts down the compactor and star feeder and activates an alarm.

4. Granulator. The granulator equipment in contact with NO_2 is of stainless steel. A shroud provides for internal inspection and periodic cleaning.

Ventilation within the unit is held at a negative pressure provided through upstream equipment.

The drive motor is located in the LAA, and rotary seals surround the drive shaft where the shaft extends through the containment wall.

5. Weight-Sensitive Platform: Oversize Particle Detector.

The weight-sensitive platform in this contaminated scrap stream from the separator is used to detect a possible malfunction in the granulator and the presence of excessively large NO_2 particles in the product. The upstream equipment, including the compactor and star feeder, will not operate if a scrap container is out of position. During operation, material flow into the scrap container is sensed as soon as possible and a signal immediately stops the compactor and star feeder. The signal also allows the granulator and separator to run for a preset time to clean out the granulator for repair and to clear out-of-specification feed material from the separator.

6. Separator. The separator consists of three segregated chambers and a sealed scrap collector which is placed on a weight-sensitive platform. The first chamber separates oversize granules from the product stream and routes them to the scrap can. The second chamber transfers the properly sized product granules downstream but intercepts any fines. The third chamber returns the fines to the compactor feed hopper through a rotary feeder valve to maintain the negative pressure in the system. A cleanout port above the rotary feeder valve is used to empty the equipment.

The product granules are fed to the rolling drum. Inlet and exit connections and chamber seals ensure that negative pressure is maintained but do not interfere with separator functions.

7. Powder Lubricant Feeder. The powder lubricant feeder is controlled automatically in sequence with the compactor. An adjustable time delay with manual override is included in the control circuit to permit process material to enter the rolling drum before the powder lubricant is added. Delayed stopping by the same time delay is included in the control circuit to assure lubrication to the material in process. Speed adjustments on this feeder are performed manually.

A level sensing system in the feeder hopper has the following level adjustments:

- LO-limit--actuates a visual warning that LO-LO shut-off is being approached and provides recovery from LO-LO shut-off;

- LO-LO limit--shuts down all process equipment between and including the star feeder to the compactor and the rolling drum.

8. Rolling Drum. The rolling drum is controlled in parallel with the compactor and is designed to roll the product for a specified retention time; the time is manually set and adjustable.

Internal ventilation maintains a negative pressure that originates upstream and travels through the process equipment.

The complete unit can be emptied conveniently during runout and enrichment changes. The drum is of stainless steel.

9. Bulk Density Check Apparatus. The bulk density check apparatus is set to perform two functions between preset density limits (by weight), which are obtained from a known constant volume sample:

- (a) Over or under set limit--recycle immediately with a visual indication of the density.

- (b) Second test

- (1) If the density is acceptable, operations continue normally;

- (2) If the density is outside the limits, the upstream equipment, including the compactor and star feeder, is shut off and an alarm is initiated.

10. Press Feed Hopper. The press feed hopper controls the process upstream and downstream as a function of its powder level as follows:

- HI-HI limit--shuts off all upstream equipment including compactor and star feeder;
- HI limit--provides a visual warning that the system is approaching HI-HI shut-off.
- Upper level--turns equipment on from LO-LO shut-off.
- Lower level--turns equipment on from HI-HI shut-off.
- LO limit--provides a visual warning that the system is approaching LO-LO shut-off.
- LO-LO limit--shuts off all cyclic functions of the pellet press.

NOTE. The above limits are adjustable and may coincide.

Ventilation for the hopper comes from the upstream process equipment.

11. Weight-Sensitive Platform (Rejected Pellets). The weight-sensitive platform does not allow the press to cycle if a scrap container is out of position or if a preset gross weight for a full scrap can is sensed.

12. Pellet Press. The pellet press compacts the feed material into pellets for sintering. The various parameters, speeds, and times of the operating sequence are adjusted by press controls. An operator control console is provided at the press in the LAA. A sensor stops the press and rejects the pellets if the press malfunctions. Recurrence stops the press. Over-temperatures shut down the entire press system and initiate an alarm if a preset value is exceeded. A vacuum unit is

connected to the pellet press table to pick up loose powder for recycle to the compactor feed hopper.

The pellet press, ribbon conveyor, green-pellet density inspection apparatus, and boat loader are controlled as a single system except as otherwise noted. Normal process controls interact with the cyclic operation of the press to keep the press from running dry.

A pellet-rejection system rejects pellet(s) that are:

- (a) Under-density--rejects all pellets pressed during that cycle; or
- (b) Outside of set length limits--rejects individual pellets.

13. Ribbon Conveyor. This unit is a belt conveyor that moves standing pellets from the table of the pellet press through the green-pellet density inspection apparatus to the boat loader. A sensor determines whether a blockage has stopped the stream of pellets to the boat loader. If a blockage occurs, the press is stopped and an alarm is actuated.

14. Green-Pellet Density Inspection Apparatus. The green-pellet density inspection unit operates on a preset time cycle that runs when the press is operating. Manual overrides allow the operator to take samples between the predetermined inspection times. The time interval is adjustable.

A density or length reject will cause the inspection unit to recycle. If results of a second inspection are within acceptable set limits, the process continues. However, if an inspection shows an out-of-limit condition, an alarm is activated and the press is stopped.

15. Boat Loader. When the pellet press is on, the boat loader receives pellets from the ribbon conveyor. The pellets begin to accumulate before entering the boat loader, which then cycles until a preset number of layers have been put into the boat. Then the loaded boat is released and an empty boat is positioned for loading. Loaded boats on the green-pellet boat conveyor are sensed and allowed to pass along the conveyor unobstructed. The presence of a boat permits the transfer of

pellets into the boat. Indexing is done by stepping motor, and all other motions are initiated by air actuators. When one step in the cycle is sensed, the next step is initiated; time delays are included where necessary.

A weight-sensitive element is provided for a pellet receptacle that catches errant pellets. When the receptacle has reached a preset weight, the pellet press, ribbon conveyor, green-pellet density inspection apparatus, and boat loader are turned off and an alarm is actuated that requires the operator to empty the container, replace it, and restart the system.

16. Backup Filter. The backup filter consists of a geometrically favorable steel filter housing. The internal filters have blow-back capability and provisions for collecting accumulated material in a standard clean scrap container. The backup filter serves the powder transfer system and acts as a prefilter to protect the HEPA filter.

The controls consist of:

- Switches, control indicators, and alarms located at the local control station;
- A hand switch override for maintenance; activating controls for the sequential filter blow-back system are interlocked so that the system blower must be in operation to permit activation;
- A low differential pressure alarm to indicate filter failure;
- A high differential pressure alarm to indicate filter plugging;
- Neutron hide-out detectors and alarms to detect a buildup of SNM.

Blow-back valves close on failure: all blow-back is shut off in the event of a power failure and when the timer is shut off.

17. Off-Gas Blower. This continuously operating blower circulates the air in the primary transfer system. It provides the primary air flow for the transfer system. Air from the transfer system is returned to the RAA atmosphere.

The controls consist of:

- A manual start-stop switch on the local control panel with lock-out capability;
- An airborne alpha radiation detector downstream from the HEPA filter alarm (administrative sequential shutdown prevents plugged transfer lines);
- A vibration detector to provide a maintenance alert and alarm the local panel;
- Automatic emergency shutdown with manual reset for restart.

C. Instrumentation and Control

Power to all equipment upstream of the pellet press feed hopper is controlled by a single hand switch with interlocks and controls as described for the individual items of equipment. The pellet press, ribbon conveyor, green pellet density inspection apparatus, and boat loader are controlled from a second switch except as described.

The process equipment (including the off-gas system) is controlled to stop under the following conditions:

- Seismic incident in excess of a preset value;
- Fire alarm in areas immediately adjacent to canyon LAA;
- Criticality alarm;
- Power interruption; or
- Loss of flow in the ventilation system or absence of a pressure differential across the containment.

Recovery from shutdown is by manual restart. Cause of the shutdown is indicated to the operator, and the indication may be cleared on restarting.

D. Operation

The operations of the pelleting system include automatic recovery from shutdowns (due to process fluctuations) to

Facilitate attainment of steady state conditions. Recovery from emergency or nonprocess stoppages is by manual start-up after inspection for damage.

The operator's constant attention is not required in this system. The controls are fail-safe and give an alarm only when the system does not recover from automatic shutdown.

E. Maintenance

Glove port access is provided to all items, including disconnects, mounts, clamps, flanges, unions, and inspection/cleanout ports.

IV. SINTERING AND STORAGE

The sintering and storage system handles the routing of sintering boats. Filled boats are loaded on the conveyor and stored along its length until a furnace calls for a boat. A shuttle car then picks up the boat and delivers it to that furnace. The boats enter the furnace through a double door arrangement on a preset cycle. A pusher mechanism pushes the end boat, which in turn advances the stack of boats through the furnace.

The furnace has a preheat section, a sintering section with three zones, and a cooling section. Each section is controlled to provide specific temperatures, heating rates, and time-at-temperature for a given push rate through the furnace. There is a high-speed push cycle for shorter sintering times.

As a boat exits the furnace, a shuttle car picks it up and takes it to the sintered-pellet density check apparatus where samples are taken for laboratory analysis and density verification. The boat is then either delivered to a conveyor for re-sintering or is committed to the process stream. The conveyor moves the boat along the selected path and serves as a boat storage unit.

At the end of the storage/transfer path, boats are held until laboratory analysis has been made of samples taken from

them earlier. If resintering is required, boats are sent back to the furnaces; otherwise, they are sent by belt conveyor to the boat unloader, where they are emptied into a scrap container or into the process stream.

Empty boats are returned to the point where they were first loaded with pellets. They are introduced to that conveyor, and as they move along to the boat loading operation, they are inspected for internal envelope and integrity. Upon reaching the boat loader, empty boats are loaded with pellets and a cycle has been completed.

A. General Description

Boundaries of the sintering and storage system extend from the point at which the boat is loaded to the boat unloader. Included are all boat conveyors, shuttle cars, furnaces, sintered-pellet density inspection apparatus, and accessories that identify, control, and route the boats on the conveyors. Figure A-8 is a block diagram of the process.

B. Subsystems and Components

1. Weight-Sensitive Platform. This platform holds the scrap can that services the boat unloader. Two conditions must be satisfied if the unloader is to cycle:

- The scrap can must be in position; and
- The scrap can must be capable of accepting a full boatload of pellets.

2. Boat Inspection Equipment. The presence of an empty boat at the boat inspection station initiates the inspection cycle. The station is activated when electrical power is supplied to the station's conveyors.

3. Gates. Gates are required in the process stream to provide for routings and for dispatching boats individually. They are positive, fail-close devices that do no damage to the boats. Gates fit all sections of the conveyor or are mounted apart from the conveyor. During normal operation, the gates

Fig. A-8. Pellet sintering.

will function if a boat is present and the downstream equipment is calling for a boat.

Gates are required at the following locations:

- Each end of the green-pellet boat conveyor;
- Each end of the green-pellet boat conveyor extension;
- Each end of the sintered-pellet boat conveyor;
- Each end of the under-fired pellet boat conveyor;
- Boat inspection equipment; and
- Boat identifiers.

The furnace entrance and exit and the boat loader also have gating systems. Unless otherwise specified, gates will release only one boat at a time.

4. Full Boat Sensor. A full boat sensor permits full boats to be routed through selected items of equipment and/or to various delivery points. Each unit of the sensor can provide appropriate routing decisions. The full boat sensor interfaces with the following pieces of equipment:

- The boat inspection equipment;
- The boat loader; and
- The end of the green-pellet boat conveyor.

5. Boat Unloader. The boat unloader elevates and dumps a boat either to the pellet feeder or to a clean scrap can. The path is selected before the boat is introduced to the cross-conveyor and is predetermined each time a boat is called for by the pellet feeder. Boats are not normally introduced to the cross-conveyor until laboratory results on their contents have been forwarded to the operator.

Acceptable pellets are moved along an inclined screening section (to remove dust and chips) to the pellet feeder. The dust and chips are routed to the same clean scrap can as the reject pellets. The boat unloader is controlled by the level controller in the pellet feeder. The receiving scrap can sits on a weight-sensitive platform.

After the dumping cycle, the unloader reverses and replaces the empty boat on the cross-conveyor. After the boat has been replaced and the lifting mechanism cleared, the cross-conveyor returns the boat to its normal routing location. The presence of a boat in the lifting mechanism and the selection and positioning of the diverter chute allow the boat unloader to start its cycle on demand from the level controller in the pellet feeder.

6. Sintered-Pellet Density Inspection Apparatus. Pellets from a boat on a shuttle car are loaded manually into the sintered-pellet density inspection apparatus. This inspection unit provides a signal that is coordinated with the operator's signal to allow the shuttle car to move onward. An operator selects the route by using the results of the density inspection.

7. Boat Identifiers. The boat identifiers sense identification marks encoded into the surface of each boat. During operation, the markings are translated into decimal form on a digital readout device. Under normal conditions, a boat will be released by the operator to a predetermined route.

8. Transfer Mechanism to and from the Belt Cross-Conveyor. These mechanisms transfer a boat from the sintered-pellet boat conveyor to the belt cross-conveyor and, in a reverse direction, back to the green-pellet boat conveyor. The transfer mechanism will not cycle unless the boat is accurately positioned. Cycling will then occur on signal demand from a control circuit or operator response, whichever is applicable.

9. Shuttle Cars. Shuttle car A picks up loaded or empty boats from the green-pellet boat conveyor and moves them to one of the four storage conveyors between the furnaces. It also takes a boat from the exit end of a demanding furnace, conveys it to the density check station, and waits there until released. Upon release, shuttle car A goes to the under-fired pellet boat conveyor or to the sintered-pellet boat conveyor. Shuttle car B picks up a boat from a preassigned storage conveyor and delivers it to a demanding furnace.

The unused space underneath each car track is blanked off from the RAA. Construction is such that the floor or bases will slope toward potential collection areas.

10. Cross-Conveyor. The cross-conveyor receives boats from the sintered-pellet boat conveyor, moves those boats designated for resinter to a discharge position in line with the green-pellet boat conveyor, and moves other boats to the boat unloader. Empty boats are transferred from the boat unloader to the discharge position in line with the green-pellet boat conveyor. When boats are in the discharge position, a boat transfer mechanism transfers them from the cross-conveyor to the green-pellet boat conveyor. This section of conveyor is in line with and connected directly to the corresponding conveyor in side B of the split process line. Crossover may be performed at this location.

Cycling is automatic once a boat is in position and the operator has selected the proper routing for that boat. An interlock installed with the boat unloader assures that the scrap/product diversion chute is in the proper position for non-resinter routings prior to conveyor start-up. Conveyor reversing is controlled by the boat unloader circuitry.

11. Boat Conveyors. Boat conveyors move pellet boats as necessary. They also satisfy equipment interfaces and permit safe, convenient maintenance.

12. Sintering Furnaces. Cooling water for the sintering furnaces is supplied through a heat exchanger and pump system. This cooling system is redundant to handle emergency shutdown conditions.

Chambers (enlarged furnace entrance/exit vestibules) have glove ports and a sectioned molybdenum rod suitable for probing boats in the furnace.

The following failure modes are provided for:

- Loss of power;
- Loss of coolant pump(s);
- Loss of forming gas;
- Loss of power to the furnace pusher or doors;

- Over-temperature in a furnace or exhaust duct;
- Lack of water in the bubbler;
- Failure of the furnace door to close;
- Presence of excess moisture in the gas feed lines or exhaust gas stream; and
- Cross-contamination between the furnace atmosphere or cooling tower water and the furnace cooling water.

13. Roughing Filter. A roughing filter on the exhaust gas system protects the HEPA filter and, when necessary, the off-gas cooler.

14. Off-Gas Cooler. The off-gas cooler is installed in the exhaust gas line to reduce the temperature of the forming gas before it is mixed with air in the ventilation ductwork. It further serves to protect the HEPA filter in this system from high temperatures.

15. HEPA Filters. HEPA filters in the exhaust gas system filter the forming gas exhaust before the off-gas is introduced into the ventilation system ductwork.

C. Instrumentation and Control

- The green-pellet boat conveyor and all connected or associated equipment along its length (excluding boat loader) are powered from a single hand switch;

- The sintered-pellet boat conveyor, cross-conveyor, boat unloader, and the connected or associated equipment for these units are powered from a single hand switch; the cross-conveyor is operated by an independent control;

- Shuttle cars are powered from single hand switches;

- The green-pellet conveyor extension and the under-fired pellet boat conveyor are powered from a single hand switch;

- Furnaces are powered from their own separate controls;

- The sintered-pellet density inspection apparatus is powered from its own hand switch.

Manual overrides are provided for cleanout purposes and to permit manual cycling and routing.

Controls also stop the process equipment under the following conditions:

- Seismic incident in excess of preset value;
- Power interruption; or
- Loss of flow in ventilating system or pressure differential across containment.

Recovery from shutdown is by manual restart. The cause of the shutdown is indicated to the operator and the indication may be cleared upon restarting.

D. Operation

The sintering and storage system operates by automatic cycling coupled with operator decisions at routing points. The constant attention of an operator is planned for the sintered-pellet density inspection apparatus: at routing points at the end of the sintered-pellet boat conveyor and after the density inspection. Manning becomes mandatory only after the buffer storage areas become full.

E. Maintenance

Conveyor sections are replaced remotely, and shuttle cars are serviced in place after the shuttle car has been moved by conveyor to a crane pickup point.

Furnaces are serviced in a separate area under a special scheme. The furnace ends are bagged off, and the furnace is lifted onto a cart. The crane hook is then disconnected. Furnace sections are replaced in reverse order. Boats from the furnace and the exit and entrance chambers are serviced in special chambers.

The grinder area crane and manipulator are used when the cross-conveyor and the boat unloader need servicing or replacement.

V. PELLET GRINDING, INSPECTION, AND STORAGE

The pellet grinding, inspection, and storage system takes the sintered MO_2 pellets and shapes them into right circular cylinders by a grinding operation that removes slight surface irregularities. The physical characteristics of the pellets are analyzed and inspected in detail before the pellets are sent to the next area where the fuel rods are fabricated. A storage area is provided.

Support systems handle the cooling water from the grinder and separate the MO_2 that was removed from the pellets for recycle back into the feed material. A system is provided for putting the pellets onto trays for orderly and controlled storage, and a versatile tray handling and storage system permits recovery of defective pellets from trays for recycle.

A. General Description

The pellet grinding, inspection, and storage system shapes the ceramic pellets to final size, inspects them, and places the acceptable pellets in a heated storage unit. The scrap material is recovered and recycled by special units designed for sludge recovery.

System boundaries extend from the pellet feeder through the pellet storage dryer. A duplicate line is in parallel with this system (side B of the split line), and there is a cross-over between the pellet storage dryers. Figure A-9 is a schematic and Figs. A-10 and A-11 are block diagrams of the process.

B. Subsystems and Components

1. Pellet Feeder, The pellet feeder receives pellets from the boat unloader in the upstream system, orients them end-to-end, and conveys them to the grinder entrance conveyor. A level-sensing element in the feeder controls the boat unloader, and downstream equipment controls feeder operation.

J	2	PELLET DRYING BLUVER	
I	4	FILTER, GRINDER	
D	6	PUMP	
C	1	SEPARATOR	
F	2	PELLET FEEDER	
E	2	PELLET GRINDER	

D	2	PELLET DIAMETER CONTROL UNIT	
C	1	WEIGHT-SENSITIVE PLATFORM	
B	2	SLUICE-SEPARATOR & DRYER SYSTEM	
A	2	PELLET GRINDER	
ITEM	QTY	DESCRIPTION	REMARKS

Fig. A-9. Flow diagram of pellet grinding, inspection, and storage.

Fig. A-10. Pellet grinding.

Fig. A-11. Pellet inspection and fuel rod loading.

Ventilation in the feeder permits separation and gathering of dust and chips which collect there. Runout and cleanout can be accomplished by the feeder.

2. Pellet Grinder Entrance Conveyor. The pellet grinder entrance conveyor moves the pellets from the pellet feeder to the grinder and has a mechanism to feed the pellets between the grinding wheels.

3. Pellet Grinder. The pellet grinder is a centerless grinder that uses a regulating wheel to control pellet rotation and a work-rest blade to support the pellets during grinding. Coolant water is furnished to the grinding area. The grinder wheels are shrouded and vented to contain the sludge (water and MO_2 dust) in the immediate vicinity of the wheels and to minimize the potential for build-up or retention of MO_2 .

A drain collection vessel with level elements collects the sludge from the grinder and controls the sump pump. The level elements function as follows:

- III level--shuts off water supply and the grinder feed system, including the pellet feeder and the grinder entrance conveyor;

- LO level--shuts off the grinder feed system; recovery is by time delay; if the condition still exists after the time delay, an alarm is activated.

An indicator senses when pellets are being ground and provides display and control input for the pellet grinder diameter control unit.

The grinder interfaces with the sludge separator and dryer system, pumps, entrance and exit conveyors, the pellet grinder diameter control unit, and the overflow sump. A filtered recirculation system separates the products of the regulating wheel dressing operation from the coolant supply system.

4. Pellet Grinder Exit Conveyor. The exit conveyor transfers the pellets from the grinder to the tray loader. It interfaces with the pellet grinder, the grinder diameter control unit, the pellet rinse and dry unit, the tray loader, a clean

scrap can located on a weight-sensitive platform, and the pellet inspection subsystem.

This conveyor has two channels and a diverter gate that is controlled by the grinder diameter control unit. If pellet diameters fall below preset limits, a signal moves the diverter gate, routing the unacceptable pellets through the vacuum dryer and into a clean scrap can. A sensor located on the exit conveyor determines when the can is full and indicates any downstream blockage. When a full condition is sensed, the pellet feeder and pellet grinder entrance conveyor are stopped and an alarm is activated if the blockage does not clear and the feed system does not recover after a preset time. The exit end adjoins the feeder of the tray loader.

5. Sludge Separator and Dryer System. This system concentrates the sludge to a relatively high solids-to-moisture ratio and then dries the sludge before transferring it to the CSRS in scrap cans. During the concentration operation the coolant is clarified for recycle back to the grinder/pellet rinse system. All parts of the coolant supply and recovery system are mounted over a grinder sump instrumented to stop the process feed and the water system if it is tripped. Actuation of this sensor indicates an uncontrolled release of coolant and a potential release of SNM from process containers.

This system is capable of SNM runout and cleanout. The unit is designed to prevent retention or holdup of MO_2 during cleaning operations.

6. Pellet Rinser and Dryer. The pellet rinser and dryer is mounted in conjunction with the pellet grinder exit conveyor and sprays coolant water on the pellets to remove dust. The rinse water and separated dust from the air dryer are collected and gravity-fed to the grinder sump.

7. Diameter Control Unit. The diameter control unit measures the diameter of pellets as they emerge from the grinding operation and displays the diametral readings. It signals a gate on the pellet grinder exit conveyor that routes to a scrap

container those pellets whose diameters fall outside the preset limits. This unit does not provide adjust or reject signals unless pellet flow in the grinder is sensed.

8. Weight-Sensitive Platform. The weight-sensitive platform prevents the process equipment from operating (1) when a scrap container is not in position or (2) when it detects a preset gross weight that indicates a full scrap can. The scrap can on this unit receives reject pellets from the diverter gate of the pellet grinder gauging system.

9. Final Pellet Inspection Subsystem. The pellet inspection subsystem inspects pellets for defects and separates defective pellets.

The pellet dimensional and density inspection equipment gauges final pellet dimensions and density, and records results of the gauging.

At the sample transfer station, samples are placed in a carrier and sent to the ASF for analysis.

10. Tray Loader. The tray loader receives pellets in single file from the pellet grinder exit conveyor and loads them onto a pellet tray. A vacuum-cleaning head to clean the tray grooves is part of this unit. Any dust is separated and delivered to a clean scrap can.

A belt conveyor provides the force necessary to advance the pellet row. Reliable tray indexing is done by a mechanized indexing device. The pellet tray conveyors deliver to and remove from this indexing system as necessary.

11. Pellet Trays. Pellet trays keep the pellets in an orderly array for operations between the tray loader and fuel rod loading. The pellet trays interface with the tray conveyors, the tray loader, the pellet tray weigh scale, the tray unloader, the pellet tray stacker and storage unit, equipment in the fuel rod loading operation, and the equipment in the pellet hydrogen analysis station. All trays are permanently identified and are fabricated to the same tare weight.

12. Tray Indexing and Transfer Device. This device moves pellet trays from a discharge position at the end of the pellet tray conveyor to the platform of the pellet tray weigh scale and from the scale platform to the pellet tray conveyor. It cycles on demand from the operator. A tray in any of the positions just described will be moved to the next position for a given cycle of this indexing and transfer device.

13. Pellet Tray Weigh Scale. This scale weighs the product on the pellet trays. At an operator-initiated signal, a tray indexing and transfer device moves trays onto and off the scale platform in a manner consistent with safe scale loading procedures. When the tray comes to rest, its load is weighed and the weight displayed to the operator.

14. Pellet Tray Stacker and Storage Unit. The storage unit holds pellets on trays in heated storage. The stacker handles trays in these possible sequences:

- (a) Receives trays from loaded tray conveyor;
- (b) Delivers trays to shelf storage to await a specified time lapse and a release based on samples sent to the ASF or to storage;
- (c) Delivers trays to the pellet hydrogen analysis station where a sample is taken and analyzed for hydrogen; this operation is done by operator demand for selected trays, and sampled, acceptable trays are returned to their original storage location or delivered to specified routing;
- (d) Delivers reject trays to the tray unloader for scrapping;
- (e) Receives empty trays from the tray unloader;
- (f) Receives trays from the rod loading operation via tray conveyor;
- (g) Delivers trays to and receives trays from the other side of the split line;
- (h) Delivers only inspected and released or empty trays to the rod loading line on demand via tray conveyor.

The storage unit consists of a shielded enclosure that is part of the containment barrier, and internal shelves, mechanisms, and conveyor sections required to perform the functions described. This unit permits entrance and operation of the rectilinear manipulator inside the storage unit. The stacker handles the trays to and from their prescribed locations. Stackers from either side of the line may work in either storage unit without interference or danger of collision.

15. Pellet Drying Heater and Blower. This unit supplies heated air to dry pellets stored on pellet trays in the pellet tray storage unit. It is thermostatically controlled to prevent the pellets from overheating and is designed to maintain a specific air flow and temperature. The unit may be idled during periods when no pellets are being introduced and a low moisture level is sensed in the exhaust stream.

16. Tray Unloader. The tray unloader is common to both sides of the split line. It receives reject trays from the pellet tray storage unit of either line and unloads them into a clean scrap container sitting on a weight-sensitive platform. Gating or dumping controls supplied with this unit interlock with the weight-sensitive platform controls to prevent overloading of the clean scrap can. The presence of a tray and of the clean scrap can in position cause this unit to cycle, dumping the pellets and routing the tray into the process stream.

17. Weight-Sensitive Platform for Reject Pellet Trays. The weight-sensitive platform holds the scrap can that services the tray unloader and is instrumented as follows:

- A scrap can must be in position or the tray unloader will not cycle;

- A scrap can must be capable of accepting a full load of pellets from a tray without exceeding its capacity or the tray unloader will not cycle.

This unit is common to sides A and B.

C. Instrumentation and Control

The grinder portion of the pellet grinding, inspection, and storage system is controlled to achieve a steady state condition by the use of fail-safe control limits. Constant attention by the operator is not necessary.

The process equipment is controlled to stop under the following conditions:

- Seismic incident in excess of a preset value;
- Fire alarm in areas immediately adjacent to canyon LAA;
- Criticality alarm;
- Power interruption; or
- Loss of flow in the ventilation system or pressure differential across containment.

Recovery from shutdown is by manual restart. The cause of the shutdown is indicated to the operator, and the indication may be cleared on restarting.

D. Operation

The units that follow the inspection portion of the system, downstream of the pellet tray scales, are automated and have fail-safe controls. Constant attention from the operator is not necessary.

The grinder and tray loader are activated by a single hand switch. The tray storage units and the tray transfer systems are activated by a separate hand switch, and the inspection equipment by another. The sludge recovery system is controlled from its own hand switch.

E. Maintenance

Maintenance is performed through glove ports from the LAA. Replacements are made by means of a grinder canyon crane and rectilinear manipulator.

I. Special Precautions

The pellet grinding, inspection, and storage area is physically separated from other canyon process areas. It is ventilated separately so that the moist air expected will not intermingle with the air in or supplied to the other process areas.

Specific items of equipment require local ventilation to control NO_2 dust and moist air. Separators and distribution to an off-gas system are provided as required. Such systems can be readily cleaned and are designed to minimize any retention of NO_2 . They can be scanned with portable instruments to verify normal holdup.

VI. ROD LOADING AND REPAIR

The rod loading and repair system inserts the released fuel pellets into tubing, seals the fuel rod, and sends it to the fuel rod inspection operation. These operations are performed in sequence in a glovebox. Support systems for ventilation, sealing, and fire control are described in this section.

The tubing and rods are carried on chain conveyors and in channels that serve to group, support, and protect the product. Pellets are introduced on trays and the fuel rod hardware is received in containers.

Facilities are also provided for manual processing of fuel rods that are to be repaired or salvaged.

A. General Description

The rod loading and repair system encapsulates the fuel pellets in the tubing with a pressurized atmosphere. The pellet length is measured, the plenum is gauged, the tube ends are cleaned, a spring is inserted, a top end plug is pressed and girth-welded, and finally the tube is pressurized and seal-welded. The tube is scanned for any contamination and the fuel rods are accumulated in a channel for transfer to the next operation.

System boundaries extend from the ends of the pellet tray conveyors to, but not including, the fuel rod leak test chambers. A duplicate line is fed from the common pellet tray storage system and runs to a duplicate set of fuel rod leak test chambers. Figure A-11 contains a block diagram of this system.

B. Subsystems and Components

1. Rod Loading/Plugging Glovebox. The rod loading/plugging glovebox encloses the pellet handling mechanism of the rod loading station, the plenum gauging station, the tube end cleaning station, the spring insertion station, the plug pressing station, and the rod end alpha-scanning station. The access face(s) of this box are provided with windows, glove ports, and shielding as required for maintenance and operating access to the equipment within.

2. Fuel Rod Pellet Loading Station. The loading station receives trays of pellets from the pellet tray storage unit via the pellet tray conveyor and positions and indexes them into alignment with its tube loading positions. When the tubes are loaded, all of the rods at this station are transferred to the next operation. After a tray is emptied, it is returned to the pellet tray storage unit via the pellet tray conveyor. When the rods have cleared this station, the operator is signaled to place more tubing into the station.

3. Plenum Gauging Station. As the fuel rods are dispensed from the fuel rod loading station, they are accumulated in a small surge area where the plenums are gauged to assure the proper drawing dimensions. The rods are held securely while a gauging head enters the tube and registers against the end of the pellet column and end of the tube. An unacceptable condition causes an alarm that must be cleared by an operator; he must either correct the equipment malfunction or adjust the plenum by insertion or removal of a pellet. Pellets removed from or added to the rods go to or come from a pellet tray at the loading station.

Repaired rods have their temporary end seals manually removed at this station before being gauged. Subsequent operations are common to both repaired and production rods.

4. Fuel Rod End Decontamination Station. As the fuel rods are conveyed into the decontamination station, they are held in place while a rotating cleaning mechanism removes surface contamination that may have been deposited during previous operations. Two stations for cleaning are provided. An alpha detector in the second station scans the end of the fuel rod to verify cleanliness before releasing the rod. If alpha contamination is present, an alarm is sounded and the unit must be manually recycled. Soiled cleaning media are put into a waste container for transfer to NWT after removal from the glovebox. After successful cleaning, the fuel rod is released from the clamp.

5. Top Plug Pressing Station. When the fuel rod with spring arrives at the top plug pressing station, it is firmly clamped and an end plug is pressed into the end of the fuel rod. The pressing mechanism retracts, the rod clamps relax, and the rod is moved to the next station.

6. Rod Welding Box. This glovebox is an extension of the rod loading/plugging glovebox. Its front face has openings for attachment of the welding equipment. Ventilation in the box extends into the rod loading/plugging glovebox.

7. Fuel Rod Top Plug Welding Station. As the plugged fuel rod enters this station, it is chucked and girth-welded. On completion of the weld, the rod is released.

8. Fuel Rod Pressurization/Welding Station. The plugged and welded rod advances into the pressurization weld chamber and the rod seal is actuated, sealing the rod in the chamber. Gas is then introduced into the rod to a preset pressure and allowed to stabilize. When the pressure has stabilized, the hole is seal-welded and allowed to cool. If a preliminary leak check shows that the rod is not sealed, an alarm sounds and the rod is manually set aside.

9. Fuel Rod Assembly Full Length Alpha Scanning Equipment.

As rods approach the alpha scanner, they are deposited by the conveyor on an accumulation ramp and then dispensed into the full-length alpha-scanning unit. As rolls rotate the rod in a fixed position, a scanning head moves along its length sensing for alpha contamination. If contaminated, the rod is manually removed; if not, it is transported to the helium leak test chamber, part of a subsequent system.

10. Fuel Rod Conveying System. The fuel rod conveying system transports fuel rods through the various process steps. The conveyors are specially designed to support and protect the fuel rods during handling.

The fuel rod assembly conveyor picks up rods at the plenum gauging station, carries them through the decontamination stations, the spring insertion station, the plug pressing station, and past an end alpha scan before depositing them on a gravity-feed ramp that carries them through a fire door opening. Interlocks prevent conveyor operation if the rod has not been cleared or if alpha contamination is detected.

The fuel rod welding conveyor picks up rods at a point near the fire door and advances them through the fuel rod top plug welding station and the pressurization/welding station, then deposits them on a gravity feed ramp that feeds the full-length alpha-scanning station. Interlocks prevent conveyor operation until the fuel rods are in a position for unobstructed transfer.

The leak test transfer conveyor holds a channel in position while finished fuel rods move from the full-length alpha scan into the channels. A counting device signals the operator when a fixed number of rods have been loaded into each channel. The operator then activates the conveyor which transfers the loaded channel to the next step in the production sequence.

11. Rod Repair Glovebox. The rod repair glovebox houses the equipment required to depressurize and prepare the end of the fuel rod for subsequent repair or salvage operations. Windows, gloves, ventilation, and utility services are provided

as required. The box permits the rods to be alpha-scanned before they are transferred to the next operation. Scrap collection and removal are accomplished through a port in this glovebox.

12. Fuel Rod Repair Mechanism. The fuel rod repair mechanism holds the rod while it is being drilled and vented. Subsequently, the end plug weld is cut, the plug and spring with drawn, and the tube end deburred and chamfered.

13. Fuel Rod Salvage Glovebox. The fuel rod salvage glovebox encloses the fuel rods during salvage operations in which fuel pellets are recovered and metal components are sent for waste treatment. The rods are introduced into the box through an air lock that prevents release of contaminants from the box. This box encloses the fuel rod salvage equipment and is provided with shielding, ventilation, and utility services as required. Scrap and fuel material are collected and removed through ports.

14. Fuel Rod/Pellet Salvage Station. The fuel rod/pellet salvage station consists of pellet removal and tube cut-up equipment which removes the fuel pellets from the tubing and cuts and/or compacts the tubing for convenient transfer. A scale is required for materials accounting purposes to weigh the amount of fuel being transferred.

C. Instrumentation and Control

The rod loading/welding portion of the rod loading and repair system requires constant surveillance by an operator to monitor operations and handle unusual situations. The rod repair and salvage portion is manually controlled and operated. System conveyors are controlled to stop (and not initiate a new process sequence) in the event of:

- A seismic incident in excess of a preset value;
- A fire alarm in this area or along an alternate escape route;
- A criticality alarm;

- A power interruption; or
- A loss of flow in the ventilation system, loss of pressure differential across the confinement barrier, or malfunction of any of the glovebox seals.

Recovery from shutdown is by manual restart. Cause of the shutdown is indicated to the operator, and the indication is cleared on restarting. Local controls with interlocks are provided for all drive mechanisms and valves in the system.

D. Operation

The fuel rod loading/welding operations are powered from a single hand switch. The repair and salvage gloveboxes are operated from a single hand switch for each. The area adjacent to the operating faces of the boxes is shielded to meet the radiation-level requirements of the NAA; this area is considered a potential contamination risk because of the glove ports in the box.

E. Maintenance

All equipment and boxes in this area can be dismantled for removal and replacement by passing them through the manufacturing building. In-box equipment is removed by a bag-out technique.

F. Special Precautions

A pressure differential is maintained on the glovebox; the system must not draw the humid air of the grinder canyon into the gloveboxes even though they are connected by the pellet tray conveyors. The air in the loading/plugging glovebox flows toward the loading station, which is the dustiest part of the operation. The air nearby flows from the normally occupied area to the gloveboxes.

The filter system consists of standard canisters mounted in the gloveboxes, with the central exhaust system providing the pressure differential; a pressure differential or flow

element controls an air-operated valve to maintain the desired flow or pressure at a preset value.

The gloveboxes are monitored for temperature and smoke with one element of the monitoring system that is located near the filters. Detection of smoke or a rise in temperature activates the Halon extinguishing system, stops all the process equipment, and closes the fire door between the rod loading glovebox and the rod welding box.

VII. FUEL ROD INSPECTION AND STORAGE

The fuel rod inspection and storage system routes rod hardware from the receiving and storage areas to the shipping area where fuel rods are prepared for transfer to final assembly. System boundaries extend from receipt of tubes and hardware to final fuel rod inspection, except for rod loading (see Appendix A-VI).

A. General Description

Each incoming shipment of fuel rod tubing and hardware is received in cardboard shipping boxes which are visually inspected for superficial damage. The hardware is then stored until time for cleaning. Bottom end plugs are pressed into empty fuel tubes and welded, and the tubes are transported to the x-ray inspection station for bottom plug weld inspection.

The empty tubes with bottom ends plugged are then sent to rod loading (Appendix A-VI) for final rod assembly, after which they are stored in air locks pending inspection.

Loaded fuel rod inspection consists of (1) a helium leak test, (2) gamma scan, (3) top plug weld x-ray inspection, and (4) physical inspection and weighing. Reject rods are sent to rod repair and salvage for repair or recovery of hardware and MO_2 pellets. Accepted rods are transferred to the rod storage unit to await final disposition. Figure A-12 is a block diagram of this system.

Fig. A-12. Fuel rod inspection, storage, and shipping.

B. Subsystems and Components

1. Hardware Preparation. The plug marking machine and feeder stamps end plugs with an identification number before cleaning. A letter on the plug end surface can be used to designate enrichment. This unit is used intermittently on production control demand.

At the hardware cleaning station, tubes, end plugs, and springs are cleaned to remove any surface contamination, and then stored until released for fabrication. Cleaning is also done as required by production control.

After cleaning, empty fuel tubes and plugs are cycled through the bottom plug press and transferred to the bottom plug welding station, where a tungsten-inert gas welding process joins the bottom end plug to the empty fuel tube.

The tube conveyor transports tubes through the cleaning, plugging, and welding processes. At the end of the conveyor, tubes are loaded onto the empty tube cart where they are visually inspected and transferred to the x-ray inspection equipment for bottom weld radiographic inspection.

2. Inspection Equipment. The helium leak test chamber checks batches of encapsulated fuel rods (rods in channels). It contains a helium leak detector, standard leak source, control panel, and the vacuum system. After the system attains a specified vacuum, a mass spectrometer (helium leak detector) determines the system's leak rate. Each fuel rod assembly line has a leak test chamber.

The gamma-scanner station scans fuel rods to determine enrichment content by gamma emission and consists of a control panel, gamma-scanning head with shielding and source, and support stands.

The x-ray inspection station tests batch quantities of empty fuel tube bottom welds and loaded fuel rod top welds. This station consists of an x-ray unit with control panel, positioning fixture, correction blocks, penetrometers, a film identification system, and film. X-ray shielding is required in

the exposure chamber, which must also have adequate shielding to prevent beta, gamma, and neutron exposure to operating personnel. Interlocks prevent operation if access ports, doors, or removable safety shields are not in place.

The film developing station processes the x-ray film. Discharge water is routed to the cold waste system through in-line filtering equipment.

After being scanned, the rod is moved to the final inspection unit, which is equipped with a rod weigh scale and surface plate for final QC tests. Rod weight and identification are input to the process information system.

Loaded rods are moved about on the shielded transfer cart, which has space for about 50 fuel rods. This cart travels between the helium leak test area and the entrance to x-ray inspection. Rods are loaded and unloaded through shielded doors located at both ends of this route. The tray loader, which transfers loaded rods into the x-ray machine, is required because of radiation exposure limits to operating personnel; it is not required for loading empty tubing.

3. Fuel Rod Storage. The rod storage unit consists of the storage device and a shielded, compartmentalized carrier to hold loaded rods. In operation, rods are inserted into the shielded carrier at the final inspection station, and then are traversed until aligned with a preselected storage shelf. Fuel rod storage location is recorded. Filtered ventilation air removes autogenous heat.

C. Instrumentation and Control

All pieces of process equipment are powered through individual hand switches with built-in interlocks and controls. Process equipment is controlled to stop under the following conditions:

- Seismic incident in excess of a preset value;
- Fire alarm in the fuel rod inspection building;
- A criticality alarm in any part of the plant; or

- Power interruption, except for those items that may require emergency power.

Recovery from shutdown is by manual restart. Cause of the shutdown is indicated to the operator, and the indication can be cleared upon restarting.

D. Operation

Recovery from emergency or nonprocess stoppages is accomplished manually after inspection for damage. Immediate and constant attention by an operator is not required in these systems. Fail-safe controls provide an alarm to an operator only when the system does not recover from automatic shutdown.

E. Maintenance

Maintenance and repair are performed in place by conventional shop procedures under normal cold conditions. If fuel rods are present, the rods are removed to a temporary storage area and adequately protected and shielded. Replacement operations on failed equipment are made with conventional auxiliary equipment and tools.

F. Special Precautions

No special ventilation considerations exist in these areas of the plant, except at the station for cleaning end plugs and springs and at the storage unit.

Shielding of x-rays is required in the x-ray inspection equipment. In addition, the x-ray unit and the storage unit must be adequately contained by appropriate shielding to prevent beta, gamma, and neutron exposure to personnel.

All efforts must be made to avoid contact between the fuel rod and contaminants.

G. Periodic Tests and Inspections

The following tests are performed on a regularly scheduled basis:

- (1) Fuel rod welder samples;
- (2) Leak test, verify calibration;
- (3) Rod weigh scales, verify calibration;
- (4) Gamma scan unit, verify calibration; and
- (5) X-ray unit, verify parameters and source strength.

APPENDIX B

PLANT INFORMATION SYSTEM DETAILS

1. PROCESS INFORMATION SYSTEM

The file structure of the process information system is described in this section. Section II-D in the main body of the report discusses the relationship of the process information system to the rest of the plant.

A. Receipt and Storage (1A, B; 2A, B)*

Material shipments are forecast months in advance and the data are incorporated into the plant plans and plant schedules information files. Shipping container and material composition data from AEC Form 741 are put into the material receiving file, which is in turn transferable to the material availability file and accessible to the safeguards coordination system and the Safeguards Officer. Advance samples of the material are received and analyzed by the ASF and the results input to the data base under the ASF samples file. Upon receipt of shipment, files are made current with actual dates. Seals are read, weights are measured and recorded, and health and safety decontamination reports are logged into the system. When shipments are placed in storage, additions are made to the perpetual inventory and control monitor system. Process monitors continuously record radiation levels, task completions, functions with time tags and identification of personnel associated with the operation, and the data are input automatically or manually into the appropriate receipt and storage process monitor file. Files affected are:

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*Numbers in parentheses are unit process designations. See Fig. II-1.

- Material receiving;
- Material availability;
- ASF samples;
- Decontamination reports;
- Inventory monitor;
- Area radiation level;
- Personnel exposure;
- Optical scan label;
- Operator identification;
- Materials release;
- Hopper weights (full and empty);
- Pneumatic pressure differential monitor; and
- Process operating history.

Approximate storage required: 2 million characters.

B. Bulk MO_2 Operations: PuO_2 and UO_2 Unloading (3A, B)

Canisters of plutonium that are placed in the unloading position generate an occupied signal that is recorded with verification of canister identification number. Weight measurements are made and input to the system and a response is generated confirming that values are within sensor measurement accuracy. Discrepancies are reported in shipper-receiver difference reports required by NRC. Decontamination survey, ASF analysis, and QC release data are generated and recorded. Canister empty weight is compared with the full weight and contents data to verify that the canister is actually empty. It is then sent back to MMT and assayed, and a record made of the event. Event records with time tags are compared with nominal values for process efficiency analysis and for any indication of possible malicious action. Corresponding steps are taken for UO_2 unloading. Files affected are:

- Process monitors;
- Operator identification;
- Canister weight;
- Material release;

- Blend record;
- Feed hopper weight;
- Weigh hopper weight;
- ASF samples;
- Vessel holdup;
- Process monitor;
- Operator identification;
- Blend calculations;
- Material release; and
- Process history.

Approximate storage required: 1.5 million characters.

E. Bulk MO_2 Operations: Milling, Sampling, and Storage (5)

Empty and full storage silo weight data are recorded, and ASF samples after size milling are analyzed and the data recorded. Silo hide-out detector data are read out and recorded, and data on off-gas moisture content are collected. Data files used are:

- Blend record;
- Hide-out detector;
- Off-gas moisture monitor;
- Process monitor;
- Operator identification;
- ASF samples;
- Material release; and
- Process history.

Approximate storage required: 800,000 characters.

F. Pelletizing (7, 8, 9, 10, 11, 12)

Samples of granules are analyzed in-line for bulk density. As green pellets are produced, a density check is made and rejected pellets are sent to a clean scrap bucket on a weight-sensitive platform. Pellet boat full indicator data are recorded with the boat identification number providing a total pellet count. Pellet samples sent to the ASF are analyzed and

- Blend record;
- Feed hopper weight;
- Weigh hopper weight;
- ASF samples;
- Vessel holdup;
- Process monitor;
- Operator identification;
- Blend calculations;
- Material release; and
- Process history.

Approximate storage required: 1.5 million characters.

E. Bulk MO_2 Operations: Milling, Sampling, and Storage (5)

Empty and full storage silo weight data are recorded, and ASF samples after size milling are analyzed and the data recorded. Silo hide-out detector data are read out and recorded, and data on off-gas moisture content are collected. Data files used are:

- Blend record;
- Hide-out detector;
- Off-gas moisture monitor;
- Process monitor;
- Operator identification;
- ASF samples;
- Material release; and
- Process history.

Approximate storage required: 800,000 characters.

F. Pelletting (7, 8, 9, 10, 11, 12)

Samples of granules are analyzed in-line for bulk density. As green pellets are produced, a density check is made and rejected pellets are sent to a clean scrap bucket on a weight-sensitive platform. Pellet boat full indicator data are recorded with the boat identification number providing a total pellet count. Pellet samples sent to the ASF are analyzed and

the data recorded. Green-pellet storage is monitored remotely by boat identification number. Sintering furnace operating parameters are correlated with boat identification numbers. Pellets are again sampled and sent to the ASF; ASF results determine any need for resintering. Measurements of pellet length, diameter, weight, density, and hydrogen analysis are recorded, and a count is taken of pellets that are within specifications. Each full tray is weighed and has an identification number for reference during storage. Boat/tray routing information is recorded and displayed. The pellet processing record consists of work order number, boat identification, furnace number, sample information, furnace cycle data, and routing. The pellet inspection record contains work order number, tray or scrap container identification, location, weight, sample information, inspection data, enrichment, QC acceptance, and routing. It provides basic data for subsequent reports on pellet availability, location, routing, process yield, job cost, inventory update, and product traceability. Storage files used are:

- Granule records;
- Green-pellet density;
- Green-pellet scrap generation;
- Green-pellet samples;
- Boat identification numbers;
- Routing;
- Green-pellet boat storage;
- Green-pellet storage;
- Sintering furnace record;
- Sintered-pellet samples;
- Sintered-pellet scrap generation;
- Sintered-pellet measurements;
- Sintered-pellet count;
- Sintered-pellet tray storage;
- Pellet processing record;
- Pellet inspection record;
- Residual material in process;

- Process monitor;
- Operator identification;
- QC release; and
- Process history.

Approximate storage required: 4 million characters.

G. Fuel Rod Operations: Fuel Rod Loading and Repair
(13, 14, 17)

Empty tubes are weighed, and visual and x-ray inspection data on the first end weld of each tube are recorded with the weight and tube identification number. Installed pellet stack length is measured and these data are incorporated into the rod fabrication and loading record containing work order number, acceptance lot number, rod identification number, weld data, and spring, plug, and tube lot numbers. Completed rod weight and rod scan data are input to the rod inspection record containing work order number, rod identification, weight, inspection, QC acceptance, and routing information. Rejected rod data are collected in the rod repair and salvage record incorporating work order number, rod identification number, scrap container identification number, routing, and details of repair. Applicable files are:

- Tube cleaning inspection;
- Rod identification;
- Rod weight;
- Rod acceptance lot numbers;
- Rod component lot numbers;
- Rod scan;
- Rod inspection;
- Rod repair and salvage;
- Scrap generation;
- Process monitor;
- Operator identification; and
- Process history.

Approximate storage required: 1 million characters.

H. Fuel Rod Storage and Shipping (15, 16)

Rod storage in channel carriers is identified by rod and channel identification number. Each shipping box holds four channels, each container holds two shipping boxes, and each truck carries four containers. A rod storage and shipping record is made up of rod identification, customer identification, shipping notice number, carrier, alpha survey, weights, assay, AEC Form 741 number, and identification numbers for channels, shipping boxes, containers, and truck. Files affected are:

- Channel identification;
- Shipping box;
- Container;
- Rod storage;
- Health and safety radiological survey;
- Shipping notice;
- Shipping schedule;
- Process monitor;
- Operator identification; and
- Process history.

Approximate storage required: 1 million characters.

I. Clean Scrap Recovery System (18, 25)

This function includes pilot operations. A measurement of green density is taken manually on material from the pilot press and the data are recorded. Blend records are kept and related to pellet measurements taken before and after sintering. QC release is generated from data falling within established specifications.

Clean scrap storage monitors check the position of each can on a sampled basis, and a graphical display of filled storage locations is generated and recorded. Scrap containers are weighed when full and empty. The CSRS furnace operating parameter monitors provide data for the CSRS furnace record consisting of container number, weight, and cycle data as needed. Recycled MO_2 storage weight is recorded for three vessels of 720-kg capacity, and samples are sent to the ASF for analysis of

plutonium, plutonium isotopes, uranium, and moisture. QC release is obtained for material within specifications. Sample/scrap records contain work order number, material identification number, weight, and analytical data as needed. Information files applicable are:

- Pilot press;
- Pilot pellets;
- QC release, pilot pellets;
- Pilot blend record;
- CSRS storage monitor;
- Scrap container weight;
- CSRS furnace record;
- Recycle MO_2 storage vessel weight;
- Recycle MO_2 samples;
- QC release, MO_2 ;
- Sample/scrap record;
- Process monitor;
- Vessel holdup;
- Operator identification;
- Blend calculations;
- Process history, piloting; and
- Process history, CSRS.

Approximate storage required: 1.8 million characters.

J. Analytical Services Facility (19)

Samples received are logged into the ASF internal material routing system, and criticality computations are made prior to material movement. Results of sample analyses are placed into respective process area files for access. Measurements are made on ASF-generated waste, and liquid waste pretreatment samples are taken to determine plutonium content. Pertinent files are:

- ASF routing;
- Criticality computation results;
- Sample analysis (individual files for each process);
- Scrap/waste generation;
- Standards available;

- Measuring instruments;
- Operator identification;
- Analysis requirements schedule; and
- Facility functional history.

Approximate storage required: 1.5 million characters.

K. Miscellaneous Waste Treatment (20)

Grinder sludge is sampled after drying, analyzed for impurities and moisture, and the data are logged into the system. After blending, treated NO_2 scrap is sampled for plutonium, plutonium isotopes, and uranium, with corresponding data acquisition. Plutonium checks on organic waste, on filtrates from shred, wash, and precipitation, and on the emergency drain-sludge separator are made through sample analysis. Neutron coincidence, high-resolution gamma scan, and seal checks are accomplished during NWT drumming, inventory verification, and drum disposal. Point-of-origin data are included with all scrap and waste. Files required are:

- NO_2 scrap;
- Plutonium check;
- Drum identification;
- Drum storage monitor;
- Drum disposal;
- Process monitor;
- Operator identification; and
- Process history.

Approximate storage required: 1 million characters.

L. Liquid Waste Treatment

Sampling for plutonium is conducted in the evaporator feed tank, liquid waste feed tank, and decontamination cell liquid hold tank. Radiation monitoring data in the evaporator feed tank and head tank and possible alarm data are input to the information store. Applicable files are:

- Plutonium check;
- Radiation monitor/alarm;
- Process monitor; and
- Process history.

Approximate storage required: 400,000 characters.

M. Liquid Effluent Treatment

Isolation, quarantine, treatment feed, treatment product, and mop water tanks are sampled for radioactive materials. In-line radioactivity monitors are read out for each absorption column in the deactivation treatment system and for the treatment feed tank discharge, quarantine tank discharge, isolation tank, and plant sanitary system. Control functions and alarms are activated where applicable, and the data transferred to storage. Files required are:

- Tank sample analysis;
- In-line monitor/alarm;
- Process monitor; and
- Process history.

Approximate storage required: 300,000 characters.

N. Health and Safety

Direct process support provided by Health and Safety consists of radiological surveys of containers, equipment, and areas in the process line, as well as in maintenance. Records of each survey, any decontamination action taken, and subsequent measurements are placed into the information store. Personnel radiation exposure history data are logged, and computer programs are run for projecting future exposure by work station. Files used are:

- Radiological survey;
- Decontamination action and results;
- Personnel exposure history; and
- Personnel exposure projections.

Approximate storage required: 300,000 characters.

0. Quality Control

Verification of adherence to product specifications is provided through sampling and direct measurement in the process line. Data are stored and analyzed, and resulting QC releases are generated and recorded on-line. Instrument calibration data are maintained with updated projections made available through data base access. End-to-end system verification and diagnostic checks are recorded for known stimuli and measured output response. Applicable files are:

- Incoming material acceptability;
- Process specifications;
- QC inspection;
- QC acceptance and release;
- Product traceability;
- Plant/process diagnostics;
- Instrument calibration history; and
- Instrument calibration projections.

Approximate storage required: 400,000 characters.

II. SAFEGUARDS INFORMATION SYSTEM

Recent and historical data files are continually updated and those related to SNM control are accessed for reference. They are available for transfer to the safeguards information system for duplication and subsequent searches, sorts, processing, and inclusion of relevant real-time data. An initial list of applicable files is:

- Plant plans;
- Plant schedules;
- Plant operating reports;
- Material availability;
- Material routing, with selective real-time monitoring;
- Sensor characteristics and status;
- Plant diagnostics and confirmatory test results;

- Item operation control event records, with selective real-time monitoring;
- LAA and RAA occupancy, with selected real-time monitoring;
- Alarm status;
- False-alarm history;
- Guard force deployment;
- Plant simulation models, parameters, and results;
- Effluent release;
- Safeguards coordination system historical file;
- All files of the MMAS; and
- Files of second and third generation processed summary information.

Approximate storage required: 1.5 million characters.

APPENDIX C

TECHNIQUES FOR NUCLEAR NONDESTRUCTIVE ANALYSIS

I. INTRODUCTION

NDA measurements are vital to the implementation of dynamic materials control, frequently being the only available means for timely measurement of in-process material and holdup. They provide direct measurements of SNM in liquid and solid scrap and wastes that are difficult if not impossible to sample reliably for CA. NDA is also used for verification in item control, rapid analysis of small samples, and for the safeguards accounting and quality assurance of product fuel rods. NDA instrumentation is included in the plant measurement system wherever SNM is handled: receiving and storage, main process line, MWT, LWT, and the ASF. NDA instrumentation has been placed only where needed for timely safeguards and to complement CA methods.

Many of the NDA instruments specified for this MO₂ facility design are used routinely in plutonium facilities and would require, at most, minor modifications for MO₂ applications. These instruments are usually amply documented and commercially available. The remaining instrumentation systems are sufficiently advanced that meaningful projections of performance can be made, and no difficulties are foreseen in developing engineered units in time to meet the earliest possible construction schedules. No attempt has been made here to provide a complete bibliography of the reports on NDA instrumentation; however, a convenient source of general information on NDA technology and its applications is the training manuals that are used for the LASL-ERDA NDA Training Program.^{37,81}

This appendix describes some of the NDA instruments and methods selected for the MO₂ facility. A description of

weighing measurements is included because of their vital role in the fuel facility, and a brief section on calorimetry, based primarily on publications by the Mound Laboratory, is included because of its potential value in the standards and measurements control program.

II. NEUTRON COINCIDENCE COUNTERS

Coincidence counting of prompt neutrons from the spontaneous fission of ^{240}Pu (and the other even-numbered plutonium isotopes) for quantitative assay of plutonium has been useful for a wide range of small samples, fabricated fuels, and plutonium-bearing scrap and waste. Application of the neutron coincidence method to measurement of scrap and waste is more complicated because of the influence of unknown matrix materials and the wide range of plutonium loading encountered, i.e., from slight contamination to hundreds of grams of plutonium per liter for recoverable scrap.

Coincidence counting of ^{240}Pu and ^{242}Pu spontaneous fission neutrons is accomplished with assemblies of ^3He (or BF_3) counters embedded in polyethylene moderators.³⁸⁻⁴² The largest devices of this type are used at the LASL plutonium facility to analyze 55-gal drums of waste.³⁴ In compounds or mixtures containing plutonium, neutrons also originate from (α, n) reactions on low-Z materials, with yields that are highly dependent on composition. Table C-1 lists estimates of the isotopic composition and neutron yields from spontaneous fission and (α, n) reactions of PuO_2 recycle fuels.⁴³ If the chemical composition and plutonium isotopic abundances are known and controlled, as in batch processing, a gross singles neutron count may suffice for QC and safeguards materials accounting. However, in many practical situations, notably scrap and waste measurements, these assumptions may not be valid because of the variability in (α, n) neutron yield. High (α, n) rates can also complicate the coincidence method through accidental (random) coincidences

TABLE C-1

EMISSION RATE FOR ONE GRAM OF PLUTONIUM

Isotope	(wt%)	Spontaneous Fission		Spontaneous Fission Prompt Neutrons		(α,n) Neutrons from PuO ₂	
		(sf/s)	(%)	(n/s)	(%)	(n/s)	(%)
<u>LNR Fuel with 35,000 MWd/TU Burnup</u>							
²³⁸ Pu	1.9	20.9	14.8	47.2	15.3	266.0	76.1
²³⁹ Pu	63.0	0	0	0	0	28.4	8.1
²⁴⁰ Pu	19.0	89.5	63.6	194.2	63.2	32.3	9.2
²⁴¹ Pu	12.0	0	0	0	0	1.2	0.3
²⁴² Pu	3.8	30.4	21.6	65.7	21.4	0.4	0.1
²⁴¹ Am	0.6	0	0	0	0	21.4	6.1
Total		140.8	100.0	307.1	100.0	349.7	100.0
<u>Average Composition (Including Recycle in 1990)</u>							
²³⁸ Pu	1.2	13.2	7.2	30.0	7.5	168.0	63.6
²³⁹ Pu	53.0	0	0	0	0	23.9	9.0
²⁴⁰ Pu	25.8	121.5	66.5	264.0	66.4	43.9	16.6
²⁴¹ Pu	13.5	0	0	0	0	1.4	0.5
²⁴² Pu	6.0	48.0	26.2	103.7	26.1	0.6	0.2
²⁴¹ Am	0.7	0	0	0	0	26.3	10.0
Total		182.7	100.0	397.7	100.0	264.1	100.0

and by the fissions induced in the fissile components of the material, i.e., the multiplication effect.

If the coincidence counting method is to be used for analysis of large amounts of PuO_2 or scrap containing light elements having high (α, n) yields, such as boron and fluorine, coincidence detectors with short die-away times are required to maximize the contribution of real coincidence events relative to accidental events, thereby reducing statistical uncertainties. This requirement has led to the concept of varying the physical die-away time of a neutron coincidence detector by changing the number and geometrical configuration of polyethylene moderators and cadmium (or boron) neutron absorbers.⁸²

Typical precisions and accuracies exhibited by neutron coincidence counters in the process environment are shown below for the general categories of product, scrap, and waste.²⁴

TABLE C-2

TYPICAL NEUTRON COINCIDENCE COUNTER UNCERTAINTIES

<u>Material Category</u>	<u>Precision (%)</u>	<u>Accuracy (%)</u>
Feed and product	1	1
Scrap	2-8	2
Waste	10-15	5-10

The data demonstrate the loss of precision and accuracy that is possible when the material composition (both elemental and isotopic) is poorly characterized and/or nonuniform.

III. HOLDUP MEASUREMENTS

The capability for measuring holdup in the main process stream of the NO_2 facility is essential for obtaining timely, accurate material balances, and a large number of NDA instruments were specified for this function (see Sec. III-E).

Two methods that have been used extensively for measuring holdup are passive gamma-ray analysis with a NaI detector and passive (integral) neutron counting with polyethylene-moderated BF_3 or ^3He proportional counters.⁸³ Most holdup measurements are best done by the passive gamma-ray method because of its energy selectivity, which permits measurement of key fissile constituents, and because of its high sensitivity, which for typical holdup problems is less than 1 g of plutonium. Another advantage of the method is its capability for localizing sources of holdup through detector shielding and collimation. For example, a section of ion-exchange column inside a glovebox can be isolated from other columns and equipment in the same box.

The attenuation corrections needed for gamma-ray measurements can be measured with an external transmission source, calculated from knowledge of the dimensions and composition of the item, or from a combination of calculations and measurements made from a holdup of the item. The reliability of gamma-ray holdup measurements is diminished if the thickness of the nuclear fuel material is greater than one gamma-ray mean free path or if the containment structure is both thick and complex.

A NaI(Tl) gamma-ray detector with shielded probes and stabilized electronics has proven operationally useful and reliable. For plutonium measurements, the counting windows are set to focus on the ^{239}Pu 400-keV complex, essentially excluding contributions from ^{241}Pu and gamma rays from other isotopes. A cart-mounted system has been designed and built at LASL.

Passive neutron measurements of plutonium holdup have been made with a portable shielded neutron assay probe (SNAP)^{84,85} and electronics.²⁷ The unit is a polyethylene-moderated thermal neutron detector that uses ^3He proportional counters (see Fig.

C-1). The detector exhibits modest directionality, which aids in isolating sources of holdup. Because of the great penetrability of fast neutrons, these measurements need not be corrected for attenuation; however, background interferences (and inability to localize sources) and variable (α, n) yields can limit the method. The sensitivity of the neutron method for typical process line geometries is 10-100 g of plutonium.

A new technique, which uses a large-area neutron detector to measure with high sensitivity the neutron field near the center of a room containing process equipment, sets an upper limit on holdup for the entire room.²⁵ Measurements made with an array of five polyethylene-moderated ^3He tubes can achieve an accuracy comparable to much more time-consuming NaI(Tl) detector gamma-ray measurements. With this technique, the fissile material must be fairly uniformly distributed, the room must be shielded from external sources, and the specific neutron activity of the material must be known. Careful instrument calibration by both calculational and experimental methods is necessary.

A vital part of any holdup measurement is the relationship between the measured signal and the amount of material it represents. Along a process line, various geometries are encountered: cylinders (e.g., ion-exchange columns), flat surfaces (e.g., gloveboxes), line sources (e.g., small-diameter piping), and extended volumes (e.g., filters measured at close distances). In many cases, an accurate calibration can be obtained from measurements with a point-source, coupled with appropriate geometric efficiency functions.³⁷ For other cases, more extensive calculations and calibrations are required. In many cases, the calibration and operation of the fixed NDA holdup devices in the MO_2 facility should be simpler and more accurate because instrument placement and calibration can be thoroughly planned in the design phase of the facility.

Fig. C-1. Assembly drawing of the portable SNAP.

IV. NDA VERIFICATION OF PuO_2 IN SHIPPING CONTAINERS

A simple measurement of the thermal neutron leakage from shipping containers will be used to verify quantitatively the PuO_2 contents, thereby supplementing ID, seal, and α -monitor checks. The measurement will be made with one or two polyethylene moderated neutron detectors (similar to SNAP⁸⁴) located 1 to 1.5 m from the shipping container. The shipping container may have to be rotated if the internal neutron shielding is not sufficiently homogeneous.

The verification measurement can be based on the specific neutron yields for the contained PuO_2 derived from calibrations and tag values of the isotopic abundances. Should the internal neutron shielding vary widely among containers, the verification would have to be compared to a similar measurement made at the shipper's station. Counting rates calculated for the proposed measurement configuration and the shipping container designed by ACNS greatly exceed 100 s^{-1} . This rate permits measurement with a statistical uncertainty of less than 3% to be made in 2 min or less. The overall accuracy of the measurement, which is dictated by uncertainties in the neutron attenuation by the shipping container and in the PuO_2 composition geometry, should be better than 5%.

NDA FUEL ROD ANALYSIS SYSTEM

The ²⁵²Cf fuel rod assay system³² described here was designed for the measurement of fast breeder reactor (FBR) fuel rods and is used routinely at the Westinghouse MHD plutonium fuel facility in Richland, WA. It will require some modification in order to measure MO_2 recycle fuel, because this fuel contains a smaller fraction of plutonium than does FFTF fuel (~30% Pu). In particular, the neutron moderator will have to be redesigned to increase the fissile/fertile fission ratio. However, the measurement principles and signatures will be the

same, and the basic characteristics of the instrument are not expected to differ significantly from those shown here.

The ^{252}Cf fuel rod assay system uses both active and passive techniques for the measurement of fissile content and pellet-to-pellet uniformity of MO_2 fuel rods. For the active portion of the measurement, a 200-600- μg ^{252}Cf source is used to interrogate the fuel rods. The source is positioned in the center of the moderator shown in Fig. C-2, and the fuel rods are moved past the source and into the gamma-ray detectors. The total fissile content is then determined by counting the high-energy delayed gamma rays resulting from the induced fission reactions.

The neutron moderator is designed to give a fast-neutron irradiation (the irradiation channel is lined with cadmium) as well as a high fissile/fertile fission ratio (400/1).

To measure the delayed gamma rays from the fuel rod, two 5- by 5-in-diam NaI detectors with through-holes for the passage of the fuel rods are positioned near the ^{252}Cf shield as shown in Fig. C-2. Only the high-energy delayed gamma rays (> 1200 keV) are used for the total fissile measurement because of their higher penetration through the rod and their good signal-to-background ratio.

In addition to total fissile active assay, pellet-to-pellet uniformity can be determined simultaneously by counting the relatively more intense, lower energy, passive gamma rays from the fuel by using the same NaI detectors. Each of the two NaI detectors examines a different low-energy window on a pellet-to-pellet basis using a tungsten sleeve with a collimation slit of ≤ 0.2 in. One detector counts 60-keV gamma rays which are mainly from ^{241}Am , whereas the second detector counts primarily plutonium gamma rays in the range of 100-500 keV. The window at 60 keV acts as a batch monitor because the ^{241}Am content of the fuel is time-dependent. The 100- to 500-keV window provides a qualitative measure of the fissile plutonium in the rod.

Fig. C-2. Schematic of the ^{252}Cf fast-neutron assay system for FBR-type fuel rods.

During operation, as many as 30 fuel rods are placed in the loading magazine of the fuel rod translator. The automated translator picks up the rod to be assayed and moves it through the NaI crystals and the ^{252}Cf assembly at 2.5 in./s so that a background count of the nonirradiated rod can be made. The direction of travel is then reversed and the rod is withdrawn at 0.36 in./s, during which time the delayed fission gamma-ray data are acquired and the pellet-to-pellet scans are made. After the irradiation and scan of the fuel column, the rod is unloaded into the tray directly below the loading magazine and the cycle is repeated for the next rod.

With the above assay cycle and typical FFTF fuel rods, the count rate (sum of both crystals for gamma-ray energies above 1.2 MeV) for the total fissile measurement is ~ 6000 Hz, with a net signal-to-background ratio of 3/1 for a 600- μg ^{252}Cf source. Typical rates in the 60-keV and 100- to 500-keV pellet-to-pellet windows are 80,000 Hz and 50,000 Hz, respectively. The relative precision of the measurement of the fissile content of a single rod is 0.5% (1 σ). A relative pellet-to-pellet nonuniformity of $\sim 5\%$ can be readily detected.

VI. SOLID TRANSURANIC WASTE ASSAY (MEGAS)

A detection system has been developed for assaying low-density, solid alpha wastes (paper, plastics, rubber, incinerator ash, etc.) in bulk form at and below the 10-nCi/g level. This is the currently recommended⁸⁶ maximum activity level for alpha wastes that are to be placed in nonretrievable storage or buried. The design objective was to develop a package assay system capable of measuring activity levels of 2-ft³ boxes containing ~ 4000 g of low-density wastes.

The detection system is a hybrid of a gamma-ray detection scheme coupled with one that detects x rays, both of which radiations are emitted in copious quantities by the transuranics. This MEGAS⁸⁷⁻⁹⁰ allows one to monitor the x-ray region for the sub-10-nCi/g samples, and subsequently to cross over to

progressively higher energy gamma rays as the activity level increases. The detector is 5-in. in diameter and 2-in.-thick NaI with a 10-mil beryllium window. The window is thin enough to allow x-ray transmission into the crystal, whereas the detector itself is thick enough to absorb high-energy gamma rays, e.g., the 400-keV complex from plutonium.

Such a hybrid system combines the high sensitivity (and relatively poor accuracy) of x-ray detection at the 10-nCi/g level with the lower sensitivity, but improved accuracy, of gamma-ray detection at higher activity levels. The errors referred to here are due to absorption by the matrix material and self-shielding by the transuranics. The self-shielding effects are severe for all photon energies considered here, particularly for the low-energy L x rays.⁹¹ Part of the self-shielding problem can be alleviated by using proper standards (e.g., dried liquid plutonium standards for assaying process-line-generated wastes from ion-exchange columns). Also, for typical room-generated wastes that are reasonably free of contamination, essentially no self-absorption effects exist.

Assay accuracy of the package scanner is approximately $\pm 50\%$ at 10 nCi/g, but can be 200% or more, depending on source location and the relative particulate size of the transuranic material in the standards and unknown. Above ~ 70 nCi/g (~ 4 mg Pu/4000 g waste), accuracy is approximately $\pm 30\%$. In this latter region, complete crossover has been accomplished from x-ray detection to higher energy gamma detection. The dynamic range of the system extends from a few micrograms to gram quantities of plutonium (a factor of $\sim 10^6$). The samples of higher activity are monitored with a 0.5-mm copper shield over the detector to remove the lower energy ($E_\gamma < 50$ keV) photons.

Typical plutonium detectability limits for the system are shown in Table C-3 and are based on 4000 g of low-density wastes packaged in a 2-ft³ cardboard carton. Detectability limits are given for both 100- and 1000-s counting times. The detectability limit is defined as that amount of plutonium giving a detected signal equal to three standard deviations above

background (3 σ level). The table shows that for 1000-s counting times, both the x-ray and 120-keV regions allow 10-nCi/g detectability for such massive and bulky samples. The transition to total gamma-ray monitoring would occur at approximately the 70-nCi/g level.

TABLE C-3

PLUTONIUM DETECTABILITY LIMITS: MEGAS

Photon Energy Region (keV)	Detectability Limit ^a (3 σ)			
	100-s Count (nCi/g)	(μ g Pu)	1000-s Count (nCi/g)	(μ g Pu)
16 (L x rays)	0.1	6.6	0.04	2.1
120	11.0	590.	3.4	190.
200	84.	4700.	27.	1500.
400	120.	6300.	36.	2000.

^aDetectability limit at the 3 σ level for 4000 g of low-density wastes in a 0.057-m³ corrugated paper box. Note that 10 nCi/g for 4000-g wastes is equivalent to 556 g plutonium with a 6% ²⁴⁰Pu content.

VII. PLUTONIUM ISOTOPIC MEASUREMENTS BY GAMMA-RAY SPECTROSCOPY

The most common method for determining the isotopic content of plutonium materials is surface-ionization mass spectrometry. This is often supplemented with alpha spectroscopy to determine low levels of ²³⁸Pu. Gamma-ray spectroscopy is an attractive alternative to mass spectrometry because it is non-destructive, instrumentally simpler, and has different sources of interferences. With varying degrees of precision and accuracy it is currently possible to obtain isotopic information from gamma-ray spectroscopy, and in a few special cases the accuracy of such NDA determinations approaches that of destructive analysis based on either mass or alpha spectrometry.

However, the NDA measurement may often be adequate and even preferable on the bases of cost and timeliness.

A total of several hundred gamma rays is emitted by ^{238}Pu , ^{239}Pu , ^{240}Pu , ^{241}Pu and ^{241}Am . The best current, complete compilation of energies and intensities is that of Gunnink and Morrow.⁹² Table C-4 is excerpted from that report and includes most of those gamma rays with energies ≥ 120 keV, useful in determining isotopic ratios and/or relative counting efficiencies. All the energies are accurate to ± 0.1 keV, but the intensities of some of the weaker gamma rays are known to be somewhat in error. The intensities are given here as a qualitative guide to the possible usefulness of a particular gamma ray. Two comments are in order. First, ^{242}Pu emits no gamma rays and therefore cannot be included directly in any gamma-ray measurement of isotopic distribution. Second, the gamma rays labeled ^{241}Pu (^{237}U) are actually emitted by the ^{237}U daughter of ^{241}Pu . Inasmuch as ^{237}U has a 6.75-day half-life, the activities will come into equilibrium in about a month, after which the gamma rays may be used as a measure of ^{241}Pu . The total amount of each isotope in the sample cannot be obtained from gamma-ray spectroscopy alone, but ratios of the isotopic masses can be determined. These are, of course, the same as the ratios of the isotopic fractions. In principle, three ratios involving the isotopes ^{238}Pu , ^{239}Pu , ^{240}Pu , ^{241}Pu are sufficient to determine their relative isotopic abundances.

Within the problem area of determining plutonium isotopic distributions by passive gamma-ray spectroscopy there are perhaps 10 different cases and situations, each requiring a somewhat different approach. Only a few have been solved in the sense of having been thoroughly investigated and of having equipment and procedures set up to operate reliably.⁹³ Two of these methods will be described here.

In the first method, which yields more extensive isotopic information for samples of arbitrary shape and composition, a gamma-ray spectrum of the sample is measured with a small Ge(Li) or intrinsic germanium detector of the highest obtainable

TABLE C-4

GAMMA RAYS USEFUL IN ISOTOPIC DETERMINATIONS

Isotope	Half-Life (yr)	Energy (keV)	γ Intensity (probability/disintegration)
^{238}Pu	87.78	152.8	1.01×10^{-5}
		766.4	2.40×10^{-7}
^{239}Pu	24,082	129.3	6.20×10^{-5}
		144.2	2.86×10^{-6}
		161.5	1.30×10^{-6}
		171.3	1.09×10^{-6}
		179.2	6.39×10^{-7}
		189.3	7.76×10^{-7}
		195.7	1.07×10^{-6}
		203.5	5.60×10^{-6}
		255.3	8.03×10^{-7}
		297.4	5.00×10^{-7}
		345.0	5.61×10^{-6}
		375.0	1.58×10^{-5}
^{240}Pu	6,537	413.7	1.51×10^{-5}
		646.0	1.45×10^{-7}
^{240}Pu	6,537	160.35	4.20×10^{-6}
		642.3	1.45×10^{-7}
		687.6	3.70×10^{-8}
^{241}Pu	14.35	148.6	1.90×10^{-6}
		160.0	6.45×10^{-8}
^{241}Pu (^{237}U)	14.35	164.6	4.50×10^{-7}
		208.0	5.12×10^{-6}
		267.5	1.77×10^{-7}
		332.3	2.80×10^{-7}
^{241}Am	434.1	125.3	3.95×10^{-3}
		169.6	1.68×10^{-6}
		662.4	3.46×10^{-6}

resolution (~ 500 eV at 122 keV). Closely spaced gamma-ray lines between 120 and 210 keV are used to determine the following isotopic ratios:

$$^{238}\text{Pu}/^{241}\text{Pu} \rightarrow 152.8 \text{ keV}/148.6 \text{ keV}$$

$$^{239}\text{Pu}/^{241}\text{Pu} \rightarrow 203.5 \text{ keV}/208.0 \text{ keV} \\ \text{or } 129.3 \text{ keV}/148.6 \text{ keV}$$

$$^{240}\text{Pu}/^{241}\text{Pu} \rightarrow 160.3 \text{ keV}/164.6 \text{ keV}$$

$$^{241}\text{Am}/^{239}\text{Pu} \rightarrow 125.3 \text{ keV}/129.3 \text{ keV}$$

All unresolved interferences are subtracted by comparison with the neighboring clean single peaks. A correction is made for the difference in relative detection efficiency at the different energies.

The relative efficiency curve for a given sample (essentially the product of detector efficiency and sample attenuation) is determined by counting a range of single peaks in the ^{239}Pu and ^{241}Pu spectra and by dividing each peak area by the best value of the gamma-branching intensity. All peaks (single and multiple) are stripped from the spectra using a simple channel summation procedure with a straight-line background subtraction. The isotopic ratios are then combined to yield the actual plutonium mass fractions (^{238}Pu , ^{239}Pu , etc.) assuming

$$^{238}\text{Pu} + ^{239}\text{Pu} + ^{240}\text{Pu} + ^{241}\text{Pu} = 1$$

Although the best results probably will be obtained only through accurate peak-fitting algorithms such as are used in GAMANAL,⁹⁴ the results obtained to date with the present procedure are encouraging. Because ^{242}Pu has no gamma signature, it must be omitted from the present analysis. In some cases (several percent of less ^{242}Pu), it may be satisfactory to assume some approximate relation between ^{240}Pu and ^{242}Pu to make this correction. For advanced plutonium recycle fuels ($^{242}\text{Pu} \sim 5\%$) this

will not be satisfactory, and other procedures, such as neutron coincidence counting, gamma-ray transmission, or K- and L-edge absorption densitometry measurements must be used.

Calibration can be accomplished either by comparison with standards of known isotopic composition or by use of the fundamental data on half-lives and gamma-ray intensities. The first procedure is recommended for routine use because of the uncertainty in some of the half-life and intensity data, but the fundamental data are extremely useful in predicting possibilities and probable performance. Evidently the following performance can be achieved:

- Ratio $^{240}\text{Pu}/^{241}\text{Pu}$: < 1% (1 σ) for samples of arbitrary geometry and composition, and better for more controlled samples.
- Ratio $^{238}\text{Pu}/^{241}\text{Pu}$: $\sim$ 1% (1 σ) for ^{238}Pu isotopic abundances $\sim$ 1%.
- Ratio $^{240}\text{Pu}/^{241}\text{Pu}$: $\sim$ 10% (1 σ) for a ^{240}Pu isotopic abundance greater than 15% and a counting time of 1000 s. For plutonium recycle ($\sim$ 28% ^{240}Pu) and 10,000-s counting times, better accuracies are obtained.
- $^{241}\text{Am}/^{239}\text{Pu}$: < 2% (1 σ).

This technique is still being developed, but encouraging results have been obtained thus far. Results from somewhat different techniques and more stringently controlled sample compositions and configurations have also been reported.^{95,96}

The second useful method for selected isotopic analysis of powders such as PuO_2 and MO_2 or other dense samples is the enrichment meter principle, which has become a mainstay for the NDA measurement of uranium enrichment and is equally applicable to plutonium.⁹⁷ The method makes use of the fact that the intensity of a low-energy gamma ray of uranium or plutonium isotopes from a uniform object that has a major weight fraction of uranium or plutonium is proportional to the isotopic abundance of the isotope emitting the gamma ray. The essential

measurement conditions are that the sample be opaque to the gamma ray being measured and that a fixed area of the sample be viewed by the detector. For example, the counting rate for 185-keV gamma rays from ^{235}U in uranium oxide is given by:

$$C = \frac{I\epsilon A}{\mu_1} F, \quad F = \left[1 + \frac{\mu_2 \rho_2}{\mu_1 \rho_1} \right]^{-1}$$

where

- I = ^{235}U isotopic enrichment
- τ = specific activity of 185-keV gamma (per s per g ^{235}U)
- ϵ = detection efficiency for 185-keV gammas
- A = area of sample viewed
- μ_1, μ_2 = 185-keV mass absorption coefficients of uranium, oxygen (cm^2/g)
- ρ_1, ρ_2 = density of uranium, oxygen (or other low-Z matrix).

The factor $\tau\epsilon A/\mu_1$ is a constant, and F is a slowly varying function of density nearly equal to unity for many practical cases (at 185-keV, $\mu_2/\mu_1 \leq 0.11$ for elements with $Z \leq 30$). For pure metal, oxide (UO_2), and residue containing only 50% uranium, F is respectively 1.00, 0.988, and 0.930.

The enrichment meter concept may also be used for QC of different reactor fuel blends, e.g., PuO_2 , UO_2 , U-C, and Th-C, or for the analysis of any fissionable material having a suitable low-energy gamma ray. In the more general case of mixtures of several components, the counting rate of a specific gamma ray from an isotope with enrichment I is given by:

$$C = \frac{I\tau\epsilon A}{\mu_1} F, \quad F = \left[1 + \frac{\mu_1}{\mu_1 \rho_1} \sum_{i=2}^n \mu_i \rho_i \right]^{-1}$$

where the running index i denotes the relevant elemental constituents of the fuel blend, and the specific subscript 1 denotes the element whose isotope emits the "signal" gamma line of interest. For the case of a PuO_2 - UO_2 blend and the detection of a plutonium gamma ray, the above expression reduces to:

$$C = \frac{I \epsilon A}{\mu_{\text{Pu}}} F'$$

$$F' = \frac{1}{1+r} K, \quad K = \left[1 - \frac{r}{1+r} + \frac{32}{239} \frac{\mu_{\text{oxygen}}}{\mu_{\text{Pu}}} \right]^{-1}$$

$$\mu = (\mu_{\text{Pu}} + \mu_{\text{U}}) / \mu_{\text{Pu}} \approx 0.061, \quad r = \mu_{\text{U}} / \mu_{\text{Pu}} = \text{blending ratio}$$

The constant K has values near unity and the factor $1/(1+r)$ reflects the essential change in attenuation of plutonium gamma rays by the addition of uranium. Values of K for the more intense ^{239}Pu gamma rays and for a range of blending ratios representative of FFTF and recycle fuels are given in Table C-5. It is clear in Table C-5 that K , for a particular gamma ray, is quite insensitive to gross changes in the fuel-blending ratio, so the enrichment meter response is directly proportional to $1/(1+r)$, i.e., it will sense variations in either the isotopic enrichment I or the blending ratio r .

Concurrent use of one of the uranium gamma rays could in principle permit independent monitoring of I (for the plutonium isotope of interest) and r , provided the uranium isotopic composition is known.

For measurements of PuO_2 and MO_2 samples at the ASF, a 10%-efficient $\text{Ge}(\text{Li})$ system with premium resolution (better than 0.7 keV at 122 keV) is recommended. With the larger detector, the ^{238}U content can be determined by counting the 1.001-MeV gamma ray from its daughter $^{234\text{m}}\text{Pa}$ (which is in equilibrium for 3-month-old material). The plutonium isotopes that can readily

TABLE C-5

ENRICHMENT METER PARAMETERS

K vs Blending Ratio r for ^{239}Pu Gamma Rays					
<u>E (keV)</u>	<u>129</u>	<u>204</u>	<u>375</u>	<u>414</u>	<u>451</u>
r=4	1.046	1.037	1.011	0.996	0.998
r=5	1.048	1.040	1.013	0.994	1.000
r=6	1.049	1.041	1.014	0.993	1.001
r=30	1.057	1.048	1.021	0.986	1.008

be determined from the specific gamma rays are ^{239}Pu (129 keV), ^{238}Pu (153 keV), and ^{241}Pu (148 keV). ^{241}Am can be derived from measurements of the gamma-ray composite (^{241}Am , ^{239}Pu , ^{241}Pu) in the 333- to 345-keV region.

Although evaluation is needed to determine the accuracies of isotopic abundances found by this method, available data indicate that accuracy of 1% or better is reasonable.

VIII. SEGMENTED GAMMA-SCANNER

The segmented gamma-scanner (SGS)⁹⁸ permits quantitative measurement of ^{235}U , ^{238}Pu , and ^{239}Pu in low- to medium-density scrap and waste. Passive gamma radiation from the various isotopes is observed, and the data are corrected for gamma-ray absorption by using a separate transmission source. The corrected data are proportional to fissile content. The system includes a high-resolution Ce(Li) gamma-ray detector, a multichannel pulse-height analyzer, a dedicated minicomputer, and a sample-positioning mechanism. The sample is rotated continuously and scanned vertically in segments to reduce the effects of fissile-content inhomogeneity. Control of scanning and data acquisition and complete real-time data analysis are performed automatically by the minicomputer; the operator is required only to enter

sample identification. Quantities of 1-300 g of fissile material can be measured. Relative precision is 1-5%, depending on container size and transmission. The assay requires ~ 10 s for each 1-cm vertical segment.

The segmented gamma-scan instrument is shown in Fig. C-3. The teletype, which is used for hardcopy output and program input, as well as the keyboard used for entry of comments, constants, and parameter interrogation make up the unit on the far left of the figure. The complete electronics rack is in the center. The two units to the right of the rack comprise the scan table and Ge(Li) detector systems. The transmission source is to the left of the sample in this figure, and the detector with its dewar of liquid nitrogen is to the right.

Segmented gamma-scanning units are commercially available and are used routinely at LASL, General Atomic Corp., Atlantic Richfield-Hanford, Nuclear Fuel Services-Erwin, Savannah River Operations, and elsewhere.

IX. WEIGHING

Weight measurements are the mainstay of the material control program for the NO_2 plant, covering the wide range from the few-gram ASF samples to the 200- to 800-kg bulk storage vessels. Two types of weight measurement will be used. The first involves a determination of gross weight, the uncertainty in which includes errors in zero balance, hysteresis, linearity, and repeatability. The second type involves a determination of both tare and gross weights in which the net weight is found by subtraction. This method minimizes, if not eliminates, errors due to zero balance (the largest error) and hysteresis, hence yields more accurate values of net weight. Regardless of the weight determination method, calibration and check weighing programs should be implemented to ensure that accurate and reliable weights result. All weighing systems should be protected from sudden overloads and horizontal forces. If properly used, weighing systems are inherently stable and dependable.

Fig. C 3. SGS system for passive analysis of uranium and plutonium scrap.

The two types of weighing instruments are load cells and balances. Load cell weighing systems are used for bulk quantity measurements in the MO_2 plant, e.g., for shipping containers, canisters, weigh and feed hoppers, and various storage vessels. The range of measurement is 1-800 kg, necessitating the use of perhaps three categories of load cells with capacities of 10, 100, and 1000 kg. Commercial units available for these categories display the following ranges of measurement errors (percent of full scale):

Zero balance	1%
Hysteresis	0.02-0.05%
Repeatability	0.01-0.03%
Linearity	0.05-0.25%

Load cell systems are well suited for nuclear materials work. The weighing platform can be physically separated from the associated electronics and readout mechanism. Only the platform need be exposed to the environment of a glovebox or other enclosure, and the electronics can be placed in an area of easy access for maintenance and calibration.

Analytical balances are used in the ASF, PuO_2 powder unloading operation and, possibly, in MWT. Sample sizes range from 2-50 g in the ASF and 0-10 g for powder unloading. For these masses, 0.01-0.02% accuracies can be readily obtained with a wide variety of commercially available units. However, high-precision balances are slow and are sensitive to environmental conditions, as well as being subject to operator error.

X. CALORIMETRY

Plutonium calorimetry involves the measurement of heat generated by the radioactive decay of plutonium and americium. ²⁴¹Am but a negligible portion of the decay energy is transformed into heat when the decay particles (alpha, beta,

and low-energy gamma) are absorbed by the sample and the calorimeter walls. Heat generated by a plutonium sample can be measured accurately by calorimetry because the heat determination can be traced to primary NBS electrical standards, thereby eliminating the need for accurate plutonium standards. Table C-6 gives the half-lives, specific powers, and errors in the specific powers for the radionuclides contributing heat.¹⁰¹

The plutonium isotopic composition and ²⁴¹Am content must be known or determined if the amount of plutonium is to be inferred from the measured heat. Table C-7¹⁰² lists the composition of recycle plutonium for different burnups, along with the fraction of the total heat produced by each isotope, the uncertainty in the determination of plutonium mass due to the uncertainty in abundance for each isotope, and the specific power of each burnup sample. Figure C-4 shows the precision of mass-spectrometric isotopic determinations as a function of abundance for both an NBS standard (optimum case) and a plutonium nitrate process solution (poorly characterized material).²⁴ If closely controlled, the nominal composition for a process line may be adequate for feed and product materials. On the other hand, scrap and waste materials tend to have variable plutonium compositions and ²⁴¹Am content. As a result, errors in the isotopic determination are usually the largest uncertainties in the plutonium measurement. Uncertainties also exist in the specific powers, heat determination, heat distribution, and heat produced by interfering reactions such as radiolysis. Still, plutonium determination by calorimetry typically is accurate to better than 0.5% with precision better than 0.2%.

Calorimetry measurements are usually time-consuming because the sample and calorimeter must come to thermal equilibrium before the heat determination can be made. For PuO₂ feed or scrap samples, as many as 10 h may be required. In cases of well-controlled geometry and small sample size, the equilibration time can be less than 1 h. A calorimeter has been built that measures ZPPR* fuel rods (each 1-cm diam by 15-cm long,

*Zero Power Plutonium Reactor.

TABLE C-6

SPECIFIC POWERS OF PLUTONIUM AND AMERICIUM

<u>Isotope</u>	<u>Half-Life (yr)</u>	<u>Specific Power (W/g)</u>	<u>Uncertainty in Specific Power (% , 1σ)</u>
^{238}Pu	87.79	5.6716×10^{-1}	0.10
^{239}Pu	24,082	1.9293×10^{-3}	0.27
^{240}Pu	6,537	7.098×10^{-3}	0.2
^{241}Pu	14.35	3.390×10^{-5}	0.06
^{242}Pu	379,000	1.146×10^{-4}	--
^{241}Am	434.1	1.1423×10^{-1}	0.14

TABLE C-7

CALORIMETRY ERROR DUE TO UNCERTAINTIES IN
ISOTOPIC ABUNDANCES FOR VARIOUS BURNUPS(in %, 1 σ level)

Isotope	Relative Abundance (%)	Fraction of Total Heat (%)	Uncertainty in Abundance (%)	Uncertainty in Plutonium Mass (%)
Burnup: 8-10,000 MWd/T Specific Power: 3.19 mW/g				
²³⁸ Pu	0.1	17.8	3.9	0.69
²³⁹ Pu	87.1	52.6	0.14	0.16
²⁴⁰ Pu	10.1	22.4	0.40	0.10
²⁴¹ Pu	2.4	2.5	0.82	0.02
²⁴² Pu	0.3	0.01	2.3	0.00
²⁴¹ Am	0.13	4.6	3.4	0.16
Total				0.66

Burnup: 16-18,000 MWd/T Specific Power: 4.62 mW/g				
²³⁸ Pu	0.25	30.7	2.5	0.76
²³⁹ Pu	75.7	31.6	0.15	0.10
²⁴⁰ Pu	18.5	28.4	0.30	0.10
²⁴¹ Pu	4.5	3.3	0.60	0.02
²⁴² Pu	1.1	0.03	1.2	0.00
²⁴¹ Am	0.24	5.9	2.5	0.15
Total				0.82

Burnup: 25-27,000 MWd/T Specific Power: 9.43 mW/g				
²³⁸ Pu	1.0	60.2	1.3	0.76
²³⁹ Pu	58	11.9	0.17	0.04
²⁴⁰ Pu	25	18.8	0.26	0.06
²⁴¹ Pu	9	3.2	0.43	0.01
²⁴² Pu	7	0.09	0.48	0.00
²⁴¹ Am	0.48	5.8	1.8	0.11
Total				0.79

Burnup: 38-40,000 MWd/T Specific Power: 15.7 mW/g				
²³⁸ Pu	2	73.4	0.89	0.66
²³⁹ Pu	45	5.6	0.19	0.02
²⁴⁰ Pu	27	12.4	0.25	0.04
²⁴¹ Pu	15	3.3	0.33	0.01
²⁴² Pu	11	0.08	0.39	0.00
²⁴¹ Am	0.7	5.2	1.5	0.08
Total				0.79

Fig. C-4. Precision of mass-spectrometric isotopic determinations.

containing 13-26 g of plutonium) in 20 min.¹⁰³ In addition, techniques for predicting calorimeter equilibrium heat values promise to substantially reduce sample turn-around time. Recent results¹⁰⁴ indicate that calorimetric assay times may be reduced by more than a factor of 2 while predicting equilibrium values to within 0.05%.

An automated plutonium assay system (APAS)¹⁰⁵ that uses a calorimeter for plutonium measurement is being developed by Mound Laboratory as an accurate in-line glovebox assay system for MO_2 fuels. A process control computer will control the movement and measurement of the samples along a glovebox line in addition to processing the resulting data as part of material control and safeguards accountability programs.

In the current MO_2 design, the benefits from in-line calorimetry did not compare favorably with less costly measurement strategies. Questions concerning nonequilibrium calorimetry and effects of entrained moisture for the feed PuO_2 material are not resolved.

APPENDIX D

EVENT DESCRIPTION OF MOXSIM: BASELINE MIXED-OXIDE PLANT SIMULATION PROGRAM

1. INTRODUCTION

MOXSIM provides a time-event Monte Carlo simulation of the baseline MO_2 plant operation.^{106,107} The plant is divided into 11 main process areas and 2 peripheral process areas. Process operation and material flows are modeled on the basis of the plant definition given in Chap. II and Appendix A. A schedule of material flow events is supplied for each unit process; the events are properly sequenced by the controller of the GASP IV simulation program.⁷² GASP IV also allows continuous simulation for treating dynamic system behavior and process control functions.

Each material flow event is associated with a particular unit process: batches are selected from uniform distributions, inventories are updated, and event data are stored. Only true material flow data are generated, i.e., no simulated measurements are applied. The code has provisions for linking successive weeks of continuous operation, for varying the process operation, and for inserting various diversion schemes. Event data from each week of simulated plant operation are stored in a permanent file for access by the measurement simulation and analysis code MACSIM. Typically, 1500 material flow events occur during 1 wk of simulated operation. This represents about 8000 individual material transfers.

The operation of each unit process is defined by the following events: an initial event that specifies starting inventories at the beginning of the week, at least one process event, and a final event of runouts that determines final inventories.

at the end of the week. Each event is defined by data entries stored in a 10-dimensional vector. With a few exceptions, the type of data stored in each entry is:

UP--unit process identification number

TE--time of the event

BI--input batch

BO--output batch

SM--scrap

WM--waste

HU--holdup, usually accumulated via an asymptotic model

AS--samples for analysis

DV--losses, including additional holdup and/or diverted material

XM--extra variable, often used for in-process inventory.

Thus, each event can represent as many as eight material transfers. For example, consider a unit process in which measurable holdup is accumulated in variable HU, additional holdup is accumulated in DV, and in-process inventory resides in XM. A true material balance MB_n for the n^{th} event is given by

$$MB_n = XM_{n-1} + HU_{n-1} + DV_{n-1} + BI_n - XM_n - HU_n - DV_n \\ - BO_n - SM_n - WM_n - AS_n,$$

and $MB_n = 0$ by definition. We have verified that the sum of all material balances in NOXSIM is zero.

Although shifts and weeks of processing are used as event fiducials, the actual processes will seldom be synchronized with them. This has no important effect on the material flow simulation, and should not be viewed as a process constraint. The shift structure is a convenient set of fiducials useful for simulation, personnel scheduling, and some discrete event timing.

II. EVENT DESCRIPTION BY UNIT PROCESS

This section outlines initial, process, and final events for each unit process in MOXSIM. Each nonzero material flow that is described as a uniform random variable is identified, and its range is given.

About 1500 events are tallied by MOXSIM for a single week of plant operation. These events contain perhaps 8000 individual material transfers which occur along some 90 flow lines. Only a representative sample of the simulation data can be given here. Material flow data are plotted in Figs. D-1 and D-2 of Sec. D-III in this appendix for a typical week of PuO_2 powder unloading and pelleting operations.

A. PuO_2 Receiving and Storage (1A, 2A)*

1. Initial. XM, initial PuO_2 inventory in shipping containers stored in the vault, in kg PuO_2 .

2. Process. One shipping container is sent to the PuO_2 unloading station 1/2 h after the start of the shift. This operation occurs during one shift each day for five consecutive days each week.

- BO, contents of one shipping container, 31.68-32.32 kg PuO_2 .
- XM, PuO_2 inventory at the end of the event, in kg PuO_2 .

3. Final. XM, final PuO_2 inventory in storage vault, in kg PuO_2 .

B. PuO_2 Unloading (3A)

1. Initial

- HU, initial holdup in the pneumatic powder transfer line to PuO_2 bulk storage, in kg PuO_2 .

*The numbers in parentheses designate unit processes in the baseline plant definition (see Sec. II B).

- DV, initial unmeasured holdup in the room filters, gloveboxes, etc., 0.1 kg PuO_2 minimum.
- XM, initial inventory in the PuO_2 storage tank to be filled, in kg PuO_2 .

2. Process. One shipping container with four canisters of PuO_2 powder is unloaded each shift. One canister is unloaded to bulk storage every 2 h. The pneumatic transfer line is run out after each canister is unloaded. This operation occurs one shift each day for five consecutive days each week.

- BI, contents of unopened PuO_2 canisters, 7.92-8.08 kg PuO_2 .
- WM, residual waste in empty canisters that are sent to MWT, in kg PuO_2 ; $\text{WM} = \text{WF} \cdot \text{BI}$, $\text{WF} = 0.001-0.003$, the waste fraction.
- EU, accumulated holdup trapped in the transfer line after runout, 0-0.1 kg PuO_2 , plus holdup trapped in the valve that routes powder to the PuO_2 storage tanks, 0.15-0.25 kg PuO_2 .
- AS, samples to the ASF from each canister, 0.002 kg PuO_2 .
- DV, accumulated holdup in the room filters, etc., at the end of the current event, in kg PuO_2 . $\Delta \text{DV} = \text{DF} \cdot \text{BI}$, $\text{DF} = 0-0.001$, the holdup fraction.
- BO, powder received in the PuO_2 storage tank, in kg PuO_2 .
- XM, inventory in the PuO_2 storage tank at the end of the event, in kg PuO_2 .

3. Final. Holdup trapped in the conveyor and routing valve is cleaned up and sent to the PuO_2 storage tank. Holdup that is cleaned up from the unloading station is sent as waste to MWT.

- WM, holdup that is cleaned up and sent to MWT, in kg PuO_2 .
- HU, final holdup in the pneumatic transfer line after cleanup, in kg PuO_2 .

- AS, sample sent to the ASF from the filled PuO_2 storage tank, 0.027-0.033 kg PuO_2 .
- DV, final holdup in the unloading room after cleanup, 0.1 kg PuO_2 minimum.
- XM, final inventory in the filled PuO_2 storage tank, in kg PuO_2 .

C. PuO_2 Blending and Bulk Storage (4A)

1. Initial

- BI, initial inventory in the PuO_2 storage tank that is feeding the blending process, in kg PuO_2 .
- HU, initial holdup in the pneumatic transfer line to the PuO_2 feed hopper, in kg PuO_2 .
- XM, initial inventory in the PuO_2 feed hopper, in kg PuO_2 .

2. Process. A batch is sent from the PuO_2 storage tank to the PuO_2 feed hopper at the blender 1/4 h after the start of the shift. This operation occurs 20 consecutive shifts per week.

- BI, inventory in the PuO_2 storage tank at the end of the event, in kg PuO_2 .
- BO, batch transferred from the PuO_2 storage hopper to the PuO_2 weigh hopper, 7.92-8.08 kg PuO_2 .
- WM, waste sent to MNT from each batch, in kg PuO_2 ; $\text{WM} = \text{WF} \cdot \text{BO}$, $\text{WF} = 0-0.0005$, the waste fraction.
- HU, the pneumatic transfer line is run out to the PuO_2 feed hopper after each batch. HU is the holdup in the line after runout, 0-0.1 kg PuO_2 .
- XM, inventory in the PuO_2 feed hopper after charging the weigh hopper, 1-2 kg PuO_2 .

3. Final

- BI, final inventory in the PuO_2 storage tank, in kg PuO_2 .
- HU, final holdup in the pneumatic transfer line to the PuO_2 feed hopper, in kg PuO_2 .

- XM, final inventory in the PuO_2 feed hopper, in kg PuO_2 .

D. MO_2 Blending (5)

1. Initial

- HU, initial holdup in the pneumatic transfer line from the blender to the MO_2 powder storage silos, in kg MO_2 .
- DV, initial unmeasured holdup in the blender filters, etc., 1.5 kg MO_2 minimum.
- XM, residual holdup in the blender, in kg MO_2 .

2. Process. The blender is charged at the start of a shift from the PuO_2 , UO_2 , and recycle MO_2 weigh hoppers as follows. The UO_2 batch is determined from the PuO_2 batch to satisfy constant plutonium enrichment (4% PuO_2 by weight); the recycle MO_2 batch is assumed to have the same plutonium enrichment. The total blender contents is one sub-blend, ~ 225 kg MO_2 . A sub-blend is transferred to an available MO_2 storage silo 7 h after the start of the shift. This process operates 20 consecutive shifts each week.

- BI, total input to the blender from the PuO_2 , UO_2 , and recycle MO_2 weigh hoppers, in kg MO_2 .
- SM, dirty scrap to MWT, 0-0.2 kg MO_2 .
- WM, waste sent to MWT, 0-0.2 kg MO_2 .
- HU, the pneumatic transfer line to the silos is run out after each event. HU is the holdup after runout, 0.25-0.75 kg MO_2 .
- AS, analysis samples from a sub-blend, 0.0225-0.0275 kg MO_2 .
- DV, accumulated holdup, in kg MO_2 ; $\Delta DV = DF \cdot BI$, $DF = 0-0.0002$, fraction of unmeasured holdup.
- XM, residual holdup in the blender. The blender is run out after each event and XM is the holdup in the blender after runout, 0.5-1.5 kg MO_2 .
- MO, material of one sub-blend transferred to a silo, in kg MO_2 .

3. Final

- SM, unmeasured holdup that is cleaned up and sent to MWT as dirty scrap, in kg MO_2 .
- HU, final holdup in the pneumatic transfer line, in kg MO_2 .
- DV, final holdup, in kg MO_2 .
- XM, final holdup in the blender, in kg MO_2 .

E. MO_2 Storage (6)

1. Initial

- BI, initial contents of the next full silo available for emptying, in kg MO_2 .
- HU, initial holdup in the pneumatic transfer line from the silos to the compactor feed hopper at the pelleting operation, in kg MO_2 .

2. Process, Start of Shift. The silo is checked for QC release. If the sub-blend is rejected, the contents of the silo are sent to recycle MO_2 bulk storage if adequate storage is available. One sub-blend is rejected each week, on the average. A QC-released silo is selected to feed the pelleting operation.

- BI, silo contents selected to feed the pelleting operation, in kg MO_2 .
- SM, silo contents rejected to recycle MO_2 storage, in kg MO_2 .
- HU, initial holdup in the transfer line to the compactor feed hopper, in kg MO_2 .

3. Process, MO_2 Powder Transfer to the Compactor Feed Hopper at the Pelleting Operation. The amount of MO_2 transferred to the compactor feed hopper is updated each hour, beginning 1 h after the start of a shift. This amount is determined by the pelleting operation. The silo is run out, normally 7 h after the start of a shift. Residual holdup in the silos is estimated to be ~ 0.05 kg MO_2 . Variation in this quantity is neglected in the model. The pneumatic transfer line to the compactor feed hopper is run out after the silo is emptied. This operation occurs for 19 consecutive shifts each week.

- BI, inventory in the silo at the end of the event; the silo is emptied and run out before the end of the shift, in kg MO_2 .
- BO, powder transferred to the compactor feed hopper during the previous hour; the rate is set by the pelleting operation, 30-35 kg MO_2 /h.
- HU, holdup in the pneumatic transfer line; the asymptotic level is 2-3 kg MO_2 . The transfer line is run out before the end of the shift, 0.25-0.75 kg MO_2 .

4. Process, End of Shift. The next full silo available for emptying is selected.

- BI, the initial contents of the next silo to be emptied, in kg MO_2 .
- HU, holdup in the transfer line at the end of the shift, in kg MO_2 .

5. Final

- HU, final holdup in the pneumatic transfer line, in kg MO_2 .

F. Recycle MO_2 Blending and Bulk Storage (4C)

1. Initial

- BI, initial inventory in the recycle MO_2 storage tank that has been QC-released to feed the blending operation, in kg MO_2 .
- HU, initial holdup in the pneumatic transfer line from the recycle MO_2 storage tanks to the recycle MO_2 feed hopper at blending, in kg MO_2 .
- XM, initial inventory in the recycle MO_2 feed hopper, in kg MO_2 .

2. Process. A recycle MO_2 batch is sent to blending 1/4 h after the start of the shift. The pneumatic transfer line to the recycle MO_2 feed hopper at the blending operation is run out after each batch. This operation occurs for 20 consecutive shifts each week.

- BO, recycle MO_2 batch that is sent to the weigh hopper at the blender, 25-30 kg MO_2 .

- HU, holdup in the transfer line is run out after each batch: HU is the holdup after runout, 0.1-0.3 kg MO_2 .
- XM, the remaining inventory in the recycle MO_2 feed hopper after charging the weigh hopper, 7.5-12.5 kg MO_2 .
- BI, inventory in the recycle MO_2 storage tank feeding the blending operation after the event, in kg MO_2 .

3. Process, End of Shift

- WM, waste that is sent to MWT, 0-0.2 kg MO_2 .
- HU, holdup in the transfer line at the end of the shift, in kg MO_2 .
- XM, inventory in the recycle MO_2 feed hopper at the end of the shift, in kg MO_2 .
- BI, inventory in the recycle MO_2 storage tank feeding the blending operation at the end of the shift, in kg MO_2 .

4. Final

- BI, final inventory in the recycle MO_2 storage tank, in kg MO_2 .
- HU, final holdup in the transfer line to the recycle MO_2 feed hopper, in kg MO_2 .
- XM, final inventory in the recycle MO_2 feed hopper, in kg MO_2 .

G. Pelleting and Green-Pellet Storage (7,8)

1. Initial

- BI, initial inventory in the compactor feed hopper, in kg MO_2 .
- HU, initial inventory in the press feed hopper, in kg MO_2 .
- DV, initial unmeasured holdup in the pelleting operation, 2 kg MO_2 minimum.
- XM, initial inventory in green-pellet boats stored on the mechanical conveyor to the sintering furnace, in kg MO_2 .

2. Process, MO_2 Powder Transfer from QC-Released Silo to Compactor Feed Hopper. The inventory of the MO_2 powder compactor feed hopper is updated hourly, starting 1 h after a shift begins. A green-pellet boat is loaded and sent to storage every 1/2 h starting 1 h after the start of a shift; a maximum of 15 boats is stored by the end of the shift. The operation occurs for 19 consecutive shifts each week.

- AS, MO_2 powder received at the compactor feed hopper during the previous hour, 27-33 kg MO_2 . (An additional 7.5-12.5 kg MO_2 are received at the beginning of the simulation for startup.)
- HU, inventory in the press feed hopper after the event, 5-10 kg MO_2 .
- DV, accumulated holdup in the pelleting operation, in kg MO_2 ; $\Delta\text{DV} = 0.015\text{-}0.030$ kg MO_2 /boat.
- BO, contents of a loaded green-pellet boat, 14.95-15.0 kg MO_2 .
- BI, inventory in the compactor feed hopper after the event, in kg MO_2 .
- XM, inventory after the event in the green-pellet boats stored on the mechanical conveyor, in kg MO_2 .

3. Process, End of Shift

- BO, the last boat of the shift that is loaded, 14.95-15.0 kg MO_2 .
- SM, clean scrap that is collected in containers, 0.5-1.5 kg MO_2 .
- WM, dirty scrap and waste that is sent to MWT, 0-1.2 kg MO_2 .
- HU, contents of the press feed hopper at the end of the shift, 5-10 kg MO_2 .
- DV, accumulated holdup at the end of the shift, in kg MO_2 ; $\Delta\text{DV} = 0.015\text{-}0.030$ kg MO_2 /boat.
- BI, contents of the compactor feed hopper at the end of the shift, in kg MO_2 .

- XM, inventory in green-pellet boats stored on the conveyor to sintering at the end of the shift, in kg MO_2 .

4. Final. Load the final boats of the blend and clean up the pelleting process.

- BO, final green-pellet boats that may consist of one partially loaded boat (~ 15 kg MO_2) or one full and one partially loaded boat, in kg MO_2 .
- BU, residual holdup in the pellet press feed hopper after runout, in kg MO_2 .
- BI, residual holdup in the compactor feed hopper after runout, in kg MO_2 .
- SM, clean scrap from runout of the compactor and press feed hoppers, and from cleanup of holdup sent to clean scrap storage, in kg MO_2 .
- DV, residual holdup after cleanup, 2 kg MO_2 minimum.
- XM, final inventory in green-pellet boats, in kg MO_2 .

II. Sintering and Sintered-Pellet Storage (9,10)

1. Initial

- BU, initial inventory in the sintering furnaces, in kg MO_2 .
- XM, initial inventory in pellet boats at sintered-pellet storage, in kg MO_2 .

2. Process. A green-pellet boat is input to a sintering furnace, and a sintered-pellet boat is removed from a furnace and sent to storage. One output sintered-pellet boat is returned to the input stream for resintering each shift, on the average. Events occur every 1/2 h and 21 consecutive shifts occur each week.

- BI, one green-pellet boat input to the sintering furnaces, 14.95-15.0 kg MO_2 .
- SM, the contents of a sintered-pellet boat that has been rejected to clean scrap storage, in kg MO_2 .

- WM, dirty scrap that is sent to MWT from a QC-released sintered-pellet boat, 0-0.02 kg MO_2 /boat.
  - AS, samples sent to the ASF from a QC-released sintered-pellet boat, 0.01 kg MO_2 /boat.
  - BO, one boat output from the sintering furnaces, 14.95-15.0 kg MO_2 :
    - (1) If the boat is rejected to clean scrap, its content is stored in SM, and BO is set to zero;
    - (2) If the boat is sent for resintering, BO is the total content of the boat;
    - (3) If the boat is QC-released, BO is reduced by the amount of dirty scrap and analysis samples (WM and AS).
  - XM, inventory in sintered-pellet boats at sintered-pellet storage at the end of the event, in kg MO_2 .
- 3. Final**
- HU, final inventory in the sintering furnaces, in kg MO_2 .
  - XM, final inventory in sintered-pellet storage, in kg MO_2 .

1. Pellet Grinding and Tray Storage (11,12)

1. Initial

- BI, initial contents of the pellet feeder, in kg MO_2 .
- HU, initial in-process material in the grinder, in kg MO_2 .
- DV, initial holdup, 2 kg MO_2 minimum.
- XM, initial inventory in finished pellet trays at tray storage, in kg MO_2 .

2. Process, Sintered-Pellet Boats Unloaded and Trays

Loaded. Events are scheduled every 0.5 h starting 0.3 h after a shift begins until 7.5 h after the start of the shift.

Sintered-pellet boats can be unloaded to the pellet feeder in two out of every three events (there is a maximum of 15 boats per shift), but no boat can be unloaded if less than five boats are in sintered-pellet storage, or if less than 1 h remains in

the shift. Trays are loaded at each event, starting 0.6 h after a shift begins until 7.5 h after the start of the shift (there is a maximum of 24 trays per shift). All trays are completely filled. The pellet feeder and grinder are run out by the end of the shift. The operation occurs for 19 consecutive shifts each week.

- BI, contents of a sintered-pellet boat that is unloaded to the pellet feeder, 14.95-15.0 kg MO_2 .
- BO, contents of a tray loaded with finished pellets that is sent to tray storage, 9.0 kg MO_2 .
- HU, in-process material at the grinder at the end of the event, 5-10 kg MO_2 .
- SM, dried grinder sludge that is collected in a container as clean scrap, 0.2-0.4 kg MO_2 /tray.
- DV, accumulated holdup in the grinding operation, in kg MO_2 ; $\Delta \text{DV} = 0-0.01$ kg MO_2 /tray.
- XM, pellet feeder content at the end of the event, in kg MO_2 .

3. Process, End of Shift. The pellet feeder and grinder are run out, and usable pellets are returned to the input stream.

- BO, retrievable finished pellets at the end of the shift that are returned to the input stream, in kg MO_2 .
- HU, residual holdup in the grinder and pellet feeder after runout, in kg MO_2 .
- SM, one tray rejected and transferred to a clean scrap container, 9 kg MO_2 .
- WM, dirty scrap and waste from the previous shift of grinding operation that is sent to MWT, 0-1 kg MO_2 .
- AS, analysis samples that are sent to the ASF, 0.04 kg MO_2 .
- XM, inventory in finished pellet trays at tray storage at the end of the shift, in kg MO_2 .

4. Final

- SM, holdup that is cleaned up and stored as clean scrap, in kg MO_2 .
- DV, final holdup after cleanup, 2 kg MO_2 minimum.
- XM, final inventory in the tray storage area, in kg MO_2 .

J. Rod Loading, Repair, and Storage (13-17)

1. Initial

- HU, initial inventory of MO_2 contained in rods at the loading or repair station, in kg MO_2 .
- DV, initial holdup, primarily in the rod repair glove-box, 0.1 kg MO_2 minimum.
- XM, initial inventory in QC-released rods at rod storage, in kg MO_2 .

2. Process. The accumulated material unloaded from pellet trays is updated, and one channel (50 rods) is sent to rod storage. Events occur at 3.5 and 7.0 h after the start of the shift. The operation occurs for 20 consecutive shifts each week.

- BI, finished pellets that have been sent in trays to rod loading since the last event, 99 kg MO_2 (11 trays). If the in-process inventory at rod loading is less than 10 kg MO_2 , an additional tray is input; if it is greater than 50 kg MO_2 , one less tray is input.
- BO, one channel containing 50 rods sent to rod storage, 100 kg MO_2 .
- HU, in-process inventory at rod loading and repair after the event, in kg MO_2 .
- DV, accumulated holdup after the event, in kg MO_2 .
- XM, inventory in QC-released rods at rod storage after the event, in kg MO_2 .

3. Process, End of Shift

- SM, clean scrap that is collected in containers, 2-3 kg MO_2 .

- WM, waste that is sent to MWT, 0-0.3 kg MO_2 .
- DV, accumulated holdup at the end of the shift, in kg MO_2 ; $\Delta\text{DV} = 0-0.1$ kg MO_2 each shift, primarily in the rod repair glovebox.
- HU, in-process inventory in rod loading and repair at the end of the shift, in kg MO_2 .
- XM, inventory in rod storage at the end of the shift, in kg MO_2 .

4. Final

- SM, in-process holdup, not in rods, that is cleaned up and stored as clean scrap, in kg MO_2 .
- WM, holdup that is cleaned up and sent as waste to MWT, in kg MO_2 .
- HU, residual in-process material contained in rods, in kg MO_2 .
- DV, residual holdup after cleanup, 0.1 kg MO_2 minimum.
- XM, final inventory in rod storage, in kg MO_2 .

K. Clean Scrap Recovery System (18)

1. Initial

- SM, initial inventory in clean scrap containers at clean scrap storage, in kg MO_2 .
- HU, initial holdup in the clean scrap reactor, in kg MO_2 .
- DV, initial holdup in the CSRS, 2 kg MO_2 minimum.
- XM, initial contents of the recycle MO_2 tank that will receive reprocessed powder from the CSRS, in kg MO_2 .

2. Process. The reactor is charged with a batch of clean scrap from storage that is processed to usable MO_2 powder and sent to the recycle MO_2 storage tank. If a sub-blend has been rejected from a silo to recycle MO_2 storage, no batch is sent from the CSRS to storage during that shift. If the inventory in clean scrap storage is less than 35 kg MO_2 , no batch is processed at the CSRS. If the inventory in the recycle MO_2

tank being filled exceeds 700 kg MO_2 , the CSRS operation is suspended until the following week. Events are scheduled at the end of each shift. The operation normally occurs for 20 consecutive shifts each week.

- BI, one batch sent to the reactor from clean scrap storage (at the start of the shift), 25-35 kg MO_2 .
- SM, inventory in clean scrap storage at the end of the shift, in kg MO_2 .
- HU, holdup in the reactor after the event, 10-15 kg MO_2 .
- WM, waste sent to MWT, 0-0.2 kg MO_2 .
- DV, accumulated holdup at the end of the shift, in kg MO_2 ; $\Delta\text{DV} = \text{DF} \cdot \text{BI}$, $\text{DF} = 0.001-0.002$, holdup factor.
- BO, a processed batch that is sent to the recycle MO_2 storage tank from the CSRS, in kg MO_2 .
- XM, inventory in the recycle MO_2 storage tank at the end of the shift, in kg MO_2 . This includes reject sub-blends from MO_2 storage silos.

3. Final

- SM, final inventory in clean scrap storage, in kg MO_2 .
- HU, final holdup in the clean scrap reactor, in kg MO_2 .
- WM, holdup that is cleaned up and sent as waste to MWT, in kg MO_2 .
- DV, final accumulated holdup after cleanup, 2 kg MO_2 minimum.
- AS, samples from the filled recycle MO_2 storage tank sent to the ASF, 0.027-0.033 kg MO_2 .
- XM, final inventory in the filled recycle MO_2 storage tank, in kg MO_2 .

I. Analytical Services Facility

1. Initial

- XM, initial inventory in the ASF, in kg PuO_2 .

2. Process. Update the ASF inventory at the end of the shift. The operation is one shift each day for six consecutive days each week.

- BI, total samples input since the last event, in kg PuO_2 equivalent.
- XM, inventory in the ASF at the end of the shift, 0.3-0.9 kg PuO_2 equivalent. To determine the amount of scrap and waste sent to MWT from the ASF, let $R = XM(\text{last}) + BI - XM(\text{now})$. If $R < 0$, then $XM(\text{now})$ is set equal to $XM(\text{last}) + BI$, and SM and WM are set to zero. If $R > 0$, scrap and waste are sent to MWT as follows:
  - (1) SM, 0.8 R is sent as scrap to MWT, in kg PuO_2 equivalent.
  - (2) WM, 0.2 R is sent as waste to MWT, in kg PuO_2 equivalent.

3. Final

- BI, input samples since the last event, in kg PuO_2 equivalent.
- XM, final inventory in the ASF, in kg PuO_2 equivalent.

M. Miscellaneous Waste Treatment

1. Initial

- SM, initial inventory of dirty scrap at MWT and in the dirty scrap storage area, in kg PuO_2 equivalent.
- WM, initial inventory of waste at MWT and in the waste storage area, in kg PuO_2 equivalent.

2. Process. Update the accumulated scrap and waste at MWT since the last event. Operation is one shift each day for six consecutive days each week.

- BI, input scrap and waste since the last event, in kg PuO_2 equivalent.
- SM, scrap inventory at the end of the shift, in kg PuO_2 equivalent.
- WM, waste inventory at the end of the shift, in kg PuO_2 equivalent.

3. Final

- BI, input scrap and waste since the last event, in kg PuO_2 equivalent.
- SM, final scrap inventory at MWT, in kg PuO_2 equivalent.
- WM, final waste inventory at MWT, in kg PuO_2 equivalent.

III. MOXSIM RESULTS

Although all of the most important unit processes have been simulated, the volume of data is too great for complete presentation. Results are given for only two unit processes, PuO_2 powder unloading and pelleting. Figures D-1(a)-(g) show material flow data generated by MOXSIM for a typical week of PuO_2 powder unloading operation.

Fig. D-1(a). PuO_2 canister contents.

ML PLUO

TIME

Fig. D-1(b). PuO_2 powder transferred to the bulk storage vessel.

Fig. D-1(c). Residual waste in empty canisters and from cleanup operations.

Fig. D-1(d). PuO₂ powder holdup at the routing valve in the pneumatic transfer line.

KG-PJ02

Fig. D-1(e). Samples taken from each canister and from the bulk storage vessel for analysis.

KG-PJ02

Fig. D-1(f). Accumulated PuO_2 powder holdup in the unloading station.

45-P-102

17

100

200

TIME-H

Fig. D-1(g). PuO_2 inventory in the bulk storage vessel.

Typical material flow data generated by MOXSIM for a week of pelleting operation are shown in Figs. D-2(a)-(h). Vertical scales are expressed in terms of kilograms of PuO_2 ; the MO_2 equivalent is 25 times the PuO_2 amount.

Fig. D-2(a). NO₂ powder inventory in the compactor feed hopper.

Fig. D-2(b). Contents of green-pellet boats (individual boats are not resolved).

Fig. D-2(c). MO_2 powder inventory in the press feed hopper.

Fig. D-2(d). Accumulated MO_2 powder held up in the pelleting station.

Fig. D-2(e). Clean MO, scrap from pelleting and cleanup operations.

Fig. D-2(f). Dirty scrap and waste from the pelleting operation.

MATERIAL, KG-MIN

TIME - H

200.

Fig. D-2(g). NO_2 powder flow (integrated each hour) from the storage silos into the compactor feed hopper.

MATERIAL, KG-MIN

TIME - H

100

200

Fig. D-2(h). Inventory in green-pellet boats on a conveyor to the sintering furnaces.

APPENDIX E

ALGORITHMS FOR DIVERSION DETECTION

The sensitivity of the MMAS can be determined quantitatively by analyzing simulated materials measurement data (see Chap. IV). The measurements provide at least approximate closures of material balances around each unit process. Analysis algorithms are applied to the material balance measurement data to detect both short-term and long-term diversions of material. This appendix describes the detection algorithms developed to evaluate the performance of the MMAS.

I. SHORT-TERM DIVERSION

Short-term diversion refers to the single theft of a relatively large amount of nuclear material. Lawrence Livermore Laboratory (LLL) has developed design curves that establish alarm levels for the detection of a single-theft event.⁸ LLL assumed that in-process holdup could not be measured or otherwise estimated. Therefore, the algorithms required uniform operation of the process so that diversion indicators could be based on the difference between measured and expected output.

Design curves for establishing alarm levels in a system based on unit process material balances (i.e., measured in-process holdup and material sidestreams) look identical to those given by LLL. However, interpretation of some of the parameters is different.

Design curves for single-theft detection are based on conventional probability arguments. Consider a true material balance for a unit process, and assume that it is normally distributed with mean B and variance σ^2 . Estimates of B and σ^2 are obtained from the measurement of input, output, scrap,

waste, and holdup during the balance period. The true mean value B is nonzero if there are unmeasured sidestreams, holdup, or diverted material. Ideally, all process material flows and holdup are measured so that B = 0 in the absence of diversion. In practice, some in-process material may not be measured because the amount of material is so small that the measurement difficulty and expense are not justified. In this case, system sensitivity to diversion is reduced because unmeasured in-process material cannot be distinguished from diverted material. The situation can be improved if an estimate of unmeasured in-process material can be based on historical data. Procedures are given below for detecting a nonzero value of a measured material balance, whatever its cause.

A. False-Alarm Probability (FAP)

The false-alarm probability (FAP) is the probability that a theft will be indicated when none has occurred. The value of FAP can be set independently of the single-theft detection probability (DP). If each material balance is normally distributed, the value of FAP for a particular balance is given by

$$FAP(n) = \int_{n\sigma}^{\infty} \frac{dx}{\sqrt{2\pi}\sigma^2} \exp(-x^2/2\sigma^2) ,$$

where σ is the standard deviation of that balance, and n is a positive number. With the customary change of variable, $y = x/\sigma$, the equation for FAP becomes

$$FAP(n) = \int_n^{\infty} \frac{dy}{\sqrt{2\pi}} \exp(-y^2/2) . \quad (1)$$

Thus, the FAP is determined by specifying the value of n , which is sometimes called the alarm level (AL). In Fig. E-1 the FAP is plotted as a function of AL measured in σ -units. For example,

Fig. E-1. FAP as a function of AL.

if the AL is set at 1, 2, or 3 σ , corresponding FAP values are 0.159, 0.023, and 0.0013.

B. Detection Probability (DP)

The DP is the probability that a truly nonzero material balance B will be detected for a specified AL. For a normally distributed material balance, the value of DP is given by

$$DP(n) = \int_{n-B}^{\infty} \frac{dx}{\sqrt{2\pi}\sigma} \exp[-(x-B)^2/2\sigma^2] .$$

By a change of variable, and expressing n and B in σ -units, the DP becomes

$$DP(n) = \int_{n-B}^{\infty} \frac{dy}{\sqrt{2\pi}} \exp(-y^2/2) . \quad (2)$$

Note that if B = 0, the DPs and FAPs are equal. In Fig. E-2, the DP is plotted as a function of the mean material balance B for several values of the AL: AL = n. The probability of a miss (not detecting a truly nonzero value of B) is plotted in Fig. E-3. The nondetection probability (NDP) is equal to 1 - DP.

Figures E-1 to E-3 are the design curves for single-theft detection. For example, if AL = 3 σ , corresponding to approximately one false alarm in 1000 material balances, the probability of detecting a nonzero balance of magnitude B is given in Table E-1.

The relationships among AL, FAP, and DP or NDP are shown in Fig. E-4. As AL is increased, the FAP decreases, but the probability of detecting theft of a given amount of material also decreases. The trade-off between a minimum number of false alarms and maximum sensitivity to theft is obvious.

Fig. E-2. DP vs magnitude of diversion for several values of AL .

Fig. E-3. Probability of not detecting a diversion of magnitude B for several values of AL .

Fig. E-4. Relationship among AL, FAP, and DP for no diversion and for diversion of magnitude B. The DP is the sum of the two shaded areas.

TABLE E-1

DETECTION AND MISS PROBABILITIES

<u>B/c</u>	<u>DP</u>	<u>NLP</u>
1	0.023	0.977
2	0.159	0.841
3	0.500	0.500
4	0.841	0.159
5	0.977	0.023
6	0.999	0.001

C. Procedure for Single-Theft Detection

For clarity, we include the procedure for using the single-theft design curves. Consider the i^{th} material balance of a unit process with true mean value B_i and standard deviation σ_i . Let x_i be an estimate of B_i obtained from measurements of input, output, scrap, waste, and holdup; s_i is an estimate of σ_i obtained from a propagation-of-error analysis based on individual measurement uncertainties. The estimator for σ_i must be specific to the measuring devices and calibration procedures used to close the i^{th} material balance. The design curves, shown in Figs. E-1 to E-3, are used with x_i/s_i as an estimate of B_i/c_i to test if diversion is indicated.

For example, if $x_i/s_i = 5$, the probability that a bias of this magnitude would be detected is 98% at the 3σ AL, and immediate action should be taken. If $x_i/s_i = 2$, the DP is only 0.16 at the 3σ AL and 0.50 at the 2σ AL (with a false-alarm rate of 1 in 25). The latter case would be noted, and the analyst would monitor subsequent material balances to see if a trend was developing. Detection of trends is the subject of the next section.

13. LONG-TERM DIVERSION

Long-term diversion refers to repeated thefts of nuclear material, each too small to be detected because of measurement uncertainties. Detection of repeated small thefts is based on identifying the presence of trends in process operations. The cusum control chart has been effective for detecting trends in industrial process data.⁷³ Past experience at LASL with cusums of material balances indicates that the cusum chart provides graphic evidence of repeated small amounts of unmeasured material.⁷⁴

Identification of trends is one aspect of the problem, but it is equally important to quantify the loss. One suggested approach applies linear filtering techniques (e.g., the Kalman filter) to materials measurement data. In this approach, predictions from a process model are compared with measurements of process operation. A thorough evaluation of the method applied to detailed process models is not yet available for fuel cycle plants. The assumption that fuel cycle plant processes can be modeled realistically as linear systems is questionable. However, the approach merits further study, particularly as an aid in extracting redundant information available in material balance data from adjacent unit processes.

A. Cusum Charts and V-Masks

An alternative approach, used successfully to evaluate industrial process operation, is the use of V-masks in conjunction with the cusum chart.⁷⁵ Figure E-5 is a cusum chart of material balance data from a fictitious batch-operated unit process. Each data point represents the cusum of measured material balances. The positive trend in the cusum data, beginning about balance number 7, indicates that the material balances have a positive bias. The fact that the slope of the data is roughly constant from balances 7 to 23 suggests that the positive bias of each balance is nearly constant during this period.

Fig. E-5. Cusum chart and V-mask for a fictitious process. The parameters h and k determine the V-mask sensitivity.

The V-shaped mask in Fig. E-5 is a geometric construction applied to cusum data to determine the presence of out-of-control (alarm) conditions. The V-mask is applied to each successive cusum data point; if any previous point falls outside the arms of the V, an alarm condition is set. The V-mask sensitivity is determined by two parameters: a reference level k and a decision level h . The value of k determines the slope of the V-mask, $k = w \tan \theta$, and the value of h determines the distance d from the vertex to the current cusum data point, $h = wd \tan \theta$; w is a scaling factor applied for plotting purposes. A suggested rule of thumb is to set the reference level k to $\sigma/2$ and the decision level h to 3σ , where σ is the standard deviation of each material balance.

Two parameters, the AL and the material balance standard deviation, govern the sensitivity to single-theft detection. A third parameter, the average runlength L , must be added for detection of repeated thefts. The average runlength is that length of a sequence of process data points required to detect an out-of-control condition, on the average. In general, the average runlength is smaller for the cusum chart and V-mask technique than for the standard method of charting individual process data points and their standard deviations; i.e., the V-mask technique is more sensitive to small changes in process operation.⁷⁶ Some improvement in V-mask sensitivity for moderate deviations from average process operation, viz., the 1σ to 3σ range, has been obtained by replacing the region near the vertex with a parabolic contour.

The V-mask technique for detection of repeated small thefts of nuclear material is still under development. V-mask theory^{75,76} is based on the assumption of independent process variables having constant and equal variance; the V-mask parameters are chosen ad hoc. The treatment given here includes a procedure for choosing the V-mask parameters h and k that is based on probability arguments, and provides quantitative estimates of FAP and DP. It is rigorous only for the case of

independent, normally distributed material balances with equal variances. In the case of unequal variances, the analysis is more complex and the present treatment is only approximate.

B. Analytic V-Masks

The graphic V-mask, Fig. E-5, has a straightforward analytic representation. Consider a set of material balances for a unit process, each normally distributed such that the i^{th} balance has mean b_i and variance σ_i^2 . The cusum obtained from a sequence of length ℓ of such material balances is

$$C_\ell = \sum_{i=1}^{\ell} b_i.$$

The V-mask can be used to test for either positive or negative bias. We shall consider only the V-mask test for a true positive bias, i.e., for diverted material and/or unmeasured process sidestreams. The test requires evaluation of the sum,

$$S_\ell = \sum_{i=1}^{\ell} (b_i - k),$$

where k is the V-mask reference level. Note that this sum is related to the cusum by $S_\ell = C_\ell - \ell k$. The V-mask test for an alarm condition (a true positive bias) has two steps.

(1) If $S_\ell < 0$, set the sum to zero and begin a new sequence; i.e., $S_\ell = \max\{0, S_{\ell-1} + b_\ell - k\}$.

(2) Let h be the V-mask decision level. If $S_\ell \geq h$, set an alarm condition.

The cusum C_ℓ is an estimate of the total bias for a sequence of material balances of length ℓ . The average bias B_ℓ is related to the cusum by

$$\begin{aligned} B_\ell &= \frac{1}{\ell} \sum_{i=1}^{\ell} b_i \\ &= \frac{1}{\ell} C_\ell \\ &= \frac{1}{\ell} S_\ell + k \end{aligned} \quad (3)$$

If the V-mask alarm condition is just satisfied ($S_k = h$) the average bias is

$$B_k = k + \frac{h}{l}$$

The variance B_k^2 of the average bias is related to the cusum variance c_C^2 by

$$B_k^2 = \frac{1}{l} c_C^2 \quad (4)$$

Note that the cusum variance is equal to the sum of the individual material balance variances ($c_C^2 = \sum \sigma_i^2$) only if the balances are independent. This is seldom true for balances based on nuclear materials measurements.

The dependence of the cusum variance on the runlength l is linear for independent balances with equal variance. In general, the dependence of the cusum variance on l is only approximately linear. We shall assume that $c_C^2 \propto l$ and define an average variance $\bar{\sigma}^2$ by

$$\bar{\sigma}^2 = \frac{1}{l} c_C^2 \quad (5)$$

where $\bar{\sigma}^2$ is only weakly dependent on l . The effect of a weakly l -dependent $\bar{\sigma}^2$ on the following analysis is under investigation.

C. V-Mask False-Alarm Probability

The V-mask AL is $k + h/l$ so that the FAP (see Appendix E-I-A) is

$$FAP = \int_{k + h/l}^{\infty} \frac{dx}{\sqrt{2\pi\sigma_B^2}} \exp(-x^2/2\sigma_B^2)$$

Noting that $\sigma_B^2 = \bar{\sigma}^2/l$ and transforming the integral to standard form gives

$$\text{FAP} = \int_{n(\ell)}^{\infty} \frac{dy}{\sqrt{2h}} \exp(-y^2/2),$$

where the lower limit is

$$n(\ell) = k\sqrt{\ell} + h/\sqrt{\ell}. \quad (6)$$

The variables n , k , and h have been expressed in units of $\bar{\sigma}$.

The function $n(\ell)$ has a minimum at $\ell = h/k$ that is equal to $2\sqrt{kh}$. Therefore, specifying the V-mask parameters k and h determines the maximum FAP. Further, this maximum FAP corresponds to an AL of $2\sqrt{kh}$ and occurs for a runlength of h/k . Setting $2\sqrt{kh} = n$ (σ -units) thus ensures that the FAP for any runlength will be less than or equal to the FAP corresponding to n .

D. V-Mask Detection Probability

The DP for a true, nonzero average bias B_ℓ is

$$\text{DP} = \int_{k+h/\ell}^{\infty} \frac{dx}{\sqrt{2\pi\sigma_B^2}} \exp[-(x-B_\ell)^2/2\sigma_B^2]$$

Again, transforming the integral to standard form and expressing the lower limit in units of σ gives

$$\text{DP} = \int_{m(\ell)}^{\infty} \frac{dy}{\sqrt{2\pi}} \exp(-y^2/2),$$

where

$$m(\ell) = k\sqrt{\ell} + h/\sqrt{\ell} - B_\ell\sqrt{\ell}. \quad (7)$$

If the lower limit $m(l)$ is set equal to $-n$, where n is the parameter that fixes the maximum FAP, then DP is related to FAP by

$$DP(n) = 1 - FAP(n) \quad (8)$$

independent of the runlength l . Note that if $n = 0$, DP and FAP are both equal to $1/2$. Alternatively, if the runlength is $l = h/(B_l - k)$, $m(l)$ in Eq. (7) is zero and $DP = 1/2$, independent of the value of FAP. The usual definition of average runlength L implies that the DP is $1/2$, that is, $L = h/(B_l - k)$ for the simple V-mask. We shall derive an average runlength L for any value of DP specified by the parameter n .

With $m(l)$ set to $-n$, Eq. (7) can be solved for l in terms of n , the V-mask parameters k and h , and the average bias B_l . Further, the condition $n = 2\sqrt{kh}$ obtained from the FAP is used to eliminate h . Then by letting k be proportional to B_l ($k = c \cdot B_l$) the proportionality constant c can be chosen to minimize the runlength l . The results are

$$k = B_l/4 \quad \text{and} \quad h = n^2/B_l \quad (9)$$

where the choice of n determines the maximum FAP, $FAP(n)$, and the DP, $DP(n)$, for an average bias B_l . The average runlength L for a fixed value of n and bias B_l is

$$L = 4(n/B_l)^2 \quad (10)$$

As noted previously, the average runlength corresponding to a DP of $1/2$ is $h/(B_l - k)$, independent of FAP. Thus, we find that the runlength for $DP = 1/2$ is equal to $L/3$, one-third the runlength for $DP(n)$. The average runlengths corresponding to $DP(n)$ and $DP = 1/2$ are plotted in Fig. E-6.

Fig. E-6. Average runlengths that produce V-mask alarms. The parameter n specifies the FAP and DP; B is the average bias in the material balances forming a sequence of length L .

E. Implementing the V-Mask Method

The V-mask analysis provides a reasonable method for selecting the parameters h and k , which set the V-mask sensitivity. Equally important, it provides quantitative estimates of the FAPs and DP that help the analyst decide whether an alarm condition signifies a real diversion. On the other hand, the analysis is still incomplete and should be used with caution. The method must be evaluated on the basis of its performance using data from detailed simulations of unit process operations and materials control measurements. Experience indicates that the V-mask alarms always correspond to positive trends in the cusum that can be identified visually.

The following steps describe a procedure for implementing the V-mask method. One should keep in mind that visual inspection of the cusum chart of material balances is perhaps the most sensitive method for detecting trends caused by repeated small losses of SNM. The V-mask test provides confirmation that a real loss has occurred and estimates the amount of material lost.

(1) Set the desired FAP and DP by fixing n in units of $\bar{\sigma}$. The analysis should be repeated for several values of n , i.e., varying FAP and DP. In Table E-2, values of DP and FAP are given for several values of n . Note that the probability of a miss (NDP) is equal to the FAP by construction.

TABLE E-2
DETECTION AND FALSE-ALARM PROBABILITIES

<u>$n/\bar{\sigma}$</u>	<u>FAP</u>	<u>DP</u>
1.0	0.159	0.841
1.5	0.067	0.933
2.0	0.023	0.977
2.5	0.006	0.994
3.0	0.001	0.999

(2) Set the average runlength equal to the current total runlength, $L = l$. Note that the analysis is repeated as each material balance measurement is added to the cusum.

(3) Obtain the current estimate of $\bar{\sigma}$ from the cusum standard deviation σ_C : $\bar{\sigma} = \sigma_C / \sqrt{L}$. We assume that an estimate of σ_C has been made from the measurement errors.

(4) Set the minimum detectable average bias B and the V-mask parameters h and k :

$$B/\bar{\sigma} = 2(n/\bar{\sigma})/\sqrt{L},$$

$$h/\bar{\sigma} = (n/\bar{\sigma})(n/B),$$

$$k/\bar{\sigma} = B/4\bar{\sigma}.$$

(5) Apply the analytic V-mask test to the total sequence of measured material balances using the current values of h and k . If an alarm condition is encountered, go to step (6); if not, return to step (2).

(6) The V-mask alarm condition has been satisfied by a subsequence of length $L' \leq L$. If a previous alarm condition has been set for sequence L' at level n , go to step (10). If not, compute the average bias B' over sequence L' ,

$$B' = \frac{1}{L'} \sum_{i=q}^p b_i,$$

where q and p are the initial and final points of sequence L' . In terms of cusums, the value of B' is

$$B' = (C_p - C_q)/L'.$$

(7) Obtain an estimate of $\bar{\sigma}'$ for sequence L' from the cusum variances. A simple estimate is given by

$$\bar{\sigma}' = \left[(\sigma_{C_p}^2 - \sigma_{C_q}^2) / L' \right]^{1/2},$$

where $L' = p - q + 1$.

(8) Obtain an estimate of $(n'/\bar{\sigma}')$ for sequence L' from

$$n'/\bar{\sigma}' = B' \sqrt{L'/2\bar{\sigma}'}$$

(a) If $n' < n$, reject the alarm and go to step (10); i.e., continue the search. Note that if $n' < n$, the FAPs and DPs for sequence L' are $FAP(n') > FAP(n)$ and $DP(n') < DP(n)$.

(b) If $n' \geq n$, the alarm condition is accepted, i.e., $FAP(n') \leq FAP(n)$ and $DP(n') \geq DP(n)$; go to step (9).

(9) An alarm condition has been accepted. Save the following parameter values:

B' the average bias over sequence L' ,
 L' the subsequence length with end points q and p ,
 $\bar{\sigma}'$ the average standard deviation of sequence L' ,
 $n'/\bar{\sigma}'$ determines $FAP(n')$ and $DP(n')$ for sequence L' ,
 B the current minimum detectable average bias,
 L the current total sequence length,
 $\bar{\sigma}$ the current average standard deviation, and
 $n/\bar{\sigma}$ determines the current $FAP(n)$ and $DP(n)$.

(10) Continue to search through the total sequence starting at material balance number $(p + 1)$; go to step (5).

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New Canaan, CT 16840
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