SAFETY ANALYSIS OF THE TRANSPORTATION OF HIGH-LEVEL RADIOACTIVE WASTE

by E. S. Murphy and W. K. Winegardner

Battelle
Pacific Northwest Laboratories
Richland, Washington 99352

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I. INTRODUCTION

An analysis of the risk from transportation of solidified high-level radioactive waste is currently being performed at Battelle's Pacific Northwest Laboratories. The analysis is part of a comprehensive study of the management of high-level waste which is being done by Battelle-Northwest for the Energy Research and Development Administration.

Risk studies of waste management systems permit the consequences of an accidental release of radioactivity to be placed in perspective by relating the magnitude of release to the probability of occurrence of the release. Results of studies on conceptual systems can be used to guide the formulation of waste management policy.

This paper describes the program presently being conducted to assess the risk of transporting solidified high-level waste from a fuel reprocessing plant to a retrievable storage facility at a Federal Repository. Goals of the transportation risk analysis program are enumerated, and the methodology being used to accomplish these goals is outlined. The methodology utilizes fault trees to identify failure events and to specify combinations of events which could result in breach of containment and a release of radioactive material to the environment.

The management scheme for transportation of solidified high-level waste includes packaging the waste in stainless steel canisters which
are then sealed inside 100-ton casks for shipment by railroad. Progress in quantification of the transportation risk is reported. Events capable of producing containment failure during shipment include (1) railroad accidents, (2) natural disasters, (3) physical or chemical reactions induced by the radioactive waste, and (4) monitoring and package closure errors. Preliminary data indicate that the highest risk events are those related to railroad accidents. Detailed evaluation of dominant failure sequences (i.e., failure sequences which result in the highest risk) is continuing.

Original contributions to the development of risk methodology are described. Contributions include procedures for screening failure sequences to determine those which dominate the risk, methods for quantifying the effects of probabilistic failure events, and computer code development.

The paper concludes with a statement of activities still to be performed which will enable the risk from transportation to be placed in proper perspective with regard to other operations of the reference waste management system and with regard to other risks experienced by man.

II. BACKGROUND

A representative scheme for the management of high-level waste in the year 2000 is shown conceptually in Figure 1. In the management scheme the high-level liquid waste resulting from reprocessing spent fuel is initially stored as a nonboiling nitric acid solution in stainless steel-lined concrete vaults. After a decay period of about three years, the liquid waste is solidified by calcination. The resulting calcine may then
FIGURE 1. Management scheme for high-level waste
be incorporated into a glass-ceramic monolith. In any case, the solidified waste is placed in sealed metallic canisters. The canisters accumulate at the reprocessing plant in a water-filled basin until the total post-processing age of the waste is ten years. The canisters are then shipped in sealed metal casks to a Federal Repository for retrievable storage. This paper describes the program being conducted to assess the risk of transporting solidified high-level waste.

Specific goals of the waste management risk program are to:

- Define a reference waste management system.
- Specify and develop data and methods needed to quantify risk.
- Quantify risk and relate it to risks from other components of the reference waste management program and to risks from other activities of man.
- Identify operations which result in disproportionately high risk.
- Evaluate system alternatives that can reduce risk.
- Identify research and development needs.

Program methodology is based on establishing a quantitative measure of risk where risk (in units of consequences per unit time) is defined as the product of frequency of system failure (events per unit time) and magnitude of system failure (consequences per event).

III. TECHNICAL APPROACH

Steps in the program leading to a quantitative assessment of the risk from transportation of solidified high-level waste are shown schematically in Figure 2.
FIGURE 2. Steps in transportation risk analysis
The first steps consist of detailed descriptions of the waste and of the system for confinement of the waste during transportation. These descriptions provide needed information for construction of a fault tree which identifies sequences of events that can result in a release of radioactive material to the environment. Fault tree analysis is used for the identification of failure sequences since it is a graphic as well as a deductive technique. Deductive techniques are preferred to inductive ones since the former force thinking in the direction of attempting to postulate all possible ways that things could have gone wrong. Graphic models are excellent for obtaining feedback and for communicating the scope of what has been done.

When the fault tree has been constructed, and failure rates and release fractions have been assigned to individual failure events in the tree, analytical techniques which make use of computer codes are used to identify failure sequences and to evaluate these sequences on the basis of probability and of risk. In this way the dominant failure mechanisms are identified and ranked.

For the dominant failure sequences, the quantity and rate of release of radioactivity near the point of failure are estimated as a function of the severity of the failure event. Information about the radioactive release is then combined with population distribution data, meteorological and hydrological data, and with information about air, water and food pathways in order to estimate the dose to man integrated over the population.

Release likelihood and consequences are combined to estimate risk. The results can be used for comparative assessments and to provide an
objective guide for decision making. The results form a rational basis for deciding where and if improvements in waste management are needed for the transportation phase of the system. Analysis of failure modes, radiological consequences and risk identify research needs and data and information needs.

A fault tree for a risk analysis study can almost always be constructed with greater detail than is justified by the extent and accuracy of the failure data which is available for evaluation of the tree. Typical fault trees can contain thousands or even millions of failure sequences which may, in theory, contribute to the overall risk from the system. If the investigator is not to be overwhelmed by the magnitude of the evaluation task, it is necessary to devise logical procedures which enable rapid identification of those failure sequences which are the principal contributors to overall system risk. At Battelle-Northwest a method for identification of dominant failure sequences has been developed based on successive rankings in terms of (1) number of events per failure sequence, (2) probability, and (3) risk. By making use of event cut-off, probability cut-off, and risk cut-off criteria, it is possible to reduce the problem to a manageable number of those sequences which dominate system risk.

Several computer codes have been developed at Battelle-Northwest for use with the fault tree and risk analysis studies. Information about these codes is summarized in Table 1. The codes have been constructed in such a way that they permit evaluation of spectrum-type release events. The codes permit identification of all failure sequences, identification of dominant sequences by means of ranking procedures, and risk evaluation
of failure sequences. The risk of each identified failure sequence is determined by coupling the consequences of the postulated release with its likelihood of occurrence.

**TABLE 1.** Computer codes developed at Battelle-Northwest for use with risk studies.

<table>
<thead>
<tr>
<th>Code</th>
<th>Purpose</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>REASON</td>
<td>Check fault tree for errors in logic</td>
<td></td>
</tr>
<tr>
<td>ACORN</td>
<td>Produce computer plot of fault tree</td>
<td></td>
</tr>
<tr>
<td>FAULT</td>
<td>Identify cut sets of a fault tree and calculate their probabilities</td>
<td></td>
</tr>
<tr>
<td>RAFT</td>
<td>Assign release fractions to events in a cut set and order the resulting risk measure terms</td>
<td></td>
</tr>
<tr>
<td>DACRIN</td>
<td>Calculate organ dose from acute or chronic radionuclide inhalation</td>
<td>10</td>
</tr>
<tr>
<td>KRONIC</td>
<td>Calculate annual average external doses from chronic atmosphere releases of radionuclides</td>
<td>11</td>
</tr>
</tbody>
</table>

IV. TRANSPORTATION RISK ANALYSIS

1. **System Description**

   In the year 2000, it is projected\(^{(2,3)}\) that approximately 20,000 ft\(^3\) of 10-year old waste will be transported from fuel reprocessing plants to a Federal Repository. The waste will be in either the calcine or the glass/ceramic form. For rail shipment the waste will be packaged in stainless steel canisters which are sealed inside of heavy lead and steel shipping casks. In the year 2000, a total of about 350 cask shipments with individual trips averaging 2000 miles and requiring from four to ten days for completion will be necessary in order to move the waste to a Federal Repository.
A typical waste canister is expected to be 12 inch I.D. x 10 ft long with 0.38 inch thick stainless steel walls. It will contain approximately 6.3 ft$^3$ (8-ft fill) of solid waste. For 10-year old waste from processing enriched uranium fuel with 33,000 MWD/MT exposure, the heat generation rate per canister will be approximately 3.5 kW.

Detailed cask designs for high-level waste shipment have not yet been submitted by industry for government approval. A conceptual design for a cask 8 ft in diameter by 15 ft long, weighing approximately 100 tons, and capable of transporting nine 12-inch diameter canisters has, however, been described. (3,4) Any conceptual cask and canister must satisfy Energy Research and Development Administration and Department of Transportation regulations (5) which set minimum standards for package integrity under specified accident conditions.

2. Fault Tree Construction

The top levels of the rail transportation fault tree are shown in Figure 3. For a release of radioactive material to occur during rail transportation, both the waste canister and the shipping cask must be breached. The risk study assumes the following possibilities relative to the condition of these containment barriers:

- Transportation with good (non-degraded) containment barriers which are both breached during transportation.
- Transportation with degraded containment barriers which are both breached during transportation.
- Breach of one containment barrier before transportation begins with the second barrier breached during transportation.
FIGURE 3. Top levels of rail transportation fault tree
Initiating events capable of producing containment failures which are included in this study can be grouped into four categories: (1) railroad accidents, (2) natural disasters, (3) physical or chemical reactions induced by the radioactive waste, and (4) monitoring and package closure errors. Individual failure events within each category are listed in Table 2. Because of the difficulty of quantifying intentional activities aimed at breach of confinement, an evaluation of intentional acts was not included in this analysis.

**TABLE 2.** Rail transportation fault tree failure events.

1. Railroad Accident
   - Collision
   - Derailment
   - Other Train Accident

2. Natural Disasters
   - Falling Aircraft
   - Meteorite
   - Tornado
   - Hurricane
   - Earthquake

3. Physical or Chemical Reactions Induced by the Radioactive Waste
   - Corrosion
   - Radiation Damage
   - Pressurization due to Radiolytic Reaction
   - Pressurization due to Temperature Increase

4. Monitoring and Package Closure Errors
   - Failure to Detect Flaws in Packaging Prior to Shipment
   - Package Closure Errors

A spectrum of radioactive releases from the containment system can be associated with each one of the failure initiating events shown in Table 2. The amount of radioactive material released depends on the
prior condition of the containment system, on the severity of the initiating event and on the nature of its interaction with the containment system. In the transportation fault tree, spectrum type releases are indicated by inhibit gates. An example of the use of an inhibit gate in connection with a collision accident is shown in Figure 4. For evaluation of the event shown in Figure 4, conditional probabilities and associated release fractions are assigned to the logic modifier titled "Fraction of Mechanical Environments Causing Containment Failure." The computer code for evaluation of the fault tree permits the use of as many as four conditional probabilities and their associated release fractions for each spectrum-type event described by an inhibit gate.

3. **Fault Tree Evaluation**

Preliminary evaluation of the transportation fault tree for which the primary failure events are shown in Table 2, indicates that the dominant failure sequences are those related to railroad accidents. Natural disasters, which presumably could result in consequences of the same order of magnitude as railroad accidents, are less probable than accidents by three to eight orders of magnitude. Waste induced reactions are also less probable than railroad accidents by about three or four orders of magnitude. Furthermore, waste induced reactions will affect the waste canister but will likely have very little effect on the integrity of the massive shipping cask.

Monitoring and package closure errors occur with about the same frequency as railroad accidents, but normally result in the breach of
CASK AND CANISTER FAIL FROM COLLISION INDUCED MECHANICAL ENVIRONMENT

FRACTION OF MECHANICAL ENVIRONMENTS CAUSING CONTAINMENT FAILURE

SEVERE MECHANICAL ENVIRONMENT ARISES FROM COLLISION

FRACTION OF COLLISIONS WITH SEVERE MECHANICAL ENVIRONMENTS

COLLISION OCCURS

FIGURE 4. Inhibit gate representation of collision accident
only one containment barrier. In addition, monitoring and package closure errors will likely result in smaller radioactive releases than could result from accidents.

Detailed evaluation of the high risk sequences associated with rail transportation of solidified high-level waste is currently being performed. Evaluation of the magnitude and consequences of a radioactive material release requires an understanding of both the frequency and the severity of the forces imposed by failure initiating events.

Some data on frequency-severity relationships for railroad accidents exists in the literature. For example, velocity-frequency distribution tables for derailment and collision accidents\(^{(6,7)}\) indicate that only about one percent of accidents occur at train speeds greater than 60 miles per hour. About 1.5% of rail accidents involve fires.\(^{(8)}\) The extent of damage resulting from a fire is a function of both the temperature of the fire and its time duration. Modeling studies\(^{(7)}\) have been performed to generate temperature-time severity data for fires associated with particular accident environments. Additional research on frequency-severity relationships for railroad accidents will allow more detailed assessment of the risk from transportation of high-level waste. Research in this area is planned both at Battelle-Northwest and at other laboratories.

In evaluating the consequences of a breach of containment which might occur as the result of a railroad accident, the amount of material released will depend, in part, on the waste form. A study of relative release rates of calcine and of glass/ceramic waste has been made\(^{(9)}\) in order to evaluate the performance of the two waste forms with regard to (1) release
upon contact with water, (2) volatization upon exposure to high temperature, and (3) airborne suspension and dispersion of particulates that are either already existing or are created by mechanical forces. The study shows that for all three mechanisms, relatively massive glass/ceramic products are less dispersible and, therefore, superior from an isolation or safety standpoint to the leachable, high surface-to-volume ratio calcines.

V. SUMMARY

An analysis of the risk from transportation of solidified high-level waste is being performed at Battelle-Northwest as part of a comprehensive study of the management of high-level waste. The risk analysis study makes use of fault trees to identify failure events and to specify combinations of events which could result in breach of containment and a release of radioactive material to the environment. Contributions to risk analysis methodology which have been made in connection with this study include procedures for identification of dominant failure sequences, methods for quantifying the effects of probabilistic failure events, and computer code development.

Preliminary analysis based on evaluation of the rail transportation fault tree indicates that the dominant failure sequences for transportation of solidified high-level waste will be those related to railroad accidents. Detailed evaluation of rail accident failure sequences is proceeding and is making use of the limited frequency-severity data which is available in the literature.

In addition to the detailed evaluation of high-risk sequences, other activities still to be performed include (1) sensitivity studies of the
reference system for the purpose of determining the effect of parameter variations and assumptions used on the calculated risk, (2) risk-cost evaluations of alternatives to the reference system, and (3) comparison of the risk from transportation with risks from other operations of the reference waste management system and with other risks experienced by man.
REFERENCES


5. 10 CFR, Part 71; 10 CFR, Parts 170-189.


