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THE ENVIRONMENTAL ASSESSMENT OF NUCLEAR MATERIALS DISPOSITION OPTIONS: A TRANSPORTATION PERSPECTIVE*

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Rodney K. Wilson, David B. Clauss and John W. Moyer
Sandia National Laboratories, Albuquerque, New Mexico USA

ABSTRACT

The U.S. Department of Energy has undertaken a program to evaluate and select options for the long-term storage and disposition of fissile materials declared surplus to defense needs as a result of the end of the Cold War. The transport of surplus fissile material will be an important and highly visible aspect of the environmental impact studies and other planning documents required for implementation of the disposition options. This report defines the roles and requirements for transportation of fissile materials in the program, and discusses an existing methodology for determining the environmental impact in terms of risk. While it will be some time before specific alternatives are chosen that will permit the completion of detailed risk calculations, the analytical models for performing the probabilistic risk assessments already exist with much of the supporting data related to the transportation system. This report summarizes the various types of data required and identifies sources for that data.

INTRODUCTION

The U.S. Department of Energy (DOE) has undertaken a program to evaluate and select options for the long-term storage and disposition of fissile materials declared surplus to defense needs as a result of the end of the Cold War. The alternatives can be defined as "end-to-end" options which involve a series of steps that take various fissile materials from their current locations through one or more processing facilities to final disposition locations. Transportation will be required for each leg of an alternative. The flow paths for these alternatives may involve different forms of material and, thus, different routes and modes of transport. For example, weapons-grade plutonium metal requires transport by the Transportation Safeguards System (TSS) while low-level waste does not.

The objective of this paper is to establish the context for the transportation of surplus fissile materials and to propose a framework for conducting environmental impact analyses as part of environmental impact studies (EISs) and other planning documents required to implement the options after the Record of Decision (ROD) has been issued. Specifically, the paper defines the materials included in the Fissile Material Disposition Program (FMDP) in terms of both form and quantity; provides a general description of the material flow paths; defines the corresponding modes of transportation based on existing transportation safety and security requirements; and discusses the key factors relating to environmental impact including the probability of radioactive material dispersal and associated consequences, incident-free risks, and non-radioactive risks. The discussion in this report must, at this point in time, remain qualitative when it comes to discussing the environmental impact since a proper probabilistic risk assessment (PRA) requires detailed descriptions of the locations of the various disposition facilities, cargo descriptions, and routes. However, there is nevertheless a great deal of quantitative information that is known at this point about accident probabilities, accident types and severities, population, and other factors, and references will be made to these data sources.

FORM AND QUANTITY OF FMDP MATERIALS

The scope of the FMDP is still under consideration by the DOE. However, the 50 metric tons of plutonium that the U.S. will place in the program and submit to international safeguards inspections may include the following forms: pits, clean and impure metal, clean and impure oxide, compounds, reactor fuel, and other, miscellaneous forms that could include some stabilized rich scrap and irradiated fuel that have been processed to forms acceptable to the FMDP. Initially, almost all of these forms will be transported in the DOE's Safe Secure Trailer (SST). It is assumed that the transportation of materials begins when the vehicle leaves the loading dock of the interim storage facility where the material is currently located. It is further assumed that the material is transportable (i.e., shipments meet all federal, state, and local statutes). Finally, it is assumed that materials are all transported in certified, Type-B packagings.

DISPOSITION ALTERNATIVES – "END-TO-END" OPTIONS

From a transportation perspective, a convenient way to define the disposition alternatives is shown in Fig. 1. This concept was proposed by D. L. Mangan, Sandia National Laboratories, at the January, 1995, FMDP Program Review Meeting in Washington, D.C. While it may appear differently in other papers and presentations, it is, from a transportation perspective, both valid and useful.

Transportation will occur along the paths between various blocks in Fig. 1 (which correspond to various disposition and storage facilities). An important feature of this figure is that safety, security, and international safeguards requirements for transportation can be easily determined according to which of two standards are met by the materials. These two standards are known as the "spent fuel standard" and the "stored weapon standard." These terms were originally defined by the National Academy of Sciences (1). They are recommended as key criteria for judging disposition options, and reflect the security necessary to minimize the proliferation risks due to theft and diversion.

The spent fuel standard was designed to define a level of inaccessibility desired for surplus weapons plutonium and was based on material form, location and institutional regulations and requirements. However, for the purposes of the FMDP and this paper, the spent fuel standard is equated with the intrinsic properties or the form of the material only (2). By doing so, judgments can be made to determine whether the (processed) material has a nature equivalent to spent fuel. In addition to assuring proliferation resistance, the spent fuel standard provides guidance on which materials can be placed under lesser levels of safeguards and security.

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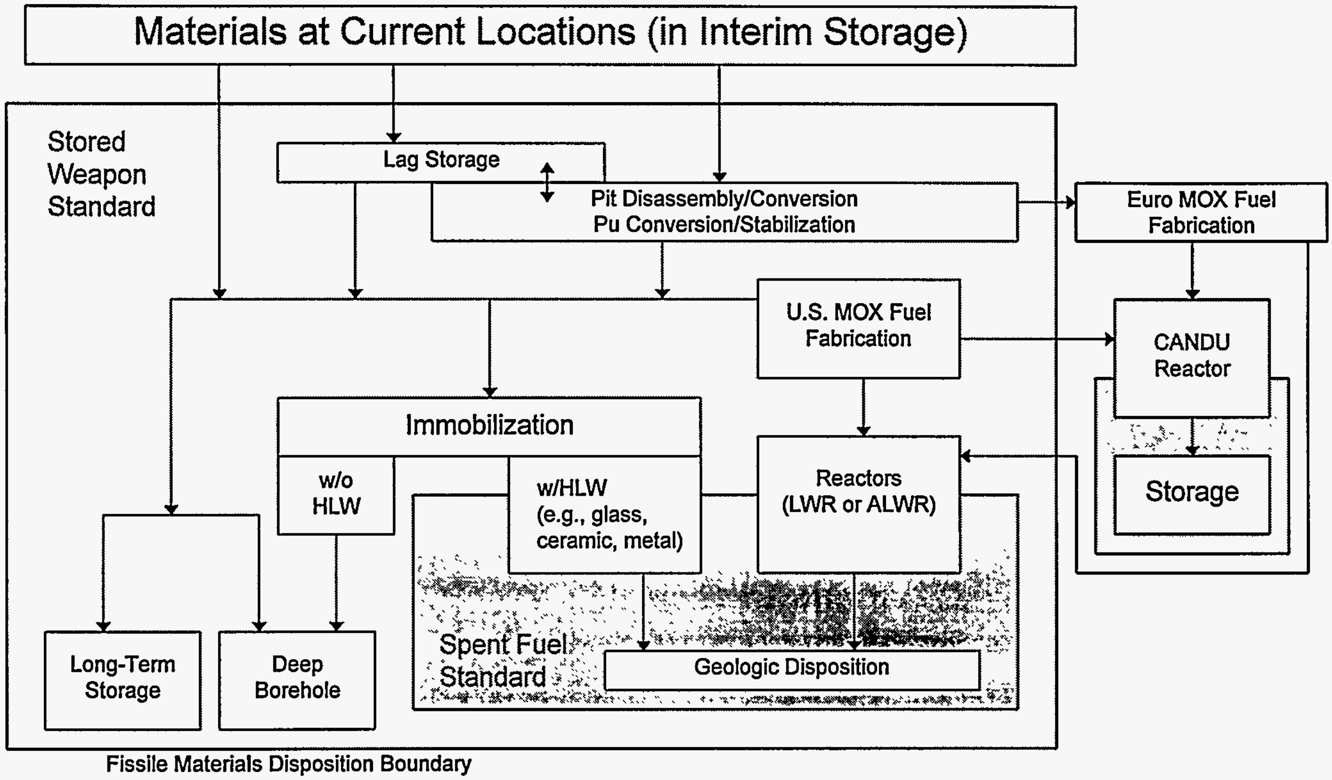

Fig. 1. Flow diagram for fissile material disposition options

The spent fuel standard consists of the radiological, physical, chemical and nuclear properties or characteristics of a disposition option that make processed excess weapons plutonium as inaccessible for recovery as commercial spent fuel. The radiological, physical and chemical characteristics must be met for a material to fall under the spent fuel standard. The nuclear properties have only a secondary effect. Details regarding the requirements for meeting the spent fuel standard are discussed in Attachment D of (2).

The stored weapon standard (Appendix A of (2)) consists of four different components: material form, attractiveness level, protection principles and security concept. The material form can provide some proliferation resistance. The form reflects the intrinsic properties of materials which determine their attractiveness for use in nuclear weapons. There is believed to be a correlation between materials with low attractiveness levels for weapons use and proliferation resistance and, therefore, lesser requirements for safeguards and security. Materials with high levels of attractiveness for use in nuclear weapons have significant safety and security requirements.

The DOE defines the attractiveness level through a categorization of types and compositions that reflects the relative ease of processing and handling required to convert the material to a form for use in a nuclear explosive device. The level of protection (i.e., safeguards level) is dependent on the quantity or concentration of material. Fig. 2 shows the relationship between attractiveness levels and safeguards categories for plutonium.

The DOE uses a graded approach to security. The concept of protection of fissile material incorporates a security in-depth approach with an immediate tactical response. Materials meeting the spent fuel standard will likely fall into attractiveness level E, and would thus, by definition, all be category IV materials. Other forms of surplus fissile material meeting the stored weapon standard will fall into other attractiveness levels, perhaps as high as level B in the case of surplus pits.

MODES OF TRANSPORT

Determining the permissible modes of transport surplus fissile materials can be determined first on the basis of security requirements and, second, by considering operational issues (e.g., will the cargo fit in the conveyance). Safety does not, strictly speaking, dictate the mode of transport. In some cases, the DOE could preclude certain modes of transport. For example, the Department unilaterally decided to suspend the use of both rail and air modes to transport nuclear explosives, as these modes were deemed either unnecessary or unnecessarily high in risk. In other cases, the packaging required for safety may preclude certain modes of transport. For example, some spent fuel shipping casks are too large to fit inside the Safe Secure Trailer (SST) used by the DOE's Transportation Safeguards Division (TSD) for highway shipments.

SECURITY

The applicable regulations for determining security requirements are defined in U. S. DOE Orders, including Chapter II of DOE Order 5632.1C (4) and DOE M 5632.1C-1 (5). Wilson (6) has provided a detailed analysis of the conditions under which transport under the control of DOE's Transportation Safeguards System (TSS) is and is not required. In summary, transport by TSS is required for all Category I and II materials, and may be required for some Category III materials. Transport by TSS is not required for Category IV materials, but may be used for shipments of classified configurations. Rail Shipment is permitted for all categories of materials; however, the TSS does not currently possess a rail capability for Category I and II materials. Air and water transport are not permitted for Category I and II materials. Thus, Category I and II materials currently must be transported by Safe Secure Trailer (SST). Category III and IV materials may be transported by air and water if not otherwise prohibited by statute or otherwise limited by implementing instructions.

TABLE I
Nuclear Materials Safeguards Categories for Plutonium

Material Form	Attractiveness Level	PU/U-233 Category (Quantities in KGs)			
		I	II	III	IV[a]
WEAPONS Assembled weapons and test devices	A	All Quantities	N/A	N/A	N/A
PURE PRODUCTS Pits, major components, buttons, ingots, recastable metal, directly convertible materials	B	≥ 2	≥ 0.4 < 2	≥ 0.2 < 0.4	< 0.2
HIGH-GRADE MATERIAL Carbides, oxides, solutions (≥ 25 g/l) nitrates, etc., fuel, elements and assemblies, alloys and mixtures, UF_4 or UF_6 (≥ 50% U-235)	C	≥ 6	≥ 2 < 6	≥ 0.4 < 2	< 0.4
LOW-GRADE MATERIAL Solutions (1 - 25 g/l), process residues requiring extensive reprocessing, moderately irradiated material, Pu-238 (except waste), UF_4 or UF_6 (≥ 20% < 50% U-235)	D	N/A	≥ 16	≥ 3 < 16	< 3
ALL OTHER MATERIALS Highly irradiated forms, solutions (≥ 1 g/l), uranium containing < 20 % U-235 (any form or quantity)	E	N/A	N/A	N/A	Reportable Quantities

a/ The lower limit for category IV is equal to reportable limits in this Order.

Otherwise, commercial highway transport is permitted for unclassified Category IV materials and some unclassified Category III materials.

SAFETY REQUIREMENTS

For off-site shipments made by TSS, procedures are prescribed in implementing orders for DOE Transportation Safeguards Division (TSD) operations (7, 8). If shipment by the TSS is not required, then a plan will have to be provided by the transporting organization and approved by the DOE (9,10).

Although Title 49 CFR Part 173.7(b) provides the so-called national security exemption from the regulations in Parts 170-189 of Title 49 for "shipments of radioactive materials, made by or under the direction or supervision of the Department of Energy or the Department of Defense, and which are escorted by personnel specifically designated by, or under the authority of those agencies, for the purpose of national security" (8), it remains the DOE's policy to comply with all DOT over-the-road requirements for which no overriding safety or security imperative exists. As noted in 49 CFR 173.7(d), "notwithstanding the requirements of §§ 173.416 and 173.417 of this subchapter, packagings made by or under the direction of the U.S. Department of Energy may be used for the transportation of radioactive materials when evaluated, approved, and certified by the Department of Energy against packaging standards equivalent to those specified in 10 CFR Part 71. Packages shipped in accordance with this paragraph shall be marked or otherwise prepared for shipment in a manner equivalent to that required by this subchapter for packagings approved by the Nuclear Regulatory Commission."

FACTORS RELATING TO ENVIRONMENTAL IMPACT AND RISK

The transport of fissile materials can cause several types of environmental and health impact: consequences associated with the dispersal of radioactive materials resulting from an accident; consequences associated with incident-free transport of radioactive materials; and non-radioactive consequences. The following discussion focuses on highway transport and on the consequences resulting from the dispersal of radioactive material which is perceived by the public to be the dominant transportation risk. The types of environmental impact resulting from rail transport incidents are not significantly different; only the specific data and some modeling details will be different.

The consequences associated with the dispersal of radioactive materials resulting from a transportation accident are the most widely recognized and most commonly addressed in environmental assessments and risk assessments of transportation. The dispersal of radioactive material can result in area contamination and/or it can result in health effects in the form of latent cancer fatalities (LCFs). Radioactive material can be dispersed by several mechanisms. First, the material can be mechanically dispersed as a result of physically breaching the vehicle and packaging and physically scattering the material. Second, given that the containment has been breached, radioactive material can be dispersed thermally in a fire. Finally, although not credible except in the case of weapon component transport, material could be dispersed as a result of a criticality incident. The probabilities of such an event are so low as to be "beyond extremely unlikely" in DOE terms (i.e., the probability of occurrence is $< 10^{-6}$).

The radiological consequences associated with incident free transport of radioactive materials are dominated by the potential for exposure to low levels of radiation. The exposed population consists of the workers (i.e., the drivers of the vehicles) and general population. No individuals in the general population are likely to receive more than a few minutes of negligible exposure. However, the consequences are typically calculated in terms of the total dose and applied to the aggregate population.

While public concern focuses on the consequences due to radioactive dispersal, and in some scenarios the total number of fatalities can be greatest for radioactive dispersal, the probability is generally very low, less than one-in-a-million for a shipment of these materials. A much greater probability exists, although still very low, that a few (less than ten) prompt fatalities due to non-radioactive mechanisms could result from the accident itself.

MODELS and EXISTING DATA FOR ENVIRONMENTAL IMPACT

Probabilistic Risk Assessment (PRA) tools have been developed to address the dispersal of radioactive materials resulting from a transportation accident involving the Armored Tractor (AT)/Safe Secure Trailer (SST) combination. This model, which is discussed here, was developed for the Defense Programs Transportation Risk Assessment (DPTRA) project, a comprehensive analysis of the risk to which the public is exposed from the transport of all weapons-usable materials, including weapons and components. The accident sequences that could lead to inadvertent dispersal of radioactive material and the likelihood of the sequences occurring are considered in a quantitative assessment that utilizes event tree logic. The analyses are conducted for each cargo separately; the results of these individual assessments can be compared or aggregated into an overall result.

The event tree is composed of questions that define the types and severities of transportation accidents that occur, the resulting damage to the vehicle and cargo, release mechanisms, accident locations, and the meteorological conditions. The event tree developed for assessing transport by SST contains 18 questions. The 18 questions include: (1) most harmful event, (2) impact direction, (3) impact location (on the vehicles), (4) rollover, (5) mechanical environment, (6) collision damage, (7) rollover damage, (8) fire, (9) separation (of vehicle from fire), (10) fire diameter, (11) effective (fire) temperature, (12) HE ignition, (13) HE violent reaction, (14) oxidation, (15) route, (16) location, (17) meteorological stability, and (18) wind direction. Each question is used in all paths of the tree (scenarios) although, for some scenarios, results of some questions might not be used. For example, if nuclear explosives are not involved, questions related to HE ignition are not relevant.

The initiating events for the tree are traffic accidents in one of four operating environments. The operating environments are based on road type (limited access or other) and population area (urban or rural). Although the structure of the tree is the same for all four initiating events, the quantification of some of the branches depends on the operating environment. Based on accident data, the initiating events are quantified in terms of an annual probability of occurrence. All other branches of the tree are quantified in terms of conditional probabilities.

The mean estimate for the rate of tow-away accident rates involving an AT/SST combination is 0.066 per million miles (11). However, the number of accidents experienced by the SST is not sufficient to quantify the accident rate in the operating environments of interest or the types and severities of accidents. Thus, general commerce data for heavy truck transportation is used as a surrogate for AT/SST data to quantify the relative accident rates in different operating environments and the types and severities of accidents. To estimate the fraction of tow-away accidents that are considered to have severities comparable to fatal accidents, influence factors have been developed for different environments (e.g., limited highway travel in urban population areas, travel on other roadways in rural population areas) (12). These influence factors indicate that accidents are less likely on limited access roads than on other roads.

Surplus fissile materials will be shipped in packaging systems designed to mitigate accident environments and to prevent releases to the environment. In general, normal transportation environments do not produce environments that threaten the integrity of the packaging system. However, the environments produced from very severe traffic accidents could exceed the capabilities of the packaging system and cause a release of radioactive material.

The risk model discussed here, considers impact, puncture, crush and thermal environments. In traffic accidents, these environments are associated with collision and rollover events and fires involving the fuel system, cargo or other elements of the vehicles and/or objects involved in the accident. The response of the packaging system to these environments is likely to be interdependent.

The accident data needed to define the probability of packaging system failure include the probabilities of various accident types and distributions of collision, rollover and fire severity. The response of the packaging system and the collision, rollover and fire severity depend on the type of accident. Questions 1-4 and 8 define the factors used to characterize the type of accident. Questions 9-11 are used to describe the fire separation, fire size and fire temperature. The peak contact velocity, skid distance and fire duration are used in the evaluation of the branch probabilities for questions 6, 7, 12, and 14. Details of the statistical distributions for each of the factors used to characterize the type and severity of accidents can be found in (12).

The response of the cargo to fire environments is addressed in questions 12-14. High explosives will not be involved in the transport of fissile materials in the FMDP. Therefore, questions 12 and 13 are not applicable. The computer code MELTER (13) was developed for use in determining the probability that aerosol is generated by oxidation of radioactive material.

For a given release mechanism, the last four questions in the event tree provide the remaining conditions to define a consequence scenario. Specific locations are sampled randomly from each route and operating environment considered. The location of the accident affects both the distribution of meteorological stability and the exposed population. The probabilities of the meteorological stability classes (as defined by Pasquil-Gifford stability A-F) depend on the accident location and are obtained from data recorded at upper air stations operated by the National Climatic Data Center. The meteorological stability affects the extent of dispersal while the wind direction affects the exposed population.

Health and environmental effects are estimated in the consequence assessment. Health consequences are expressed in terms of the expected number of excess LCFs produced in the exposed radiation. The exposed population is defined as those members of the public subject to a maximum individual risk of contracting an excess latent cancer resulting in fatality greater than one in ten thousand. Collective committed effective dose is calculated based on dispersal analysis using the ERAD Code (14) and exposed populations determined from route characterization and population counts obtained from the 1990 Census Data (15). The number of excess LCFs is determined from the collective committed effective dose based on conversion factors in the BEIR V report (16). The dispersal analysis depends on the dispersal mechanism, meteorological stability, and the cargo of interest. The exposed population depends on the accident location and wind direction. Environmental Consequences are expressed in terms of land area contaminated to levels greater than 0.1 $\mu Ci/m^2$. The contaminated area is taken directly from the dispersal analysis and depends only on the cargo, release mechanism, and meteorological stability.

SUMMARY

The transport of surplus fissile materials will occur in one of three modes of transport: Safe Secure Trailer (SST) used by the Department of Energy for the transport of materials meeting the stored weapon standard; commercial vehicles used for transporting unclassified materials meeting the spent fuel standard; and rail transport for the transport of materials meeting the spent fuel standard and other materials too large for highway transport vehicles. Determining the mode of transport is a matter of evaluating security requirements associated with the stored weapon standard and spent fuel standard.

The consequences resulting from an accident occurring during transport include: area contamination, health effects resulting in latent cancer fatalities and prompt fatalities and injury resulting from the accident itself. In addition, there is a very small, but still non-zero risk of health effects due to exposure to incident free radiation.

The methodology for assessing the risk due to radioactive dispersal is straightforward and involves three elements: probabilities of release and specific consequence scenarios developed from an event tree; consequences evaluated for each end event in the event tree through an assessment which integrates dispersal calculations, route characterization, population data and dose-health effects models to provide estimates of LCF and contaminated area; and uncertainties evaluated by incorporating a Latin Hypercube Sampling scheme into the calculations for probabilities and consequences.

While the specifics of the routes and schedules still need to be determined, the basic models and data required for determining the risk exist including accident rates, statistical databases on accident types and severities, test data on vehicle response to impact and fire, population and meteorological data, and dose-conversion factors for determining LCFs from the committed collective dose.

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