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ABSTRACT

The Simplified Risk Model Version II (SRM-II) is a quantitative tool for efficiently evaluating the risk from Department of Energy waste management activities. Risks evaluated include human safety and health and environmental impact. Both accidents and normal, incident-free operation are considered. The risk models are simplifications of more detailed risk analyses, such as those found in environmental impact statements, safety analysis reports, and performance assessments. However, wherever possible, conservatisms in such models have been removed to obtain best estimate results. The SRM-II is used to support DOE complex-wide environmental management integration studies. Typically such studies involve risk predictions covering the entire waste management program, including such activities as initial storage, handling, treatment, interim storage, transportation, and final disposal.

I. INTRODUCTION

Department of Energy (DOE) environmental management integration (EMI) studies characterize base case programs and potential alternatives for environmental management of DOE wastes and materials such as high-level waste (HLW), transuranic waste (TRUW), low-level waste (LLW), mixed low-level waste (MLLW), and spent nuclear fuel (SNF). These efforts are also termed EMI trade studies. In order for alternatives to be compared with base case programs, information is required concerning relative costs, schedules, risks, and other factors. The SRM-II risk model was developed to efficiently provide comprehensive, consistent, and quantitative risk estimates of base case and alternative waste management programs. This risk input is then used with other factors (relative costs, schedule impacts, and others) to evaluate the merits of each alternative.

The SRM-II risk model is an enhanced and expanded version of the original model, the SRM. Documentation on the SRM can be found in several reports and conference papers.[1 through 5] Additionally, an independent peer review of the SRM was conducted.[6] That review found the SRM to be "potentially useful in that it provides a viable option, in terms of cost and time, for quantitative risk assessment at a point when a decision making process is commonly guided by qualitative risk assessment." However, the review also identified areas where both the risk models and documentation could be improved. The SRM-II was developed in response to the review comments and the desire to have a complete environment, safety, and health (ES&H) risk model. Details concerning the SRM-II are documented in the reference manual for the model.[7]

II. SRM-II STRUCTURE

The SRM-II models human safety and health risk and environmental risk resulting from waste management activities. Human safety and health risks include those associated with storing, handling, processing, transporting, and disposing of radionuclides and chemicals. Exposures to these materials, resulting from both accidents and normal, incident-free operation, are modeled. In addition, standard industrial risks (falls, explosions, transportation accidents, etc.) are evaluated. Finally, impacts to the environment from releases of radionuclides and chemicals are estimated in an approximate manner.

The accident portion of the SRM-II models releases of radionuclides and chemicals to the atmosphere and resultant exposures to workers, other DOE site personnel, and the public within 80 kilometers (50 miles) of the DOE site. The accident equation for atmospheric releases is the following:

$$\text{Risk} = (1a)(1a_{decay})(1b)(2a)(2b*3a+2b*3b)(4*5w+4*5s+4*5p)(6);$$

where	1a	=	inventory [curies (Ci's) or mass (for chemicals)]
	$1a_{decay}$	=	fractional decay of inventory
	1b	=	toxicity of inventory (rem/Ci or equivalent, inhalation or ingestion)

2a = respirable airborne release fraction (function of material form and accident characteristics)
2b = containment failure probability or leak path factor
3a = summation of natural phenomena accident frequencies multiplied by material at risk and damage fractions
3b = summation of operational accident frequencies multiplied by material at risk and damage fractions
4*5w = unit Ci exposure to facility workers (resulting from atmospheric dispersion and inhalation)
4*5s = similar to 4*5w but for other DOE site personnel
4*5p = similar to 4*5w but for the public within 80 kilometers (50 miles of the site)
6 = time duration for activity.

This accident equation is similar to those used in DOE environmental impact statements (EISs) and safety analysis reports (SARs). The product $(1a)(1a_{decay})(1b)(2a)(2b)$ represents the toxicity-weighted amount of Ci's (or kg's of a chemical) released to the atmosphere from accidents. The term (3a+3b) represents the accident frequencies (weighted by material at risk and damage fractions). The term (4*5w+4*5s+4*5p) models the resultant exposure and consequence from such releases. Finally, the term (6) is the time interval for the activity. This accident risk equation is used individually for the actinide and non-actinide groups (for radionuclide releases) and for each chemical of concern. For radionuclide exposures, the risk units are person-rem. For chemical exposures, the risk units are latent cancer fatalities.

Lookup tables are provided in the SRM-II for most of the accident equation elements. For example, decay curves are presented for representative HLW, TRUW, LLW, MLLW, and SNF, indicating the fraction of actinide and non-actinide Ci's remaining as functions of years of decay. Radionuclide toxicities for these waste and material types are provided as functions of the DOE site. (Each site may have different mixes of radionuclides.) Respirable airborne release fractions are suggested for various material forms, with consideration for the types of accidents covered in the (3a+3b) term. [8] Guidance on the types of accidents to consider and their frequencies and material at risk fractions is also provided. The accident frequencies depend upon the design characteristics of the facility being modeled (for natural phenomena) as well as the type of process, adequacy of fire protection, explosive potential of the process and the waste, and other factors (for operational accidents). The frequency choices in the SRM-II lookup tables typically allow for order of magnitude differentiation, rather than the two orders of magnitude frequency bins used in many EISs. Finally, the exposure and consequence term is a function of the DOE site (for 4*5s and 4*5p) and the type and size of the facility (for 4*5w). The exposure terms 4*5s and 4*5p were determined for each DOE site from unit Ci atmospheric release and exposure calculations performed for the *Waste Management Programmatic Environmental Impact Statement* (WM-PEIS). [9]

Releases of radionuclides and chemicals to the groundwater at DOE sites are also modeled. Site-specific characteristics such as travel times through the vadose zone to the groundwater, site size, off-site population, and others are considered in the groundwater pathway model.

Exposure to workers during normal, incident-free operation is modeled as a function of the number of workers associated with the activity in question. The total worker-hours for the activity is multiplied by an assumed yearly exposure (a user input). The default value for this yearly exposure is 200 mrem/year. Exposure to site personnel and the public from treatment off-gas releases is also modeled.

Standard industrial risk is calculated based on the numbers of worker hours and support personnel hours associated with each activity. These hours are multiplied by appropriate fatality rates (fatalities/hour) for various activities. The default fatality rates were obtained from a review of *Accident Facts* (1998 Edition). [10] For workers, the default rate is 5E-8 fatalities/hour. (The WM-PEIS value, obtained from older data up through 1993, is 9E-8 fatalities/year.) For support personnel, the default rate is 7E-9 fatalities/hour.

Risk from transportation of waste includes both accident and normal exposure, as well as standard industrial risk (fatalities resulting directly from a truck or rail accident). The accident risk from radionuclides or chemicals uses the accident equation discussed previously. Accident rates (accident/kilometer or mile, obtained from the WM-PEIS) for truck and rail transportation are multiplied by the one-way trip distance and the number of trips. The containment failure probability term (2b) is used to model the transport cask failure characteristics (obtained from the WM-PEIS and the SNF programmatic EIS [11]). The atmospheric dispersion and exposure term 4*5p represents an average value for transport between DOE sites.

Normal exposure (to the crew and the public) occurring during transportation was modeled using the following equation:

Risk = (C)(X)(one-way trip distance) (number of trips);

where C = constant (function of waste type and mode of transport - truck or rail)
X = radiation field at one meter outside cask (function of waste type).

The SRM-II has lookup tables for the constants C and X. The constant C in this equation was calibrated using the more detailed transportation models and results in the WM-PEIS. In general, this simplified equation matches the WM-PEIS transportation risk results within 20% on a complex-wide basis when comparable values for X are used. However, the WM-PEIS and the SNF programmatic EIS used conservatively high values of X for HLW and SNF. The SRM-II lookup table for X recommends values that are best estimate, rather than conservative.

To predict fatalities caused by transportation accidents (part of the standard industrial risk), information from the WM-PEIS was obtained concerning the predicted number of fatalities per truck and rail accident. The resulting values, 0.1 fatalities/accident for truck and 0.04 fatalities/accident for rail transport, also include the predicted number of fatalities from vehicle emissions. Note that the trip distance for this calculation is a round-trip distance rather than a one-way distance.

Disposal risk is evaluated for LLW/MLLW, TRUW, and HLW/SNF over a 10,000-year period. The risks considered include intrusion events and transport to the groundwater and subsequent public exposure from wells. The TRUW disposal model is calibrated to the detailed assessments performed for the Waste Isolation Pilot Plant (WIPP).[12] The HLW/SNF disposal model is calibrated to studies performed for Yucca Mountain.[13] LLW/MLLW disposal characteristics depend upon the DOE site in question. In order to determine population risk impacts, the off-site population used in the WM-PEIS was assumed to be constant during the 10,000-year period.

Finally, the environmental impact module covers impacts from accidental releases of radionuclides and chemicals. Environmental impacts considered include the following: extent of land, wetlands, and surface water contaminated and a measure of non-health impacts on the surrounding population; potential for impacting aquifers; potential for impacting endangered or threatened species; and potential for impacting cultural resources (archaeological, pre-historic, and historic). DOE site-specific information on these potential impacts is included in the model. The risk units are dollars. This environmental impact model is more subjective than the human safety and health models in the SRM-II. Both the scope of environmental impacts and the methods for quantifying such environmental impacts are less well developed compared with human safety and health.

The different types of risk modeled in the SRM-II – person-rem from radionuclides, latent cancer fatalities from chemicals, fatalities from standard industrial risks, and environmental impacts measured in dollars – can be presented separately or combined into a total ES&H risk picture. Conversion factors in the model are used to convert person-rem to latent cancer fatalities and then to dollars. Standard industrial accident fatalities are also converted to dollars. The conversions of fatalities to dollars also has the option to account for dollar impacts from standard industrial injuries, based on a general ratio of number of injuries to number of fatalities. The risk analyst has the option to change any of the conversion factors.

III. SRM-II SOFTWARE

The SRM-II has been implemented using the Microsoft Access software platform. For new applications, the user is directed to input general information such as the application title, type of waste and inventory (Ci's and volumes), and initial start date (for the decay of radionuclides). Then information is entered for each activity to be modeled (e.g., initial storage, handling, treatment, transportation, and disposal), using the lookup tables as guidance. When all of the information has been entered, the code calculates the various types of risk for each activity. These risk results can then be added to obtain risk information for the entire program of activities.

The software includes numerous reporting options:

- Radiological risk (person-rem) by activity and for the entire program of activities
- Chemical risk (latent cancer fatalities) by activity and program
- Standard industrial risk (fatalities) by activity and program
- Environmental impact risk (dollars) by activity and program
- Combined radiological, chemical and standard industrial risk (fatalities) by activity and program

- Combined radiological, chemical, standard industrial, and environmental risk (dollars) by activity and program.

These results can be presented for a baseline program or for a comparison between baseline and alternatives. Also, risks can be subdivided into contributions from accidents versus normal operation, public versus worker/site personnel, types of activities, and others types of breakdowns. Finally, risks can be presented by year or by activity.

IV. SAMPLE APPLICATIONS

The sample applications of the SRM-II cover a wide range of examples, from removal of lead from a building as part of the decontamination and decommissioning (D&D) process to the entire DOE complex-wide waste management programs for various waste and material types. Also presented are some preliminary results for constructing site risk curves and benefit-cost comparisons.

The first risk application involved removal of approximately 50 tons of surface-contaminated lead boxes and bricks from a building as part of the D&D process. Figure 1 shows the breakdown of the program into discrete activities. Lead is removed from the building, loaded and transported to an off-site disposal facility, macroencapsulated, and placed into disposal. Risk from each activity is calculated and summed to obtain the overall program risk. Risk results are summarized in Figure 2. The main risk contributors are normal radiation exposure and standard industrial accidents to workers removing the lead from the building (retrieval activities in Figure 1).

The second risk application involved the removal of TRUW from several small quantity sites (SQSs). In general, the base case covered continued storage at the SQS until shipment to WIPP and disposal. The alternatives covered the shipment of the TRUW to one of several DOE sites for interim storage and later shipment to WIPP and disposal. Risk analyses covered initial storage at the SQS, preparation for shipping, shipment to another DOE site, interim storage, certification, shipment to WIPP, and disposal at WIPP. Sample results for one of the SQSs are presented in Figure 3. Although not shown in the figure, the dominant risk contributor for the baseline and alternatives is from off-site transportation of the TRUW.

The third analysis was performed with the original SRM but will be re-analyzed using SRM-II. This analysis covered the DOE complex-wide programs for HLW, TRUW, LLW, MLLW, and SNF.[4] The baseline programs for each DOE site and waste or material type were subdivided into discrete activities. SRM risk results for each activity were then combined to obtain site-wide and complex-wide risk results. Risk results at the DOE complex-wide level are presented in Figure 4. Note that the risk results are radiological risks, presented in terms of person-rem, because the SRM did not have a standard industrial risk module at the time of the analysis. Also shown in Figure 4 are the comparative results for a potential alternative program of waste management, involving various cost savings and schedule enhancement changes to the baseline programs. This alternative is described in detail in the report *A Contractor Report to the Department of Energy on Environmental Management Baseline Programs and Integration Opportunities (Discussion Draft)*.[14]

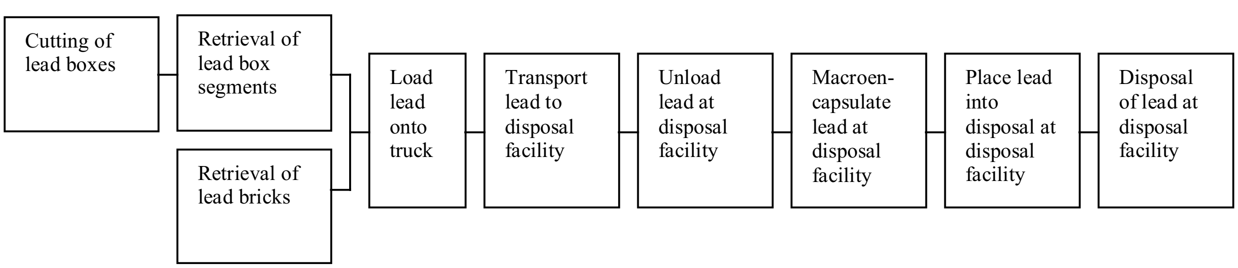

Figure 1. Activities modeled as part of lead removal program.

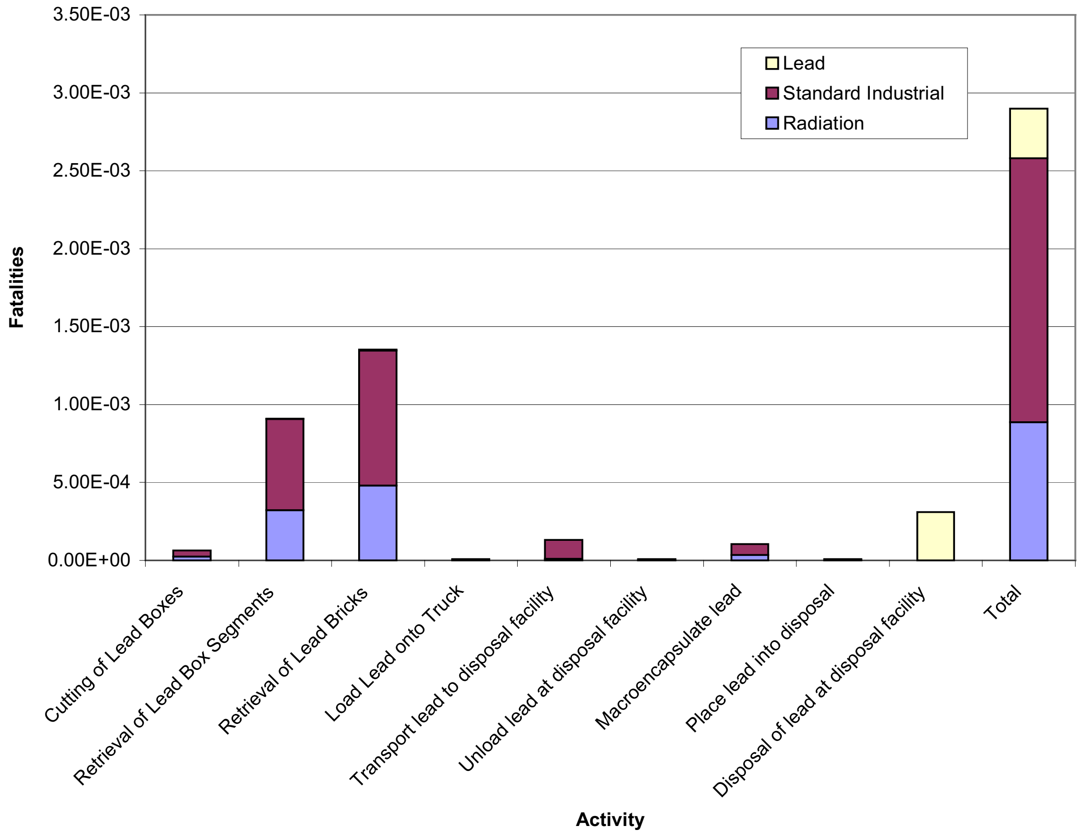

Figure 2. Human safety and health risks for lead removal program.

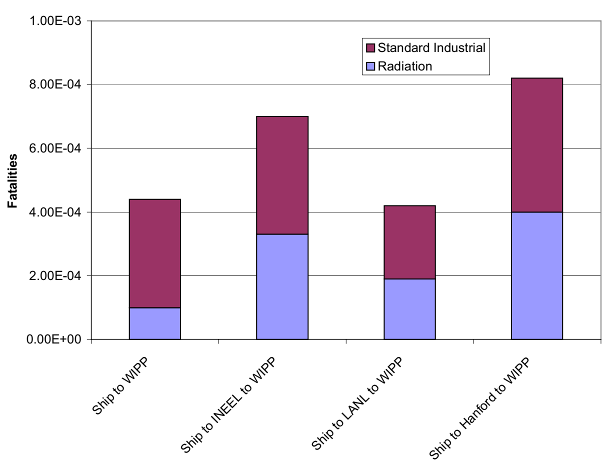

Figure 3. Human safety and health risks for SQS baseline and alternatives.

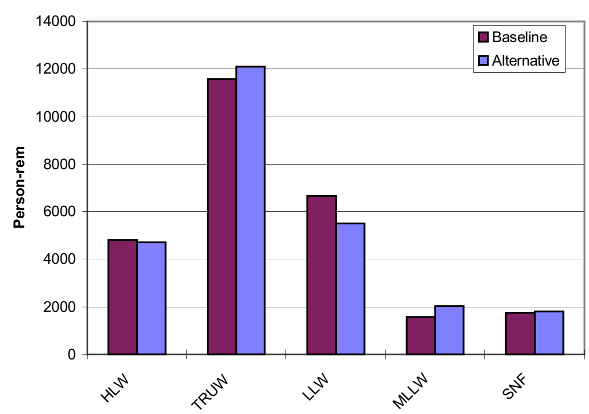

Figure 4. Human safety and health risks for DOE complex-wide programs.

The final sample risk application involves the development and application of site risk curves with time. The EMI program at the Idaho National Engineering and Environmental Laboratory (INEEL) has been investigating ways to measure the risk benefits of waste management activities. The EMI program has also been looking for ways to evaluate and portray the risk impacts of intersite transfers of waste materials. One approach being investigated involves the concept of a "no action" risk. The "no action" risk for a waste stored at a DOE site might be defined as the human safety and health risk from the waste for a 10,000-year period, similar to the assessment period for waste repositories. Waste stored at a site is analyzed for a 100-year institutional control period and a 10,000-year uncontrolled period. The 10,000-year risks include those from human intrusion into the waste (after the 100-year institutional control period), resuspension (into the atmosphere) of surface-stored waste that eventually degrades and mixes with the soil, and transport to the groundwater. This "no action" risk scenario was evaluated in the WIPP EIS for several major DOE TRUW sites under the "No Action Alternative 2." [12] The resultant "no action" risk for each waste type and form at a given site can be converted to a "no action" unit risk factor (URF), with units of fatality/Ci. Representative URFs for waste stored at the INEEL are presented in Figure 5. For HLW, the liquid stored in underground tanks has a URF that is almost ten times higher than the calcine (powder). This is mainly the result of the material form change; the calcine is better at inhibiting releases of radionuclides to the groundwater or to the atmosphere (from accidents). When the HLW is converted to a glass form (vitrification process), the URF drops to a level even lower than the calcine HLW. Finally, if the vitrified HLW is placed into disposal at a repository such as Yucca Mountain, then the URF drops several orders of magnitude. For TRUW, the URF for WIPP disposal is many orders of magnitude lower than the INEEL value for TRUW storage above ground in buildings. In both cases, the repository is much more effective in protecting the public from risk than is long-term storage (and subsequent loss of institutional control) at the INEEL.

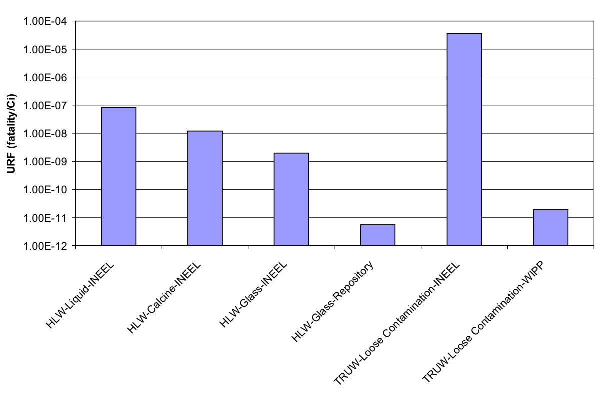

Figure 5. "No action" URFs for INEEL and repository waste forms.

Given yearly information concerning the number of Ci's for each material type and form at a site (these Ci's may change yearly as waste management operations occur), one can construct a site risk curve as shown in Figure 6 for the INEEL. The site risk for each year is just the sum of the products of URFs and corresponding Ci's. Each year's risk total represents the "no action" risk from all of the waste and material types stored at the site. This risk typically drops over time as less stable waste forms are converted to more stable forms, and wastes are shipped off-site and placed into disposal.

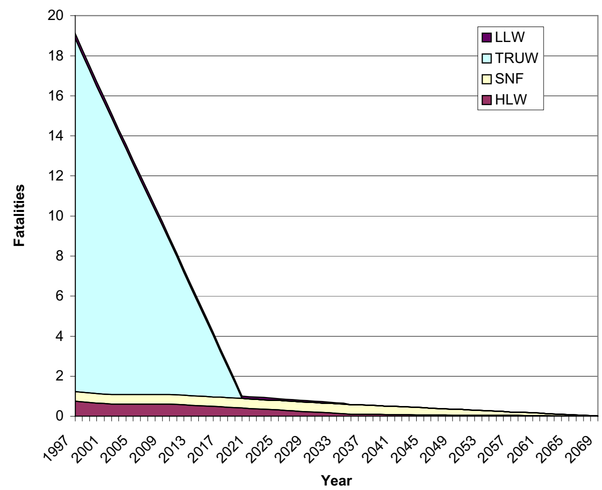

Figure 6. INEEL "no action" site risk curve.

The site risk curve is especially effective in illustrating the risk benefits of moving DOE waste to a repository. The INEEL site risk curve drops dramatically as TRUW is shipped to WIPP for disposal. The HLW contribution also drops as liquid HLW is converted to calcine, later converted to glass, and finally shipped to a repository.

Site risk curves might also be effective in illustrating the site risk impacts from intersite waste and material transfers. Acceptance of waste from another site results in an increase in site risk. However, waste management activities at the site or shipment of other wastes off-site would tend to reduce the site risk. Therefore, the site risk curve may continue to drop with time even with shipments of waste to the site.

A final use of the "no action" site risk curve concept is to develop human safety and health risk benefit-cost comparisons. If INEEL HLW is converted from liquid to calcine, the benefit could be defined as the drop in site risk resulting from the conversion (site risk resulting from the liquid HLW minus the site risk from the same HLW in a calcine form). The cost could be defined as the risk incurred from the conversion activities, as determined from an analysis using the SRM-II. A sample benefit-cost comparison for INEEL HLW is presented in Figure 7 (on a 1E+6 Ci basis). As indicated in the figure, the human safety and health risk benefit from converting INEEL HLW from liquid to calcine is much greater than the cost (risk incurred from the operations required to convert HLW liquid to calcine). The same is true for conversion from calcine to glass, and for shipment of the glass and placement into a repository. It should be noted that decisions concerning whether to perform such conversions must be made using a wide variety of inputs, such as cost, regulatory compliance, and others, as well as human safety and health risk. However, the SRM-II analysis can be used to provide to the decision-maker a clear and consistent benefit-cost comparison for the human safety and health risk.

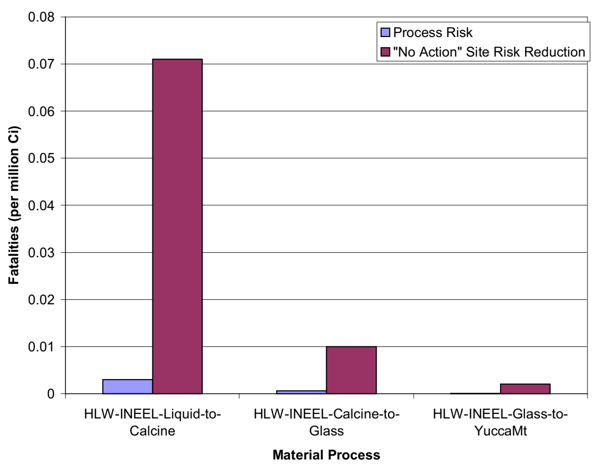

Figure 7. Human safety and health risk benefit-cost comparison for INEEL HLW processing.

It should be noted that these "no action" URF and site risk curve concepts and applications are preliminary. Further work is needed to define the range of URFs possible given various modeling assumptions. The usefulness of these concepts to the EMI program and to DOE still needs to be evaluated.

V. DISCUSSION AND INSIGHTS

The newly developed SRM-II is an efficient and quantitative risk methodology and software package for application to DOE waste management activities. The methodology allows for comprehensive coverage of all types of activities, which can be important in cases where it is not clear which activities might be most important from a risk perspective. The SRM and SRM-II analyses performed to date have indicated that, depending upon the application, a variety of activities (storage, treatment, handling, or transportation) and types of risk (accident or normal; public or worker; or radiological, chemical, or standard industrial) can contribute significantly to the overall S&H risk picture. It should be noted that in many applications, enough variables are present (type and form of waste, types of activities, and others) to make it difficult to qualitatively compare risks. The strength of the SRM-II analyses lies in its quantitative basis.

Although the SRM-II methodology involves simplifications of more detailed risk models and applications, the comprehensiveness and flexibility in the risk applications allow the risk analyst to obtain insights that may not be available from the more detailed analyses. For example, the SRM-II can cover all significant risk activities in a program, ranging from initial storage through final disposal. Most detailed risk analyses focus on only a subset of possible activities. Also, these more detailed analyses are often performed to obtain conservatively high risk estimates. Finally, the flexibility in the SRM-II lookup tables allows the risk analyst a wide range of choices for facility accident characteristics. If initial storage of waste is in an old building with a substandard seismic design, the analyst can choose the appropriate seismic accident characteristics from the lookup tables.

Another potential benefit of the SRM-II methodology and software is the ability to efficiently perform sensitivity studies. Many of the risk model parameters are contained in lookup tables, allowing the analyst to make global changes to these parameters (affecting the risk estimates of all activities modeled) and immediately see the impacts on the risk estimates.

Finally, the preliminary risk work involving "no action" URFs and resultant site risk curves and benefit-cost comparisons appears to have promise to be beneficial to the EMI program and to DOE. The *EM Integration Handbook* [15], which provides general guidance for the identification and analysis of integration opportunities, indicates that the two main risk questions to be considered are the following:

1. How much risk reduction is achieved from the EMI activities? (What is the difference in risk between the present state and the proposed end state?)

2. What are the risks to the public, workers, and the environment from (during) the EMI activities?

The site risk curves developed from the SRM-II can be used to answer the first question. Also, typical SRM-II analyses of EMI activities answer the second question. The use of benefit-cost comparisons provides a way to answer both questions at once. Finally, the site risk curves may be effective in illustrating impacts on site risk from intersite transfers of waste and waste management activities.

VI. ACKNOWLEDGMENTS

The authors would like to acknowledge several contributions to the development of the SRM and SRM-II. The precursor to the SRM was the risk modeling performed by G. A. Beitel and T. H. Smith as part of a site-wide integration effort at the INEEL in 1995. Also, T. H. Smith, R. G. Peatross and I. E. Stepan contributed significantly to the development of the original SRM. Finally, J. A. Murphy was instrumental in the development of the site risk curve concept.

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