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Parameterization of Structures in HE Composites Using Surrogate Materials : A Small Angle Neutron Scattering Investigation

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Introduction

High explosive materials used in the nuclear stockpile are composites of crystalline high explosives (HE) with binder materials, such as Estane. In such materials, there are naturally occurring density fluctuations (defects) due to cracks, internal (in the HE) and external (in the binder) voids and other artifacts of preparation. Changes in such defects due to material aging can affect the response of explosives due to shock, impact and thermal loading. For example, porosity and pore size distribution exert a strong influence on the ignition threshold behavior. Shifts in the pore size distribution or pore location in an explosive can markedly change the explosive response to shock and impact stimuli. Modeling efforts are attempting to provide quantitative descriptions of explosive response from the lowest ignition thresholds to the development of full blown detonations and explosions, however, adequate descriptions of these processes require accurate measurements of a number of structural parameters of the HE composite.

Since different defects are believed to affect explosive sensitivity in different ways it is necessary to quantitatively differentiate between defect types. Standard metallographic techniques, such as cutting and polishing samples can be adequate for measuring particle size distributions, but are may be inadequate for measuring pore size distributions because the softness of the materials causes the surface pores to be filled in polishing. Even for measuring particle size distributions, extreme care must be taken to avoid introducing bias, as a result of preferential ejection of the smallest particles from the surface. Small angle neutron scattering (SANS), however, provides an important non-destructive complementary method to provide detailed information on important structural parameters over length scales relevant to properties predictions and the impact of changes in these parameters. Employment of the SANS technique will enable measurement of the scattering function arising from specific defects. As structural changes due to specific damage mechanisms or environmental factors (impact, aging, thermal cycling, etc.) will result in changes in the scattering function, SANS will enable a quantitative assessment of the magnitude of these external factors. These issues impact on understanding the characteristics of materials in the nuclear stockpile and are important in planning surveillance and rebuild strategies.

We report here preliminary results of SANS measurements on surrogates for HE materials. The objective of these measurements was to develop methodologies using SANS techniques to parameterize internal void size distributions in a surrogate material, sugar, to simulate an HE used in the stockpile, HMX. Sugar is a natural choice as a surrogate material, as it has the same crystal structure, has similar intragranular voids and has similar mechanical properties as HMX. It is used extensively as a mock material for explosives. Samples were used with two void size distributions: one with a sufficiently small mean particle size that only small occluded voids are present in significant concentrations, and one where the void sizes could be larger. By using methods in small-angle neutron scattering, we were able to isolate the scattering arising from particle-liquid interfaces and internal voids.

Small Angle Neutron Scattering

SANS can provide detailed structural information on length scales ranging from 10 Å to a tenth of a micron and is widely used in materials¹, polymer² and colloidal science³. In a scattering experiment, a collimated beam of neutrons of wavelength, λ , illuminates a sample. A fraction of the incident beam will be scattered by the sample at some angle, 2θ from inhomogeneities in neutron scattering length density, ρ . The $\rho(\mathbf{r})$ at any particular point, $\mathbf{r}$, in the sample is defined as the sum of the atomic neutron scattering amplitudes, the scattering lengths, in a small volume around that point divided by the volume. Thus, $\rho(\mathbf{r})$ reflects microscale structure in the sample in both density and chemical composition. The scattered intensity, $I(Q)$, is measured as the absolute differential cross section per unit scattering mass ($\text{cm}^2 \text{mg}^{-1}$) as a function of the magnitude of the scattering vector, Q . For elastic scattering events, $Q = (4\pi/\lambda) \sin\theta$. There is a Fourier transform relation between $I(Q)$ and $\rho(\mathbf{r})$. Though this relationship can be stated in general form, we will discuss it for the case of interest in this study, a system containing a collection of particles uncorrelated in position and orientation,

$$I(Q) = K \left\langle \left| \int \rho(\mathbf{r}) \exp(-i\mathbf{r} \cdot \mathbf{Q}) d\mathbf{r} \right|^2 \right\rangle \quad (1)$$

where $\langle \rangle$ represents a spherical average. The expression in the angle brackets is the particle form factor, $P(Q)$. The constant, K , in Eq [1] is itself proportional to $\Delta\rho^2$, $\Delta\rho = \overline{\rho_p} - \rho_s$ is the contrast between the average scattering length density of the particle, $\overline{\rho_p}$, and the solvent scattering length density, ρ_s . Thus, $I(Q)$ gives information about particle size and shape.

The initial step in data analysis for particles, the shape and average size of the scattering body can be determined by Guinier analysis⁴. There are three forms of the Guinier approximation, each form applying to a different local particle geometry.

For particles (defects), in the range $Q < R^{-1}$, where R is the average radius of the particles, the Guinier approximation has the form :

$$I(Q) = \frac{fV_p^2 \Delta\rho^2}{M} e^{-\frac{Q^2 R_g^2}{3}}, \quad (2)$$

where f is the volume fraction of scatterers of volume V_p , M is the mass of the scatterers and R_g is the radius of gyration.

Once a general idea of the particle size and shape is obtained (from Guinier analysis), the models may be further refined by fitting the observed scattering, over a wide range of Q , to a particle form factor, keeping in mind that the observed scattering intensity is Eq. [1] convoluted with the instrument resolution⁴. In general the particles are not all the same; rather, there is at least some polydispersity in size and shape. In modeling this system, we must take into account possible polydispersity by calculating the appropriate population average of the form factor, $\langle P(Q) \rangle$.

Over length scales such that $QR \gg 1$, where R is the average size of the scattering particle (domain), the scattering can be described as a negative *power-law* :

$$I(Q) = I_0 Q^{-\alpha}, \quad (3)$$

where α and I_0 are constants. This type of scattering is common in fractal systems, with the value of α being indicative of the dimensionality of the system. For the special case of spherical interfaces, $\alpha = 4$ and the scattering is termed *Porod-Scattering*⁴. In this case, $I_0 = 2\pi A \Delta\rho^2$, where A is the interfacial area per unit volume of the sample.

contrast variation

In order to obtain additional information on particle-size and internal structure, the method of contrast variation is often used. The sample of interest can be thought of as a population of particles suspended in a uniform solvent. The structure of the particles can then be modeled as^{1,4}:

$$\rho(r) = \rho_s + (\bar{\rho}_p - \rho_s)\Omega(r) + \zeta(r),$$

where $\bar{\rho}_p$ is the average of $\rho(r)$ within the particle, $\Omega(r)$ is the shape of the solvent-excluding parts of the object and $\zeta(r)$, equal to $\rho(r) - \bar{\rho}_p$, is the internal structure function. The contrast is the difference between the average of the object scattering length-density and that of the solvent, $\Delta\rho = \bar{\rho}_p - \rho_s$. The condition that $\Delta\rho = 0$ is known as the contrast match point.

From Eq. [1] the scattering intensity can be written as a quadratic in $\Delta\rho$ ^{1,4}:

$$I(\Delta\rho, Q) = \Delta\rho^2 I_\Omega(Q) + \Delta\rho I_{\Omega\zeta}(Q) + I_\zeta(Q). \quad (4)$$

Here, the coefficients, $I_\Omega(Q)$, $I_{\Omega\zeta}(Q)$ and $I_\zeta(Q)$ are the scattering intensity due to the shape of the sample region that excludes solvent, the scattering due to correlations between the shape and internal structure of the solvent-excluding part of the sample and the scattering intensity from the internal structure of the solvent-excluding part of the objects, respectively. In an experiment, a minimum of three values of $\Delta\rho$ are needed to well define these contributions. Typically, measurements are performed, at, above and below the contrast match point.

Experimental

SANS measurements were performed at the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory, employing the Small-Angle Neutron Diffractometer (SAD). Scattering data were acquired on a 2-dimensional area detector using the time-of-flight method and were corrected for empty cell, background and solvent scattering. The data were reduced to yield intensity vs. Q plots and placed on an absolute scale using the known cross section of an irradiated aluminum sample, Al-4. The resulting data were analyzed by the methods discussed in the preceding sections.

Component	$\rho (\times 10^{10} \text{ cm}^{-2})$
sugar	1.7
dichloroethane	1.4
d-dichloroethane	4.3

Table I : Calculated scattering-length densities for the sugar and solvent components.

The samples consisted of granulated sugar and powdered sugar as well as a mixture of granulated and powdered sugars, providing three distinct particle distributions. Samples of each particle size were pressed into disks at different densities, 21 mm in diameter and 2 mm thick, to provide differences in external void size. The disks were saturated with a mixture of deuterated and non-deuterated dichloroethane before being sealed between two quartz windows. Sugar is not soluble in Dichloroethane; thus the intragranular voids will not be accessible to contrasting medium. The amount of deuterated solvent was systematically varied in order to adjust $\Delta\rho$. Table I lists the scattering length densities for the different components involved in this study. For this work, three different contrast levels ($\Delta\rho = -2.6, 0.0$ and $1.7 \times 10^{10} \text{ cm}^{-2}$) were studied for each sample, enabling a determination of the different contributions (I_Ω , I_ζ and $I_{\Omega\zeta}$, Eq. [4]) to the overall scattering.

Data and Analysis

In all, six different series of measurements were made. Each series consisted of scattering measurements at three different contrasts. Figure 1 displays Intensity vs. Q plots for the P86 series which are representative of all of the samples studied. Here, the notation P stands for powdered

sugar (G $\Rightarrow$ granulated and M $\Rightarrow$ mixed) and the number 86 implies that the sample was pressed to 86% of its maximum density. As can be seen from Fig. 1, There are significant contrast-dependent effects observed in the scattering.

Figure 1: Intensity vs. Q plot for the P86 series. The zero-angle scattering scales as $\Delta\rho^2$, as expected.

The results of contrast variation analysis, for the P86 sample, are shown in Figs. 2-4. The basic scattering functions are calculated by root mean squared, weighted linear regression of the contrast using Eq. (4). The first term, I_α , gives information about the contribution of the shape of the particle, to the total scattering, independent of the contribution of the internal structure. As seen in Fig. 2, the scattering can be described as power-law scattering. A fit to Eq. 3 (shown as a solid line in the figure) yields a value of 3.79 ± 0.25 for α , suggesting that the surfaces of the sugar granules are not entirely smooth. Similar shape functions were found for the other samples. A summary of the fitted values of α can be found in Table II.

	G31	G58	G78	P78	P86	M78
α	—	3.94 ± 0.45	3.56 ± 0.72	3.81 ± 0.29	3.79 ± 0.25	3.63 ± 0.44

Table II: Summary of exponents obtained from simple power-law fits to the shape functions (I_Q), resulting from contrast variation analysis, of the different samples. Note: due to poor counting statistics, no value of α was obtainable for G31.

Figure 2: Shape function for the P86 sample. The solid line is a fit to a simple power-law. A value of -3.79 ± 0.25 was obtained for α and is consistent with the scattering from surface fractals.

Figure 3 shows the calculated internal structure function, I_s , which, being from the solvent excluding parts of the crystal, should reflect the internal void structure. Guinier analysis of I_s using Eq. (2) indicated the presence of globular particles with R_g equal to 223 ± 5 Å. The solid line in the

figure is the calculated scattering for a spherical particle of 275 Å radius plus a flat, incoherent background. The model calculation shows reasonable agreement with the data. Both the model and Guinier result are consistent with spheroid internal voids. The slight discrepancy is likely from the anticipated polydispersity in void size. Similar analysis of the P78 sample gave a value of 325 Å for the average internal void size. This value is in good agreement with that measured for P86, as would be expected, since the two samples differ only in external void size. Quantitative analysis of the internal structure functions for the remaining samples was not possible, due to the poor statistical nature of the data. These experiments are preliminary measurements intended to determine the feasibility of using SANS and the method of contrast variation to measure sugar void sizes. We will use the facilities at LANSCE to obtain data with sufficient Q-range and statistics to characterize the polydispersity.

The cross-term, $I_{\alpha\beta}$, is shown in Fig. 4. A striking feature of the data is the negative values

Figure 3: Internal structure function as calculated from Eq. 5. The solid line is a model calculation for a sphere of 275 Å radius.

observed for Q less than $0.04 \text{ \AA}^{-1}$. Normally, such a feature reflects the characteristic of the internal structure such that material of higher scattering length density surrounds material of lower scattering length density. In the current system, this might indicate the presence of water, from the manufacturing process, inside the voids. However, it is still possible that this result is merely an artifact which reflects the polydispersity of the system and insufficient statistics of the measurements. In which case, additional measurements should clarify this point.

Contrast variation analysis of the other samples gives similar results. The shape functions are consistent with slightly rough surfaces and the internal structure with that of polydispersed spheres. There is no general trend to the cross-term with some samples displaying scattering functions similar to Fig. 4. and others displaying weak power-law behavior. This behavior supports the notion that the negative values seen may be artifacts and that additional measurements are needed.

Figure 4: Cross-term, $I_{\alpha\zeta}$, obtained from contrast variation analysis. The negative values at low- Q may be artifacts, arising from poor statistics.

Conclusion

In summary, we have used SANS in conjunction with the contrast variation technique to measure the scattering function of HE surrogate (sugar) materials. Contrast variation analysis indicated that the sugar granules contain internal voids which are, on the average, spherical in shape. However, the data obtained on correlations between scattering from internal and external surfaces was, due to poor statistics, inconclusive.

The preliminary results described here are very encouraging. We have shown that SANS can distinguish between scattering contributions arising from external surfaces (internal/external) and internal voids within a system and, with the application of the contrast variation technique a more definite determination of particle shape and structure can be made. Thus, we have demonstrated that the SANS technique is applicable to the investigation of HE composites and, with refinement of methodologies, can provide the necessary structural information required by advanced material models.

Future Plans

Further Analysis of the current data is limited by insufficient counting statistics and a limited Q-range. Improvement in these two areas will enable a precise determination of particle structure and size distributions. We plan to repeat these measurements at the Manuel Lujan Jr. Neutron Scattering Center (MLNSC), low-Q instrument, LQD, which offers a much wider Q-range (~ 2 times) and an increased source strength (3 to 4 times) compared to that of the current measurements at IPNS. With these additional measurements, we are confident that a more definitive statement about the structure and size distribution of the current system can be made. We also note that the current measurements, due to the small difference in scattering length density between voids and the sugar, present a much more difficult problem than measurement of actual HE material which, due to its high nitrogen content, has a significantly larger scattering length density than the voids.

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TITLE: Reviewer's Perspective: Prioritization Using Risk-Based
Methods Within a Regulatory Environment

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REVIEWER'S PERSPECTIVE: PRIORITIZATION USING RISK-BASED METHODS WITHIN A REGULATORY ENVIRONMENT

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ABSTRACT

Risk-based prioritization (RBP) has been recognized as a potentially useful tool for allocating limited resources and to provide critical information into the management and regulatory decision-making process. Although several methodologies have been developed over the years, there is no generally accepted RBP methodology in use today.

The RBP methodology presented here uses the results of the hazard analyses (HAs) developed in preparing Safety Analysis Reports (SARs) for Department of Energy (DOE) facilities. The goal of RBP is an analysis that evaluates and prioritizes the identified hazards for a facility or activity to generate the needed risk-based information for assisting management and regulators in the decision making process.

Care must be exercised when developing a RBP system within a regulatory environment because of the tendency to overly standardize the process, causing the process to lose its flexibility and thus lose its effectiveness in maximizing safety. However, standardizing does have its benefits, such as facilitating the review and approval process and providing an even "playing field" for comparing the relative risks from one facility or activity with another. A "rigid" safety program often finds itself ineffective when applied to a wide range of activities, especially in the research and development environment. The action of just meeting regulatory requirements often leads to nonconservative steps within the safety analysis itself.

The imposition of Risk Acceptance Guidelines complicates the process as well. These are effectively constraints on the allocation of resources because they may require allocation of resources to lower benefit-to-cost-ratio activities to meet regulatory requirements. This leaves fewer resources available to use on higher benefit-to-cost-ratio activities (assuming resources are fixed).

The key to making the system work effectively is to balance the regulatory-driven steps in the process with "sound" safety principles. Prioritizing the hazards using a risk-based method is an effective means for judging the need and cost-effectiveness for mitigative systems and procedures. It is within this process that the safety analyst has the opportunity to make the "system" work to enhance safety.

I. INTRODUCTION

The principles of decision analysis can be used to develop a risk-based decision process that integrates required Department of Energy (DOE) Safety Analysis Reports (SARs) with risk management policy to provide facility managers with a decision process for systematic and consistent management of risk.

Risk management activities, such as prioritizing risk-reducing projects, often are commissioned for facilities as special tasks supported by special task forces and conducted independently of other on-going risk assessment and risk management activities. Many DOE facilities have hazard assessments (HAs) as part of their efforts to upgrade their SARs to meet the new DOE Standard that was issued in 1994. Although a complete SAR would contain more resource allocation information than the HA, the HA usually is completed before the SAR.

This paper describes how SAR results, and particularly HA results, can be used directly to support managers' risk-based prioritization (RBP) of project funding. This can reduce the time to conduct prioritization modeling, raise the quality of the results, and, perhaps most importantly, integrate the results into the on-going risk management activities of the site. This paper is based on work done previously by one of the authors.¹

II. BACKGROUND

DOE-STD-3009-94 (STD-3009)² provides guidance for the preparation of SARs for nonreactor nuclear facilities and is based on DOE Order 5480.23.³ STD-3009 gives the "new standard" guidelines for managing risk at DOE facilities dealing with nuclear materials.

DOE STD-3009 defines *hazard* as "a source of danger" to health, the environment, or operations, "without regard for the likelihood" of occurrence of the accident resulting in the danger. It defines *risk* as the expression of the probability that an event will occur and the consequence (the hazard) of that event. This paper uses these terms consistent with the DOE definitions. The Standard formally incorporates under "hazard" the DOE concern for worker safety and the environment in addition to on-going protection of the public. This represents "a new emphasis for SARs" within DOE according to the Standard.

The initial SAR analytical effort for all facilities is a HA that systematically identifies facility hazards and accident potentials through hazard identification and evaluation. Detailed discussion of hazard identification and evaluation is presented in Ref. 4. This is a qualitative effort that forms the basis for the full SAR, "including specifically addressing defense in depth and protection of workers and the environment." The HA

- considers the complete spectrum of accidents that may occur;
- analyzes potential consequences to the public, the workers, and the environment;
- estimates likelihoods of occurrence;
- identifies preventive and mitigative features; and
- identifies a selected subset of accidents for formal quantitative analysis.

The HA uses information from sources *outside* the SAR process, develops an understanding of the hazard sources, and then provides these estimates to management for operational responses to manage the hazards. This process is shown in Fig. 1 for worker safety hazards.

The HA results provide the link between important resources available for assessing facility risks and the operational safety changes that are developed to manage risks at a facility. Because of its logical importance in translating existing risk assessment information into future risk management activities, the HA can play a crucial role in influencing budget decisions and maintaining risk control at DOE facilities.

The accidents identified in the HA process are ranked qualitatively using a "likelihood and consequence ranking matrix;" an example is shown in Fig. 2. This qualitative ranking is the basis for focusing analysis efforts on the most significant risks. The accident analyses use quantitative

methods for evaluating the risk and the effectiveness of preventive and mitigating features to control it.

A. Levels of Hazard Evaluation

The level of information appropriate for hazard evaluation depends on, among other things, the life-cycle stage of a facility. Figure 3 shows how the level of hazard evaluation varies over the life cycle of a facility.

In addition to the life cycle stage of the facility, the level of information is influenced by the type of the process, its size and complexity, and the nature of the operations taking place in the process or facility.

- *Type of process.* This refers to the inherent functions of the process and includes the chemical, physical, mechanical, biological, electrical, computer, and human components of the process. Some techniques are better suited for modeling some processes than others. For example, failure mode and effects analysis (FMEA) is effective in evaluating computer systems, but hazards and operability analyses (HAZOPs) are more useful in analyzing processing systems.
- *Size and complexity.* Hazard evaluation should be conducted at a level compatible with the purpose of the study. The complexity and size of the hazard problem should be matched by the appropriateness of the evaluation technique so that useful insights are produced in a timely manner, consistent with the level of effort and information available.
- *Nature of operations.* The operations may be continuous, batch, fixed in location or mobile, robotic or labor intensive, long-lived or transient.

Fig. 1. HA process for worker safety issues.

Fig. 2. Basis for qualitative ranking of risks in the HA process.

Fig. 3. Levels of hazard evaluation used at different stages in a facility's life cycle.

The charts in Figs. 2 and 3 show that HAs use a large amount of external existing information; they integrate this with facility-specific accident analyses; and they are conducted early in the life of a facility. In addition, they are required by DOE as part of the SAR process. Clearly, HAs represent a valuable source of information that can aid risk-based decision making. In addition to obtaining valuable inputs to the risk management process, the resulting insights can be incorporated into the formal SAR process at an early phase in the facility's life cycle.

B. Linking HA Results and Risk-Based Prioritization

Because HAs occur early in the development of SARs, they are frequently available when decisions about possible upgrades or improvements of facilities are being evaluated. In addition, the facility SAR becomes a living document and is updated annually. HA results can be used as input to RBP of mitigative features both early in the facility life cycle or later when upgrades are considered. In turn, RBP of mitigative features can aid further detailed accident analysis and risk assessment that comes later in the SAR process. This is done by identifying the hazards and potential mitigations that have the best benefit-to-cost characteristics.

RBP serves the SAR process in two ways.

1. It uses HA analysis results to produce insights for risk managers that aid them in determining how best to allocate scarce resources to improve the overall safety of their facilities.
2. It provides analyses that are useful in conducting the quantitative analyses later on in the SAR process by focusing analysis on the most cost-effective hazard reduction options.
3. It also can use and integrate results from other parts of the SAR that call for resource allocation.

HAs provide key inputs to the SAR process by identifying hazards; prioritization uses HA results to help focus attention on those activities that most effectively reduce hazards.

III. RISK-BASED DECISION MAKING: THE METHODOLOGY

Risk management, or "risk-based" decision-making, is not a particular technique or methodology but rather a general description that can be applied to any decision-making procedure that explicitly takes risk into consideration when evaluating activities. Because "risk" can mean different things to different people, it is important for the organization to clearly define what risk means and how it will be taken into account in evaluating decision options. In this paper, we propose to define risk as any threat against achieving an organization's fundamental objectives. The next section describes the methodology used to formally incorporate HA results into risk-based prioritization of risk-reducing activities for plutonium risk management.

The prioritization methodology used in this application is based on multiattribute utility theory. This is a prescriptive methodology for modeling uncertainty and consequence values when there are multiple objectives to be achieved, multiple stakeholders, and significant uncertainty. The methodology uses probability to quantify uncertainty and uses utility to quantify the value of consequences. The axioms underlying the methodology guarantee that if the axioms hold true, the best way to prioritize activities is based on their expected benefit-to-cost ratio. Several references provide general descriptions of the underlying theory and its development, including Clemen,⁵ Keeney and Raiffa,⁶ and Raiffa.⁷ Multiattribute utility theory has been applied to the evaluation and prioritization of risk-reducing activities in many different contexts and at different levels of detail.

A. Defining and Identifying Risk

Because risk can mean very different things in different contexts, it is important to make the meaning as specific as possible for each application. The structure for this definition process for a given application begins with the general definition that risk is the possible occurrence of an undesirable outcome. This definition includes the idea of *value* because the outcome is identified as undesirable; it also includes the idea of uncertainty because the outcome is possible but has not already occurred.

1. Value and Its Role in Defining Risk. The definition of risk begins not with scenarios but with identification of the resources of value that a facility is trying to protect. This is accomplished by specifying the objectives of the facility; risk is the possibility of an undesirable effect on the achievement of these objectives. When the objectives have been identified, quantitative scales are developed to measure the severity of impact on these objectives. These evaluation measures do two things: (1) they make specific what is meant by the objective statement, thereby clarifying facility objectives and (2) they make explicit the degree of risk associated with an outcome.

2. Objectives. Defining objectives is the basis for defining consequences—the first step in identifying hazards. The DOE standard for SARs identifies the common objective for all DOE facilities: accomplishing the mission of the facility while protecting the public, worker safety, and the environment.

The DOE standard is not specific about what values of the public are protected, but it would include at a minimum the public health and safety. DOE "Programmatic Commitment" as described in the SAR standard is a means for achieving the fundamental objectives listed above. Because only fundamental objectives are used in identifying hazards, programmatic commitment is not listed explicitly but is implicitly present as a means to achieving these safety objectives.

3. Measurement Scales and Value Functions. It is still necessary to define what "undesirable" means for each of the objectives. This requires development of measurement scales and associated value functions. The measurement scales show the units in which impacts on the objectives are measured, and the value functions show what is preferred as an outcome. The DOE standard refers to this issue regarding worker safety as "the fundamental question of how worker safety is most appropriately addressed [measured] in the SAR."

This two-step process reflects both technical and value judgments. The technical judgment is the determination of the appropriate scale for measuring impacts on the objective; for example, the best way to measure impacts on human health. The value judgment is the determination of what is preferred.

The HA process is an aid in developing both measurement scales and value functions. There are often existing databases reflecting regulatory requirements for reporting effects in various operational areas such as worker health, environmental impacts, or regulatory violations that can help in establishing measures. HAs also provide direction for developing value functions by indicating relative risk ranks for various levels of impacts, ranging from very serious (risk rank 1) to almost benign (risk rank 4). This value structure can aid the decision process by identifying the most significant risks.

4. Uncertainty. Scenarios are the sequences of events that can result in an undesirable impact on the facility's objectives as measured by the measurement scales and associated value functions (telling how great the impact was and how undesirable it was). The event uncertainties are quantified by probabilities and the sequence of events is represented by event trees.

The HA process provides a structured approach to this activity. Process flow diagrams describe the normal operations of the facility; base maps describe the surrounding context within

which the facility operates; policies and procedures describe the work processes at the facility. Using these descriptive documents, a team of persons familiar with the operations can identify the following components of risk scenarios.

- Process hazards such as (a) inventories of hazardous materials, (b) extreme operating conditions such as erosion processes or bad vibrations, and (c) extreme procedures such as overcrowding exits
- Initiating events such as (a) processing upsets resulting from interrupts, (b) management system failures such as inadequate staffing, (c) human errors such as operating errors, and (d) external natural events such as earthquakes
- Intermediate or propagating events such as protection failure, detection failure, power failure, ignitions, and lack of system response
- Incident outcomes such as discharge, fire, detonation, release, exposure, and so on. The outcomes are defined further in terms of the facility objectives and the measurement scales used to capture the severity of impact. These might include health impacts, violation levels, environmental degradation, community concerns, and so on.

Probabilities are estimated using both frequency data and expert judgment. There are often frequency data for initiating events. These can be used as a base-level frequency estimate for a scenario. The HA team then can estimate the probabilities of various events following the initiating event. These estimates can be made by developing models of the processes involved, doing simulations, performing statistical analyses, or obtaining judgmental assessments from process experts. In each case, the basis for the estimate is made explicit, and the auditability of the assumptions, judgments and data use is maintained.

The result is an estimate of the scenario probabilities and consequences because the sequence of events for which the probability estimates are made defines an outcome. This provides the basis for developing a risk profile describing a risk distribution: probability of occurrences and the consequences associated with these occurrences.

B. Developing Responses to Identified Risks

The HA process involves identifying problems before they occur; evaluating the risk associated with these problems, including the probability of occurrence and the magnitude of the consequences; ranking these risks; and exploring possible preventive or mitigative actions.

Risk-based prioritization ranks responses to risks based on the effectiveness of the responses rather than ranking risks. However, the process uses the HA ranking because after potential high-risk problems are identified, it is possible to identify responses to reduce these potential risks. Risk reduction can include reducing the frequency, or the consequences—or both—for a given risk scenario.

The process of developing mitigating responses uses the process diagrams developed for the HA, the accident scenarios developed from the process diagrams, and the structured development of responses to the accident scenarios. The outcome of this activity is that risks and the projects explicitly designed to reduce risks have been identified systematically.

C. Estimating the Value of Risk-Reducing (Mitigative) Activities

The degree to which risks are mitigated by proposed projects requires that the hazard level and likelihood be considered under two different sets of conditions. The first, or "baseline," condition is the estimated risk associated with the occurrence of the scenario if no mitigative action is taken.

The second, or "modified," condition is the estimated risk associated with the scenario as if the mitigating activity were fully implemented and in place. The implementation of the mitigating activity can affect the seriousness of the hazard (less severe, less widespread, or both), the likelihood of the impact, or both.

The amount of risk reduced by implementing an activity is defined by the following relation:

Reduced risk = Baseline risk (the risk if an activity is not done) **minus Modified Risk** (the risk if an activity is implemented and completed).

The difference between the baseline and modified risks represents the reduction in risk attributable to implementing an activity.

D. Expressing Benefits in Economic Terms

To give an economic value to the overall risk reduced by an activity, some value must be attached to adverse impacts for each of the objectives. This economic value can be estimated by determining the importance of each of the objectives in economic terms. These economic "weights" for each of the objectives represent decision-makers' willingness to pay to reduce adverse impacts against each objective. Establishing willingness to pay is a routine part of risk management and is often done commercially in determining the value of intangibles.

In practice, the economic weight associated with each objective is determined using a series of tradeoffs in which decision-makers indicate at each step their willingness to pay for certain types of outcomes. This process is similar in concept to bidding activity that determines the values of products in the market. The monetary value of averted risk is based on these estimates of the decision makers' willingness to pay for changes in the level of risk impact for all the objectives.

DOE, along with other Federal government agencies, have established willingness-to pay ranges to prevent a statistical fatality among the public. This range centers at approximately \$5M. The willingness to pay to prevent adverse impacts (as measured by the impact scales) can be established using tradeoff comparisons with the \$5M value of preventing a fatality.

E. Evaluating Activities and Prioritizing Their Implementation

Implementing an activity to reduce risks typically requires expenditure of resources. Prioritizing mitigative activities is based on the economic value of the risk reduction an activity provides and the resources required to support the activity. Prioritization of activities is usually approached in one of three ways, each of which yields different insights.

The first, and easiest, is to consider only the amount of benefit provided by each activity. The activities are implemented according to their total risk reduction, so the activity that reduces risk the most is the first activity funded and so on. This method ignores costs.

A second means of prioritization is to consider the activities against a single resource. In this case, activities can be viewed in terms of their economic benefit and economic costs and compared on a risk-based cost-benefit basis. This view of the activities can aid decision-makers when considering which activities to drop when budgets are decreased or, similarly, the rate of decrease in benefit for each unit decrease in resource availability. The optimization principle in this selection process is to maximize the amount of risk-reduction benefit achieved for each incremental dollar spent.

Because it is common for resources to come from different sources in different years with different limits, it is not possible to just "follow a list until you run out of money" as a strategy for

implementing risk-reducing activities. Taking into account the more realistic picture of activity selection leads to a third way of prioritizing the allocation of resources based on risk-reduction value, including resources from multiple sources over multiple years. In this context, decision makers select a *portfolio* of activities consistent with a multiyear budget so that the total economic benefit of risk-reduction achieved over the activity horizon is maximized rather than maximizing the economic benefit per incremental dollar spent.

IV. LESSONS LEARNED AND CONCLUSIONS

The life cycle chart in Fig. 3 shows that HAs are conducted for almost all DOE facilities fairly early in either their construction or in the development of their SARs. The result is that HA results are often available to managers when decisions must be made regarding the allocation of resources for risk management or facility upgrades. Although more detailed risk assessments can be used to prioritize projects, our work demonstrates that HA results can be a very useful aid in evaluating funding allocations.

There appear to be several benefits from using the HA results and, ideally, the overall SAR recommendations as well.

- The HA team expertise is used to rank risks under current HA procedures but incorporating project evaluation along with the HA allows the team expertise to be used in prioritizing risk-reducing projects as well.
- The evaluation of projects using HA results helps identify areas in which additional information is valuable; this insight influences future investigations of both risks and mitigative activities or projects.
- Linking risk-based prioritization to the overall SAR process helps institutionalize this risk management activity along with the risk assessment activities required to continue supporting the SAR. This provides a much more natural link with operational responses to SAR findings that later become a part of facility risk management policy.
- Using SAR results reduces redundancy of effort, increases the breadth of influence of the analysis, and encourages early attempts at quantifying and storing (database) scenario analysis and information on all recommended activities requiring resource allocation. These logistical improvements make the SAR process a more productive effort in terms of its immediate effects on risk reduction at the facility.

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