METHODOLOGY AND COMPUTATIONAL FRAMEWORK USED FOR THE U.S. DEPARTMENT OF ENERGY ENVIRONMENTAL RESTORATION AND WASTE MANAGEMENT PROGRAMMATIC ENVIRONMENTAL IMPACT STATEMENT ACCIDENT ANALYSIS*

C. Mueller, J. Roglans-Ribas, S. Folga and A. Huttenga
Argonne National Laboratory
Argonne, Illinois

R. Jackson, W. TenBrook and J. Russell
Science Applications International Corporation
Golden, Colorado, and Pleasanton, California

ABSTRACT

A methodology, computational framework, and integrated PC-based database have been developed to assess the risks of facility accidents in support of the U.S. Department of Energy (DOE) Environmental Restoration and Waste Management Programmatic Environmental Impact Statement. The methodology includes the following interrelated elements: 1) screening of storage and treatment processes and related waste inventories to determine risk-dominant facilities across the DOE complex, 2) development and frequency estimation of the risk-dominant sequences of accidents, and 3) determination of the evolution of and final compositions of radiological or chemically hazardous source terms predicted to be released as a function of the storage inventory or treatment process throughput. The computational framework automates these elements to provide source term input for the second part of the analysis which includes 1) development or integration of existing site-specific demographics and meteorological data and calculation of attendant unit-risk factors and 2) assessment of the radiological or toxicological consequences of accident releases to the general public and to the occupational work force.

INTRODUCTION AND OVERVIEW

This paper describes the methodology, computational framework, and database for the facility accident analysis for the U.S. Department of Energy Environmental Restoration and Waste Management (EM) Programmatic Environmental Impact Statement (PEIS). The EM PEIS is being developed for radioactive and chemically hazardous waste management in the DOE complex. It addresses waste management and site consolidation alternatives for six different waste types: greater-than-Class-C low-level waste, hazardous waste, high-level waste, low-level mixed waste, low-level waste, and transuranic waste. Each alternative involves both existing and conceptual design facilities at DOE sites throughout the country; a number of treatment technologies will be assessed for each waste type.

The scope and objectives of the accident analysis are described in detail elsewhere (1). In summary, the scope is driven by the comprehensiveness of the EM PEIS and the graded approach for preparation of environmental impact statements (EISs) called for in the latest National Environmental Policy Act (NEPA) guidance (2), which requires emphasis on the risk-dominant scenarios within the spectrum of accidents constituting risk. The objectives that emerged for the accident analysis included 1) development of a strategy that would facilitate focusing on the risk-dominant sites and facilities under consideration, 2) development of a methodology that would provide uniform treatment across sites, and 3) characterization of risk in terms of the waste inventories and treatment throughputs imposed by the various alternatives.

Figure 1 is a graphical overview of the risk-based analytical approach developed to meet these objectives. This paper describes the major elements of the methodology and computational framework that make up this approach. The accident source terms and associated annual frequencies are being developed at Argonne National Laboratory and provided to Oak Ridge National Laboratory for exposure and health effects evaluation.

SELECTION OF RISK-DOMINANT FACILITIES AND PROCESSES

Because of the large number of processes and facility configurations possible within the waste management alternatives, an initial screening was performed to delimit the analysis to only those configurations with accidental radiological or chemical releases important to overall risk. For screening purposes, the storage and treatment modules were categorized as falling within five operational regimes: 1) current or pretreatment storage, 2) retrieval from storage and transfer to pretreatment or treatment facility(ies), 3) pretreatment (which applies only to high-level waste), 4) treatment, and 5) interim or predisposal storage. Facilities considered ranged from outdoor pads or weather protection facilities offering almost no containment capability to DOE Performance Category 1 facilities (equivalent facilities with the structural capability to withstand significant structural challenges from natural phenomena such as earthquakes without loss of containment and filtration functions). Facilities also considered included operating facilities, preoperational facilities, and facilities in the design phase. The storage inventories, treatment throughputs, and conceptual designs for facility sizing are all functions of the strategic alternatives being investigated by the EM PEIS.

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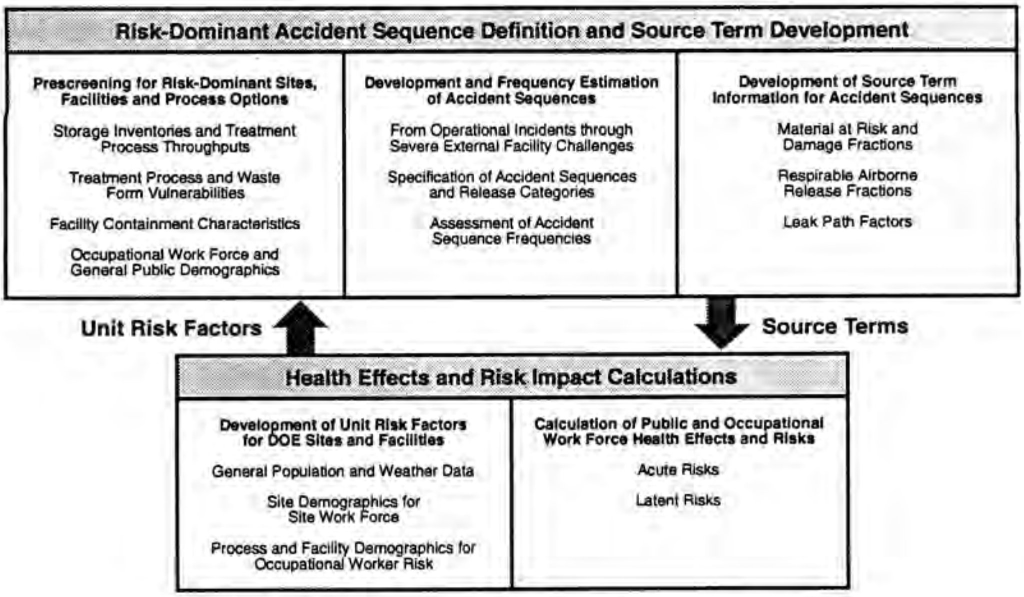

Fig. 1. Major components of facility accident analysis.

The following criteria were used to select specific risk-dominant facilities and storage and treatment operations for each waste stream for subsequent, more detailed radiological and toxicological risk evaluation:

1. The total radioactivity inventory of material at risk (MAR) and the hazards characteristics of its radionuclide or chemical composition.
2. The vulnerability of the MAR in storage and treatment processes, especially with respect to the potential of fire or explosion in accident sequences.
3. The operational and containment characteristics of the facility.
4. The demographics of the facility and storage and treatment operations for characterizing both the work force and general public populations likely to be exposed to radioactivity or toxic chemical releases.

The process by which these criteria were used to identify the facilities and processes expected to dominate risk follows.

Facility Inventories of Material at Risk

This aspect of the screening focused on the radioactivity or toxicity content of the MAR. Each alternative discussed in the EM PEIS implicitly defines unique projections for pretreatment and posttreatment storage inventories and treatment throughputs for each waste type at each DOE site. Accordingly, for each alternative, DOE sites were ranked to determine those sites with the largest projected relative radioactivity inventories for existing and projected pretreatment and posttreatment storage. Similarly, those sites with the largest projected hazardous waste inventories were also ranked. The inventories within individual facilities storing the bulk of the waste for these dominant sites were obtained from DOE's Integrated Data Base (3), the Waste Management Information System (4), and individual site records. Specification of the radionuclide or chemical composition of the wastes for these storage facilities was obtained from site inventory characterization studies supporting the EM PEIS. This information completed the preliminary radioactivity or toxicity hazards characterization of storage inventories potentially at risk from facility accidents at risk-dominant sites.

The required treatment throughput for each waste type at each DOE site is also defined within the EM PEIS for each alternative. These sites were ranked by projected throughput volume and radioactivity to determine those sites with the largest treatment inventories. Existing or planned facility capacities were compared with the required throughputs to determine throughput requirements for new facilities and treatment processes on these sites. The major existing and planned facilities, as well as those new conceptual facilities with the largest throughputs, were then identified as potential candidates for more detailed accident analysis.

Vulnerability of the Material at Risk in Storage and Treatment Processes

This aspect of the screening focused on the vulnerability of the radioactive or chemical waste MAR to airborne releases as a result of accidents. Processes involving high temperatures or pressures were carefully reviewed in light of the potential energy source for propagating airborne radiological or toxicological material, as well as for challenging the facility's integrity and filtration capability. Similarly, storage or processes involving radioactive combustible materials, or processes being performed in the presence of combustible materials were carefully reviewed in light of the potential for ignition and subsequent fire and/or explosions. The physical and chemical stabilities of the waste were also reviewed to preclude unnecessary analysis of process operations involving highly stable wastes that would require extremely severe and unlikely conditions to attain significant airborne releases.

From these considerations, pretreatment or treatment processes such as fractionation using ion-exchange columns, metal recovery, incineration, wet-air oxidation, and vitrification were identified for closer evaluation. Conversely, shredding and compaction, repackaging of untreated wastes, and packaging of treated solidified wastes were removed from consideration for more detailed analysis except for the analysis of a few specific accidents relevant to occupational risk. Although these operations are prone to mechanical stresses in industrial accidents, such stresses can be shown to lead to insignificant airborne releases.

Facility Characteristics

This aspect of the screening focused on the potential for airborne releases resulting from accidents to escape the confinement building (if applicable) and pose a threat to downwind personnel. It also involved review of the containment characteristics of the existing or proposed storage or treatment facilities. For new or proposed facilities, these characteristics were largely defined by their perceived Hazard Category and the attendant operational and emergency procedures and structural capabilities implied by the related Performance Goal Category. For older existing facilities, these characteristics were determined from descriptions obtained in safety analysis reports (SARs) or related documentation, as available, and from discussions with site personnel.

Many storage operations take place in areas or buildings that essentially have little or no confinement. For example, much storage of packaged waste exists in outdoor pads or weather protection facilities that offer essentially no barrier to airborne releases. Much liquid waste is stored in underground tanks, although some tanks are above ground. For related operations, such as retrieval of liquid waste from underground storage tanks, accidents could result in releases directly to the atmosphere. Accordingly, operations involving the potential for direct release were identified for more detailed evaluation.

Conversely, storage or treatment processes in robust facilities with high structural integrity and multiple filtration banks, as typified by DOE Hazard Category 1 or 2 facilities or their equivalents, would involve atmospheric source term releases only under the most severe and improbable accident conditions. Therefore, analyses of accident sequences in Hazard Category 1 and 2 facilities were limited to those involving severe accident initiators, which would challenge very large and hazardous inventories.

Demographics

This last aspect of the screening focused on the populations likely to be exposed to airborne releases. The occupational work force hazard from releases due to accidents is directly related to the radiological or chemical inventory involved in the accident, the number of workers affected, and the relative proximity of the workers affected. Worker population estimates for each treatment technology and facility were developed for the EM PEIS as a function of the throughput of the waste inventory to be processed. From these worker populations, estimates of the number of workers likely to be exposed to radiological releases from accidents were developed for each process and facility. Consideration of these populations and their proximity to the point of release vis-a-vis the appropriate radioactivity or toxic chemical inventories of the process MAR provided an initial identification of those processes and facilities potentially dominating the worker population risk.

Demographics related to the general public were also reviewed to determine those sites for which even minor airborne releases had the potential for off-site health effect consequences. These sites were identified as candidates for more detailed evaluation of potential accidents in their facilities.

DEVELOPMENT OF RISK-DOMINANT ACCIDENT SEQUENCES

This part of the analysis involved the development of a framework that would accommodate the spectrum of accidents possible over the range of DOE facilities managing the different waste types. Orders, standards, and other regulatory guidance from DOE, the U.S. Nuclear Regulatory Commission, and the U.S. Environmental Protection Agency, as well as key supporting documents were reviewed to identify the spectrum of accidents and potential releases routinely evaluated in safety analyses. The accident analyses performed for or in support of other major ongoing EM PEIS efforts for the DOE were also reviewed to provide guidance for the selection and evaluation of accidents (5,6). Finally, recent SARs, EISs, and related facility-specific analyses were reviewed for applicability to both explicit facilities and related generic facilities.

Selection and Categorization of Accident Initiators

All generic accident initiators were categorized into the following accident groups: (1) operational events initiated from industrial accidents, procedural errors, or equipment failures leading to primary storage or treatment process vessel containment breaches or ruptures with attendant airborne releases; (2) external challenges to the facility from generally man-made events, such as aircraft crashes and site or adjacent facility fires and explosions; and (3) external challenges to the facility from potentially catastrophic natural phenomena (e.g., earthquakes, extreme winds/tornadoes, floods, and volcanoes) with likely impacts to other facilities at the site. Nuclear criticality events, when applicable, were treated as a separate category.

Accident sequences arising from these initiator categories can generally be mapped into the following frequency classes: greater than 10^{-2} per year, from 10^{-4} to 10^{-2} per year, from 10^{-6} to 10^{-4} per year, and less than 10^{-6} per year. The first three of these classes typically encompasses accidents generally treated in SARs and EISs. For the EM PEIS, accident initiators were generally ignored if their estimated annual frequency was less than 10^{-6}, or all sequences associated with the initiator had nominal annual frequencies less than 10^{-6}. Exceptions were made when 1) the predicted consequences were so high that the risk (defined here as the product of frequency and consequence) was likely to be dominant or 2) the uncertainty in the estimated frequency of the sequence was so large that there was a significant chance that the true frequency was greater than 10^{-6}.

In general, operational safeguards and equipment designs are in place to ensure that the radiological or toxicological impacts on the public health from all events are extremely limited in consequence, except in the most severe (and unlikely) accident situations. Accordingly, the higher frequency operational events, such as spills or drops, generally contribute little to public health risk although they have a much higher contribution to worker risk. Key characteristics of the much less frequent severe accidents in Accident Groups 2 and 3 are the potential for breaching multiple containment barriers and filtering systems and short-circuiting standard emergency procedures. Thus the low frequency of these accidents is offset by their larger consequences, and typically, severe accidents are predicted to dominate overall public health risks. In light of their potential for affecting different populations and consistent with recent NEPA guidance, risk-dominant accident sequences from each of the frequency ranges shown above were assessed.

Specification and Evaluation of Accident Sequences

Starting with the accident initiators defined above, functional event trees were developed to project the progression of the accident initiators through plausible generic sequences. The extent of any release is a function of 1) the accident stresses affecting and rendering airborne the material involved in the accident and 2) the transport of airborne activity, especially as impacted by the response of the containment (if any). Accordingly, the functional event trees were structured to incorporate the key accident stress mechanisms and the containment and filter failures affecting the amount of airborne activity released to the atmosphere. This structuring allowed a step-by-step characterization of the sequence likelihood and the magnitude of the release as the accident sequence progressed.

Figure 2 shows a representative event tree structure for external events. Because nearly all accident scenarios capable of major airborne releases involve fires or explosions, event tree branches were specifically defined to delineate fire and explosion categories for which analysis or experimental information is available to support appropriate release fraction estimates (7,8,9). Event tree branches were also defined to reflect the integrity of the containment.

The accident sequences were developed and analyzed as much as possible for categorical classes of facilities rather than individual facilities at each site. Within the DOE complex, a number of existing storage and treatment facilities have similar confinement and functional characteristics. Moreover, many of the facilities for DOE/EM waste management are in the design phase. Broadly categorizing facilities within generic classes thus allowed a mechanism for providing a uniform accident analysis treatment for a wide range of facilities across the DOE complex with similar characteristics and for reducing the number of actual analyses performed to a manageable level.

To implement this approach, existing treatment and confined storage facilities were generally mapped into DOE-STD-1021-92 facility Hazard Categories 1, 2, or 3 (10). A No Confinement category was assigned to concrete pads used for packaged storage, weather protection sheds, or facilities providing no real barriers to release, up to and including general purpose buildings. Some facilities, such as high-level waste storage tanks for which no generic mapping was appropriate, were treated as special cases. For situations where treatment of a given waste stream is as yet undefined, judgments were made as to the DOE Hazard Category that would be required of the treatment facility. In general, conceptual treatment process facilities were assumed to be Category 2.

The probabilities for an accident progressing along various branches were developed to be consistent with realistic facility responses to the accident initiator magnitude and related contributing or subsequent failures, as well as to reflect the safety characteristics of the facilities. For example, because Category 1 facilities are extremely robust, have redundant safety systems and filtration systems, and detailed operating and emergency procedures, they were assigned higher probabilities of maintaining containment effectiveness under severe accident conditions than were Category 2 facilities. Similarly, Category 2 facility accident sequence probabilities reflect greater safety characteristics than Category 3 facility sequences. No credit for filtration or containment of

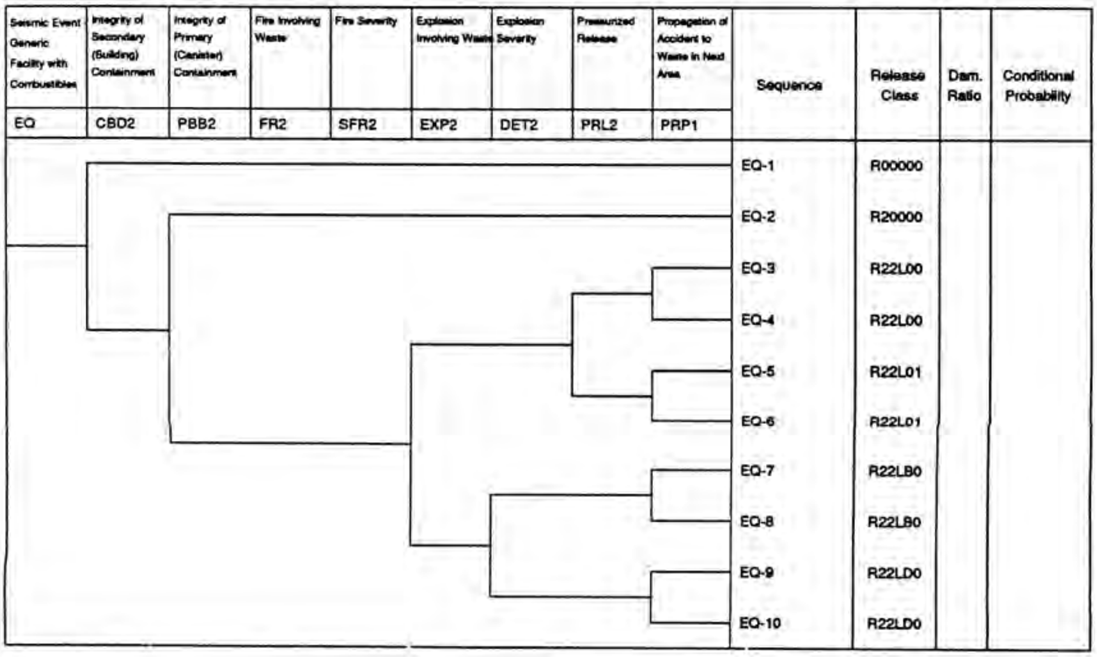

Fig. 2. Event tree for: seismic event - generic facility with combustibles.

source term releases was taken for facilities with safety characteristics below those of Category 3. For catastrophic releases in general purpose buildings, this treatment is appropriate; for more benign sequences, this treatment is conservative.

DEVELOPMENT OF RADIOLOGICAL SOURCE TERMS FOR ACCIDENT SEQUENCES

The radiological or chemically hazardous source term associated with each accident is the product of four factors that vary for each radionuclide or chemical species within the inventory affected by the accident:

Source term = material-at-risk (MAR)
× damage fraction (DF) or fraction of MAR available for release
× respirable airborne release fraction (RARF)
× leak path factor (LPF)

The disaggregation of the source term into these components broadly follows the treatment used in analyses performed for DOE defense programs (5). However, treatment of these components was extended to integrate source term development with accident progression analysis. Accordingly, a generic matrix of release characteristics was developed as a function of the accident stresses and facility conditions composing the event tree branches. The stresses were categorized as much as possible to allow mapping of airborne release fractions for applicable experimental conditions (8,9). This approach enabled the determination of the fractional amount of each radionuclide or toxic chemical in the original inventory available for release at each point in the progression of the accident. Each accident sequence was then terminated in a generic release category.

The MAR was defined as the inventory of waste impacted by the accident. The composition of the MAR was characterized by its radionuclide or toxic chemical content and its physical form. The volume of the MAR was developed as a function not only of the process and facility configuration, but also of the severity of the accidents. This reflects accident initiators such as earthquakes, which have the potential to affect greater inventories of waste than more localized industrial accidents. The damage fraction was defined as the volumetric fraction of MAR actually susceptible to airborne release. It also was developed as a function of the physical form of the waste, the process and facility characteristics, and the severity of the accident sequence.

The final evaluation step involved the integration of the radionuclide or chemical compositions of the waste process inventories of materials in the accidents (MAR) with the accident data to derive the actual source terms to be released. The radionuclide profiles developed for the EM PEIS facility assessments for both storage and treatment processes were used in the radiological source terms. Representative chemicals were selected from the facility inventories to establish the toxic chemical source terms.

HEALTH EFFECTS CALCULATIONS

Preliminary estimates of the health effects were obtained by integrating the source term information with unit-risk factors provided by Oak Ridge National Laboratory for each site. From these results, risk-dominant accident sequences from the above accident categories and over the range of frequency categories were selected for more rigorous analysis. For these latter evaluations, the accident sequence frequencies were reevaluated to ensure that process and facility-specific information was accounted for to the extent possible. Similarly, the damage fraction, airborne release fraction, and leak path characteristics were also reevaluated. With the upgraded information, a reduced set of risk-dominant source terms covering the plausible frequency spectrum is being developed for transmittal to Oak Ridge for final health effects and risk calculations.

SUMMARY

The work reported above was developed to provide an automated capability for source term development that could be used to support risk impact analysis for the DOE EM PEIS. The various waste management strategies available to DOE EM result in an extremely large number of combinations of site consolidation options; attendant waste storage and process throughput inventories; and resulting treatment, storage, and disposal facility configurational and operational options. The methodology, computational framework, and related database developed in support of the EM PEIS and reported herein have enabled the analyses of potential facility accidents to be done systemically and uniformly and to focus on the risk-dominant configurations and accident considerations for each management strategy.

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