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THE METHODOLOGIES OF HAZARDOUS MATERIALS TRANSPORTATION RISK ASSESSMENT*

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Summary

Intense interest now exists in the potential of risk assessment as an aid to public and private decision making on hazardous activities. Inadequacies in its methodologies and supporting data have nevertheless so far limited its efficacy in practice. Among attacks on the problem of improving this efficacy is a project supported by the National Science Foundation which identifies and focuses on improvements in particular areas of uncertainty in risk assessment methodologies. This paper presents some of the project's material that pertains to hazardous materials transportation. It overviews the general risk assessment problem, presents a structured review of the types of methodologies employed in estimating the contribution to risk of the different phases of a hazardous material incident, and then reviews the procedures available for the evaluation of the significance of the risks estimated, and of potential means for their mitigation. Comments are made throughout, and in the paper's conclusions, on the problems arising in these estimation and evaluation processes, and on general approaches to their resolution.

The concept and goals of hazardous materials transportation risk assessment

It has become generally accepted that risk assessment is usefully considered to consist of two separate and, in important ways, largely independent activities: risk estimation and risk evaluation [1]**. Risk estimation entails acquisition of appropriate data, and their application to estimation of the probabilities of occurrence of possible deleterious consequences or losses that may result from a subject hazardous activity. It then combines these probabilities and consequences or losses into an appropriate measure of the risk deriving from this activity. This measure may be a single number; e.g., the expected number of fatalities per year, or per shipment; or the expected number of fatalities per exposed person (equivalent to the probability of death

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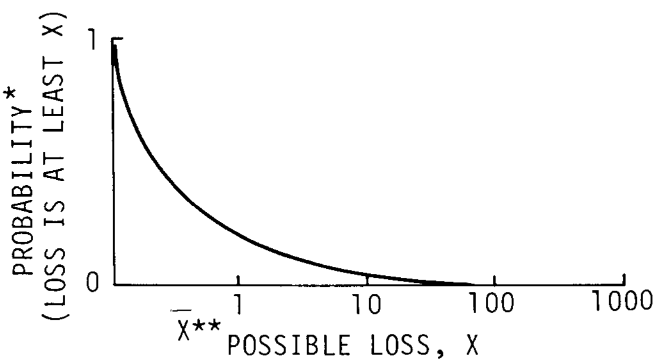
**See the glossary at the end of the paper.



*e.g., per year, per shipment, etc., for given hazardous materials transportation activity

**$\bar{X}$ is the expected loss (per year, etc.) the mean of the distribution from which the risk profile derives

Fig. 1. Illustrative risk profile.

per person) per year. To avoid the loss in perspective of low probability—high consequence events that the simple expected value* measure entails, a complete "risk profile" may be developed, as illustrated in Fig. 1.

The risk profile is defined by the (complementary) cumulative probability distribution function describing the probability that a loss of at least x will occur; e.g., the probability per year or per shipment of x or more fatalities, where x ranges from zero to its maximum possible value. More generally, it may be a "vector" of risk numbers, or of risk profiles, whose components relate to the specific kinds of consequences or losses that are possible; such as fatalities, injuries of various severities, property damage in dollars; and each of these for each exposed group, such as the public, transportation system workers, system owners, shippers and insurers. If a risk vector is developed, however, means are usually required to reduce it to a scalar, single-number measure, by summing its components appropriately weighted; e.g., in terms of dollar equivalents, or utility values, as will be noted later in this paper.

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*An expected value results from the combination of the losses of all possible events weighted by their probabilities of occurrence. Thus a low probability—high consequence event, which may be of the greatest importance to decision makers, may contribute only relatively little to the expected loss. A hazardous activity could then appear to be less risky than another because its expected loss is lower, but could nevertheless entail a larger chance of larger accidents and so in fact be of greater concern. Thus, for example, a nuclear power plant is of greater concern than a coal-fired plant of the same capacity, even though the latter's expected loss is larger. This consideration gives rise to the need to consider "the tail of the probability curve" as well as its expected value, or mean, in assessing risks, and so motivates the development of the risk profile.

Risk evaluation consists of assessing the significance of the estimated risk with respect to its acceptability, as feasible, or with respect to the risks of alternatives to the subject hazardous activity. It also considers the worth and cost of means for mitigating the risk to a lower level.

It may first be noted that the problem of defining criteria for acceptable levels of risk for hazardous activities in our contentious society has so far been insoluble, although investigations and proposals for the development of such criteria abound.

The second and third kinds of risk evaluation noted above are somewhat less subject to controversy. They can be based on comparatively more objective considerations; first, of the relative risks of hazardous activities providing the same benefit; and second, of balancing the cost of a risk mitigation against the value of risk reduction. (This latter process may still become troubled if arguments arise about such issues as the "value of a life", or about factors that should be included as benefits.)

Just as this paper describes various applicable risk estimation techniques, so it will also attempt to outline the general approaches to risk evaluation.

The general risk estimation model

The risk estimation concepts introduced in the previous paragraphs can be applied to hazardous materials transportation in the following way. Possible losses accrue from a hazardous materials transportation activity as the result of a sequence of events. As illustrated in Fig. 2, they may generally be considered to be the occurrence of a basic event, such as an equipment failure, that leads to an initiated event (the occurrence of a particular accident), like a derailment. A container, such as a tank car, then fails and releases its contents, all or in part, and generates thereby one or more possible effects (e.g., fire, explosion, BLEVE (boiling liquid—expanding vapor explosion), toxic cloud, flammable cloud). When they impinge upon some target structure (adjacent people and buildings, etc.) these effects induce certain consequences and losses (number of injuries, etc.). The effects, consequences and

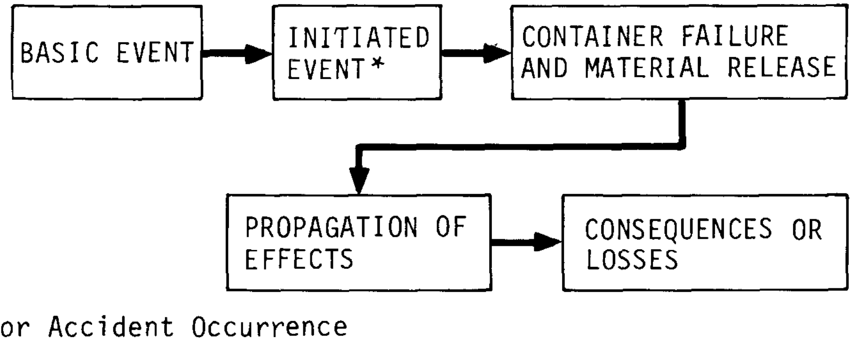

Fig. 2. General risk estimation model.

losses may occur with a range of possible magnitudes. A distinction between consequences or loss is not always required. It may be helpful, however, when consequences take several forms but a single loss measurement (e.g., equivalent dollars) is employed.

The probability of each event is then estimated, or, for effects and consequences, perhaps only an average magnitude or a "credible worst-case" magnitude may be estimated. The results are then combined into a risk profile, such as is represented typically by eqn. (1) (assuming that only one kind of loss, say public fatalities, is of interest). As has been noted, the result is often compressed into a single expected loss measure, which is merely the mean of the probability distribution equivalent to the risk profile.

$$\begin{aligned}\text{Prob}^* (\text{Loss at least } x) = \sum_i \sum_j \sum_k \, & [\text{Prob} (\text{Loss at least } x \mid \text{Effect } k \text{ occurs}) \\ & \bullet \text{Prob} (\text{Effect } k \mid \text{Release of material occurs}) \bullet \text{Prob} (\text{Release} \mid \text{Accident type } j \text{ occurs}) \\ & \bullet \text{Prob} (\text{Accident type } j \mid \text{Basic event } i \text{ occurs}) \bullet \text{Prob}^* (\text{Basic event } i)] \qquad (1)\end{aligned}$$

The asterisk in the equation signifies a given unit of exposure for the probability, as per year, per shipment, etc. A vertical bar indicates that the probability involved is conditional on the occurrence of the event following the bar (and is read "given that"). As x is allowed to range over its possible values, the risk profile is built up, as shown in Fig. 1.

The general profile expression shown in eqn. (1) will vary in detail for different kinds of applications. A risk analysis might begin with statistics on the initiated event (accident occurrence) and basic events would then not need to be considered. A chronic exposure risk analysis might begin with a given effect (as a chronically present concentration of a carcinogenic material) and might also incorporate a term for the probability that some number of individuals will be exposed to it; a sabotage risk analysis would assume a given sabotage attempt occurs, and derive a risk profile conditional on this.

Risk evaluation and the character of risk assessment applications

The role of risk evaluation has been noted. It is concerned with considerations of the significance of an estimated risk with respect to acceptability, and of ways to mitigate the risk where this is deemed necessary or desirable. These considerations relate to a set of possible kinds of applications of risk assessment, which may perhaps be usefully defined in terms of the questions below.

- How safe is a particular hazardous activity?
- How does this safety compare with the safety of other activities?
- How much additional safety could be attained for a given cost, through some set of alternative modifications?
- How much would it cost to attain some required level of safety, through some set of alternative modifications?

- Which would be the safest means of accomplishing a given objective (e.g., transport of a given amount of a given material in a year over alternative routes or by alternative modes or by alternative shipment sizes)?
- How much added risk would be imposed in some other activity due to a modification or alternative that decreases the risk in a given activity (e.g., energy from coal instead of nuclear will cause more rail crossing accidents, more coal miner deaths and illnesses).
- Central socio-political issue: is the estimated (perceived?) risk "acceptable"? What are ways of appraising this?

It will become increasingly evident that these questions underlie the philosophical issues in the use of risk assessment, and the objectives of applicable risk assessment methodologies that will be discussed in the remainder of this paper.

Techniques applicable to the several phases of risk estimation

Four general types of risk estimation methodologies have so far evolved and have been applied to hazardous materials transportation risk analysis. These are statistical inference, fault tree modelling, analytical/simulation modelling, and formal subjective estimation* of risk parameters. (Subjective estimation is also potentially useful in the development of inputs for the first three methodologies.)

The discussion of the four methodologies is oriented around their utility in the several phases of a transportation risk analysis: (1) estimation of the probability of occurrence of an accident and/or incident; (2) determination of the nature and probabilities of occurrence of possible effects (hazardous material tank rupture, spill and fire; explosion; etc.); (3) determination of the possible consequences and, finally, (4) determination of the possible losses that derive from these effects (e.g., number of public fatalities, injuries, property damage; worker injuries; dollar equivalent thereof).

Procedures related, but not necessarily identical to the basic risk estimation procedure, are also needed to identify and analyze (or rather, predict) the effectiveness of possible risk mitigation measures. Finally, it is to be noted that sabotage risks are not amenable to complete risk analyses, due to the fundamental inability to predict occurrence probabilities. However, system vulnerability and consequence assessments can be made.

Accident/incident occurrence probability estimation

The applicability of the four methodologies to this initial phase of risk estimation is discussed in this section. Data development problems, their implications to uncertainties of concern to the user, and possible approaches to improvements are noted in particular.

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*Informal subjectivity, of course, is inherent to a greater or lesser extent in the data development and modelling assumptions in all methodologies.

Statistical inference

The most regularly employed procedure for estimating accident or incident occurrence probabilities is that of statistical inference. However, it is directly usable only if an adequate system-level accident/incident data base exists, with significant sample sizes at the various levels of the specific hazardous conditions of concern. Also, it has to be able to be assumed that the past record satisfactorily represents (or can be modified so as to represent) what the future will hold.

In its basic form, statistical inference assumes a system's accidents or incidents occur independently and with constant probabilities, and then develops estimates of these probabilities. The past record of such accidents and incidents then provides the frequency of their occurrences over the record period and thus, for instance, the frequency per year which is then extrapolated to future years. If the frequency per shipment, per mile or per ton-mile, for example, is desired, the "exposure" in terms of the number of shipments, miles, or ton-miles that were accumulated during the record period must also be known or estimated. The result is then an inference of the future probability of occurrence of an accident or incident per shipment, given as the ratio of the frequency of accidents or incidents to the frequency of shipment. A confidence interval for the inferred probability can also be established.

A number of important problems arise in this superficially simple process, however. First, the estimation of the exposure requires that records on shipments of the hazardous material are kept and are accessible. Such records are not generally available. Thus, estimates must usually be made employing samples of shipment data, often of uncertain accuracy or even validity, with liberal judgmental interpretation. Second, adequate data for a meaningful statistical inference may also not exist on accident or incident occurrences. This is always the case for the rare, catastrophic events that are usually of greatest concern. If the record of exposure (e.g., number of shipments) is great enough, it may be possible to estimate credible upper bounds on the probabilities of such events, but these are often too conservative (that is, too large) to support practical decision making on the control of future shipments with just as large or larger expected rates of exposure.

Instead of generating such upper bounds on the probabilities of accident or incident occurrences, it is sometimes attempted to establish a "surrogate" sample of recorded data larger than the real one of interest, and sufficiently large to permit direct inferences to be made. Thus, the record of accidents with LNG tankers, with no significant entries and a relatively limited exposure, is expanded by use of the record for oil tankers, modified subjectively in various ways, to reflect the differences between oil tanker and LNG tanker operations. With somewhat greater refinement, a record for a given hazardous material transported in a particular container and in a particular mode is extended by incorporating all accidents or incidents for other materials that employ the same container and mode, it being agreed that as far as the occurrence (per shipment, mile, etc.) of an accident or incident is concerned, the material makes no difference. Lastly, a most common use of the "surrogate" approach is the application of nationwide modal accident statistics, on a per mile basis, to inferences of the probabilities of accident occurrences in particular routes for which adequate route-specific accident records do not exist. Clearly, this neglects the potentially significant differences in the physical and environmental characteristics of specific routes from nationwide averages of these conditions.

Another problem area in statistical inference is the even more fundamental one of the "stationarity" of the process giving rise to the accidents/incidents. That is, it must be assumed that the past record also represents the future (or that it is understood how to modify it so that it will). There are many reasons why this may not be the case, e.g., if a major accident occurs once, significant actions may be taken to decrease the chance of occurrence of such an accident in the future. Or, "familiarity breeds contempt", or at least lack of concentration, among human operators so that the chance of a major accident where humans are involved may gradually increase over time. An increase in accident frequency may also be due to wear of equipment under inadequate maintenance. The validity of statistical inferences that do not, or cannot, reflect such considerations, is clearly questionable.

Finally, while not an explicit element of a risk analysis, multivariate statistical analyses of a file of coded accident reports has the potential to be an important means for identifying those hazards, or "causes", whose associated risks may be significant, and worthy of analysis. Univariate trend analyses are already carried out by all modal agencies in the Department of Transportation. These identify apparently important single-factor accident causes. Adequate data samples are needed so that multivariate analyses of the interactions of several factors recorded in accident reports could also be conducted.

Overcoming fully the problems that have been noted, and others that could also be brought forward [2], is not possible. However the situation for the user could be improved by first making the uncertainties in the inference procedure as explicit as possible, so that the user can incorporate them in his decision process, and second by defining improvements and carrying out accident/incident and exposure record keeping procedures. This may require regulatory, as well as data acquisition and management system design changes. Finally, methodological enhancements are needed that respond to the weaknesses in the various assumptions made in the quantitative development of the inferences, including assumptions of stationarity and independence.

Fault tree modelling

This approach synthesizes the possible sequences of events initiated by the activation of some hazard and culminating in particular deleterious consequences to people (operating personnel, neighboring public, etc.), property or the environment. Its application requires that all significant consequences be traced back through all possible event sequences to their initiating basic events. To realize the full power of fault tree modelling, the probabilities of occurrence of the initiating events and all related action initiations (e.g., a successful or unsuccessful activation of a corrective action) need to be estimated with adequate precision, and the magnitudes of consequences accurately predicted. If these requirements are met, a series of combinatorial probability calculations results in assessments of probabilities of occurrence of specified consequences with given magnitudes; i.e., the risks arising from the hazards under analysis.

The principle difficulties with the fault tree procedure are the uncertainty that all significant event sequences have been considered, and that sufficiently precise data necessary for predicting, with reasonable accuracy, the initiating and related action event probabilities, have been acquired. These difficulties are central to the controversies on the application of fault tree methods in nuclear power plant and other fixed facility risk assessments, and their generally complete failure in transportation accident occurrence probability determinations. Since there are so many possible kinds of accidents and interactions of possible accident causal factors in the dynamic operational environment of transportation systems, descriptions, in terms suitable for probability analysis, of all important sequences of events culminating in transportation accidents, cannot be accomplished. However, fault trees have been applied effectively to post-accident event analyses, most notably in those of radioactive material container failures under accident stresses, and to mishandling and normal operations incidents.

Despite these severe difficulties, some potential has lately appeared for the application to transportation problems of computer-based fault tree synthesis and analysis methods (based on "digraphs") that have recently been developed for nuclear and chemical processing plants [3].

Certainly, if fault tree methods can be applied to transportation accident occurrence modelling, at least three important advantages not provided by statistical inference methods would accrue. First, the input data acquisition problem would be changed from that of obtaining meaningful samples of accidents for all sets of conditions of interest at the system level to that of obtaining only basic event data, such as on the failure of specific equipments, or procedures. It is, of course, recognized that to develop basic event probability data properly generally still requires statistical methods (and some subjectivity). What is emphasized here is that large enough sample sizes, even for different sets of conditions, are clearly more easily and correctly developed for basic events than for actual accident occurrences. While certainly not trivial, this problem can possibly be solved with appropriate record keeping systems, experimentation, simulation and testing.

Second, fault trees lend themselves conveniently to the evaluation of the effectiveness of given mitigating measures. Any such measure should be able to be assessed through the changes that it would induce in the original fault tree describing the accident occurrence that it is intended to prevent, or whose probability it can diminish. Using statistical models for the evaluation o the effectiveness of mitigating measures currently requires highly, if not entirely, subjective postulations of what the changes in the given accident data would have been (and, it is presumed, would be in the inference for the future) if the mitigation had been in place during the period in which the data were acquired.

Third, even when basic event data are not available, qualitative analyses of fault trees (employing, if desired, existing computer programs) can provide significant insights on accident-initiating event sequences (or "accident modes" that are potentially most important to system safety. This kind of analysis can proceed one step further with quantitative rankings of the relative importances of such modes if at least relative basic event data can be provided, such as the relative likelihood of failure of one equipment compared to that of another.

To gain these advantages, fault tree modelling techniques need to be deepened (as with the digraph procedures) to better reflect accident dynamics, including human operator actions. Improved means are required for acquiring data on the probabilities of initiating events, equipment and human faults and failures, and control action time delays. Comprehensive testing, experimentation and simulation programs will be needed for this.

Analytical and simulation modelling

Analytical and simulation modelling approaches to risk analysis* begin with functional descriptions of the system under study. The operations of the system are then modelled in terms of appropriate performance parameters that express the functions, and the interaction of the functions, of system components (human, as well as equipment) and interfacing external factors. The conditions under which accidents and incidents occur, or when particular consequences arise, are associated with specific combinations of the values of these parameters. Their probabilities of occurrence and/or the effects of their occurrence are then assessed by means of probability or effects formulae (in analytical models), through numerical accumulations from repeated runs of system operation "scenarios" (in simulation models), or by combinations of both procedures.

The main problem with analytical models is the need for acceptable simplifying assumptions that the derivation of their formulations usually require, and the related departure of their modelled factors from direct physical significance. Simulations are better in this regard in that they usually tend to replicate real-world factors in a fairly recognizable way. However, to the extent that they avoid arbitrariness in their simplifications, their complexity and computational requirements increase. The need to run many simulated

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*As here defined, such approaches exclude combinatorial analyses of probabilities developed from statistical data. These latter analyses are subsumed under "statistical inference" methods.

operations in order to derive usable accident statistics (as in Monte Carlo simulations) exacerbates the computational requirements. Simulations are, therefore, expensive means for risk analysis (other than in specific, and limited, data development support roles).

Analytical models have been applied primarily in assessments of normal operations incident occurrences, and post-accident effects and consequences. Simulations have been used, but without great success, for estimating accident probabilities in marine transportation. It is not believed that analytical or simulation modelling of accident occurrences is worth further consideration.

Formal subjective estimation

When all else fails, an approach to augmenting sparse data in developing statistical inferences and estimates of other forms of model parameters is that of subjective estimation by panels of experts. These experts are assumed to be sufficiently familiar with the detailed circumstances of operations similar to those of interest so that they can meaningfully extrapolate their experience to new conditions, employing only their individual judgments in combination with those of the other experts [4].

Two approaches can be considered in applying this process in hazardous materials transportation risk analysis. The first is exemplified by a "Delphi" procedure that was carried out in developing risk parameter estimates for hydrogen sulphide transport as extrapolations from general experience with the material and from a "baseline" set of specific incident experience data for a more common hazardous material, propane.

The second is typified by an attempt that was made to estimate oil tanker spill risks. It developed numerical estimates from rankings of the likelihood of possible causative events by a team of experts on oil spills (since oil spills and their circumstances were not so rare as to require some basis for comparison with experience with another material).

Subjective estimation is perceived as inherently a relatively low confidence risk analysis methodology. However, this perception may be at least in part a result of the general lack of appreciation of the perhaps more subtle but sometimes just as significant subjective elements of the other possible methodologies. This has been evidenced to some extent in the preceding discussions of these methodologies. To improve the subjective estimation process may therefore be a worthwhile endeavor, even if less formal procedures than, say, Delphi are considered. The objective of this effort would be to enhance the selection and control of, and the input information development for, expert panels.

Consequences and losses estimation considerations

The determination of the losses resulting from an incident consists of several steps: (1) Generally, the container fails and the material escapes. (2) The material disperses into the environment. If flammable, it may be ignited immediately upon emerging from its container, or it may find an ignition source at some time and distance from its origin. (3) Exceptions to steps 1 and 2 apply to the class of materials for which external events such as fires from hot boxes or adjacent material containers can cause a reaction in a commodity within its container. (4) Depending upon the characteristics of the material being released, there may be damaging effects and the potential for losses, due to fires, explosions, toxic effects on people and vegetation, contamination of ground water, and so on.

Container failure and release

Containers can fail due to many possible "external" causes, such as an accident (e.g., a train derailment) or a fire in another container; or "internal" causes, such as an undetected structural defect in the container or the vehicle or mishandling in its use or maintenance.

The analysis of such failures frequently involves comparing the impinging loads developed in the postulated incident with the strength of the container. For most external causes of incidents, a dynamic situation is involved and the loads tend to be impact-induced. Some examples are the collision of one vehicle with another, leading to rupture of the container due to direct impact or overturning; or a coupler impacting and penetrating the headshield of a tank car. These and other accident scenarios are readily treated by analysis. Estimates can also be made of the size of the opening in the breached container as a result of the impact, and then of the resulting rate and quantity of material release.

Although the engineering methods are mature for quantifying (a) the conditions under which a container will be breached, (b) the size of the opening, and (c) the rates and quantities of materials released, it is nevertheless desirable to verify analytical predictions by tests. Testing is also often desirable when it is not cost-effective to construct an adequately sophisticated analytical model; nor does one always readily have available the detailed materials properties data required for model analyses. Testing can range from small-scale laboratory experiments, to full-size testing of a component in the laboratory (e.g., headshield/coupler interaction, or brake systems behavior under load), to full-scale testing of an actual vehicle with a simulated commodity on a test track. Care must be exercised in designing laboratory tests, however, because often parameters of interest in the responses of containers to certain types of accidents do not scale.

Testing can take the form of non-destructive, instrumented tests for the purpose of measuring physical parameters such as stress and temperature in the container, or its supporting structure, as functions of various input parameters related to normal and abnormal operating conditions. Other testing methods are destructive tests which simulate an accident situation or an internal failure. These tests are instrumented so that one knows the actual test parameters (the input loads), such as angle of impact and force—time relationships at various locations.

Finally, there are some situations where testing exclusive of any associated analysis is the only feasible approach. These instances are generally related to effects of wear (i.e., service life coupled with environmental stress) on safety related components.

Material dispersion

In the event of a release of a liquefied gas or volatile liquid, as primary examples, the escaping material will spread, evaporate, mix with the air surrounding the spill, form a cloud and move downwind. (If flammable, the air—fuel mixture will burn if a suitable ignition source is present.)

The details of the spreading and cloud formation depend upon the rate of release of the material, its density, vaporization rate and buoyancy, and on meteorological and terrain conditions. The cloud that is formed is characterized by its size and concentration at any location relative to the release point and at any time after release.

A number of mathematical models that attempt to describe these complex events have been developed. The models differ significantly from one another in sophistication, because of their approximations and assumptions in their characterizations of the source (point or area source, instantaneous or continuous release) or of the manner of spreading and air entrainment. Since input data on material properties are lacking for the majority of materials, data for similar materials are often used, giving rise to errors of uncertain magnitude.

For liquefied natural gas (LNG), for instance, these models generally agree for small spills, but not for large spills. This is due to the fact that the models have been calibrated for the only data available, those of small spills. For the case of large LNG spills on water (a much studied problem), there are more than order-of-magnitude differences in different model predictions for such parameters as the distance downwind a flammable vapor cloud will travel. The differences again depend upon the simplifying assumptions made by the analyst [5].

Adequately instrumented tests involving large spills are needed to verify the mathematical models, since reliable observations from the few accidents where large quantities were spilled are lacking. Relatively small spill tests of LNG, liquid ammonia and several light hydrocarbons on land and water have been conducted using limited instrumentation. Larger tests are planned, but they will still be small compared to potential accidental spill sizes. Wind-tunnel simulations of LNG spills have also been carried out to better understand the effects of terrain features and obstructions on the dispersion and concentration of the resulting vapor in air [6].

Characterizing the effects of the released material

The dispersed material can lead to a number of effects. Volatile liquids and liquefied gases when dispersed in air can cover areas orders of magnitude larger than when they were contained. A material in this state may be flammable, explosive, toxic, corrosive or carcinogenic.

In order for a material in its vapor phase to burn or explode, for example, its concentration must be within its flammable limits, and an ignition source must be present. A fire or explosion gives rise to thermal radiation or overpressure, and impulsive forces which can harm nearby people and property. The flammable limits of many commonly shipped materials are known. The explosive effect of a material is expressed in terms of energy release, e.g., TNT equivalency, and can be estimated from the heat of combustion of the material, if this property is known. It is to be noted that the maximum possible energy release is never realized in accident situations because optimal conditions are never met. For maximum energy to be released in an explosion, all of the material would have to be within the explosion limits when it encounters an ignition source. Accidents tend to yield about 10%, or less, of the maximum energy possible. Meteorological conditions, structures, terrain features, etc. can give rise to areas where there is focusing or blast enhancement and also to areas where little damage occurs. Asymmetric initiation of a vapor cloud can give rise to enhanced blast in one direction. Predictions of fire and explosion effects tend to be conservative, since calculations generally consider the worst case. It is sometimes also possible to draw on past accident experience to establish a credible energy release case.

For toxic materials, the effects of various concentrations on people and other biota are known for only a fraction of the materials being shipped. Moreover, much of this information has been developed for occupational exposures, i.e., for people exposed on an eight hours per day basis. How large a concentration is acceptable for a single exposure resulting from an accident is known only for very few materials.

To better understand how toxic and flammable materials behave in actual incidents, the National Transportation Safety Board (NTSB) has recently developed an investigation and reporting format that utilizes maps of the accident area. A series of maps may be used for each accident, with each map indicating the elapsed time after the accident. The maps thus can show events that are time dependent, such as the growth of the dispersion pattern. In this way the sequence of events and the resulting effects are readily visualized. The following information is to be displayed on the maps [7]:

(1) The relationship between the dispersion pattern(s) formed by material releases, and the size and nature of the hazardous material container.

(2) The relationship between the environmental conditions and the hazardous material dispersion patterns.

(3) The relationship between the dispersion pattern, the location of casualties, and the degree of injury or damage.

(4) The relationship between the times associated with the dispersion patterns and injuries.

This approach gives promise of aiding the understanding of complex phenomena arising in hazardous material incidents. It can also support the validation of consequence factors in risk estimates.

Accidents when the container is not initially breached

Fires, explosions, BLEVE's and releases of toxic materials can occur due to external causes. In the case of trains, for example, fires caused by hot boxes or overheated brake shoes can lead to major fires or explosions. In some cases an external fire can cause the degradation of the strength properties of a container and the subsequent release of a flammable or toxic hazardous material. Similarly a fire in a box car adjacent to a car carrying hazardous materials is a credible major incident cause.

A more "exotic" cause of serious fires and explosions is that arising in materials not believed to be explosive or flammable but sensitized by a small amount of contaminants. An example is scrap metal turnings, where a serious problem has been identified in the marine mode of transportation. The material can spontaneously ignite, and temperatures of the order of 260°C (500°F) have been measured. It is not yet known if the hazard is size-dependent, and occurs only in large bulk cargo ships. The problem is currently being studied.

It is expected that in the future more of such materials will be transported as "non-hazardous" wastes. A protocol must be developed for evaluating their hazards.

Sabotage risks

The probability of occurrence of a particular sabotage attempt cannot meaningfully be estimated, although some effort has been applied to correlate the likelihoods of such attempts with such large scale societal factors as the general crime rate. Thus, sabotage risk analyses have generally been conditioned on the occurrence of a specific attempt. The effectiveness of the attempt and the system's vulnerability, along with the performance of its security capabilities, if any, are then assessed quantitatively in relation to this attempt.

Approaches to risk evaluation

It remains to deal with how judgements are made on whether a calculated risk level for a given activity is sufficiently low for the activity to be instituted or continued, and/or whether mitigation measures may be beneficial.

Risk acceptability evaluation

While no single approach has yet been established that enables a universally appreciated evaluation of the acceptability of the risk of a hazardous activity, a number of attempts have been made to develop such an approach. These are discussed here in three categories: comparisons to "ambient" or historically accepted risks, comparisons to risks of equi-benefit alternatives, and balancing of risks and benefits.

Comparison to ambient or historical risks

In 1969, Chauncey Starr published the first of many articles on public risk acceptance in relation to benefits, as revealed by historical data [8]. Expected fatalities per hour or per year and per individual in various groups exposed, due to voluntary or involuntary hazardous activities, to potential accidents and other deleterious factors were estimated from past data and then compared to assessments of the benefits accruing from these activities. Starr found that historical levels of risk acceptance increased in proportion to the cube root of the increase in benefits, and that voluntary acceptance levels were about three orders of magnitude greater than involuntary acceptance levels. (These particular conclusions have since been disputed, however [9].)

Starr's concepts have been extended by many others in attempts to establish numerical acceptable risk levels for hazardous activities such as petrochemical and energy facilities that provide specific benefits or meet specified societal needs. These numerical levels may also reflect the confidence in the risk estimates that are evaluated [10].

Three major philosophical problems exist with the approach to risk acceptability evaluation based on Starr's concepts. First for involuntary risks, the groups accepting the risks often differ from the groups receiving the benefits (or at least do not share the benefits in a manner reflecting their exposure to the added risks). Second, the use of a risk measure based on expected, or average, or mean, losses, while convenient, foregoes any ability to distinguish low probability/high consequence, from higher probability/lower consequence risks. The former are often of more critical concern to the public and other decision makers. The societal "disutility" of accidents appears clearly to be non-linear as accident magnitude increases. The utility functions to express this have been discussed, but they have not yet been developed meaningfully. Finally, the groups evaluating the risks of a hazardous activity may differ greatly in their perceptions of its benefits as well as risks, and thus differ on the acceptability of the activity.

Several psychometric experiments have been reported that attempt to assess how individuals balance their perceptions of the risks and benefits of hazardous activities. While consistent with Starr's generic results in some aspects, great differences were also exhibited, depending on the availability to individuals of information on the activities, their familiarity (or their beliefs that they were familiar) with these activities and so on. The problem of obtaining a consensus on the acceptance of risks to provide specified benefits is evidently one which is very difficult to resolve [11].

The second of the philosophical problems noted above is the only one that so far has been meaningfully attacked. This was in the well-known attempt at risk acceptability evaluation (albeit not presented in such terms explicitly) in the Nuclear Regulatory Commission's Reactor Safety Study. Complete risk profiles reflecting the probability distributions of all possible losses, rather than only their means, are generated for nuclear power plants and compared to the profiles for various ambient and historical hazards, natural and man-made. This approach has also been employed in many LNG and other hazardous materials transportation risk analyses.

The principal weakness of the ambient/historical risks comparison method (over and above arguments on the validity of the profile functions developed) is its neglect of the fact that even if the incremental risk of the hazardous activity is small compared to the total ambient risk, the proposed involuntary risk takers do not often happily accede to even the small addition. Overcoming this attitude, when it is justified to do so, is a major problem of society at present. All risk evaluation procedures imply that this can best be done by increasing the risk-takers' benefits (real or perceived). Secondarily, any means for enhancing the credibility of the risk estimates to them would be helpful, but probably not decisive.

Risk comparisons of equi-benefit alternatives

A second risk acceptability evaluation approach is the standard operations research technique of assuming that some activity must be put in place to satisfy a specific need, and then establishing which alternative means of implementing it would give rise to the least risk. On this basis, for example, nuclear power has been argued to be safer overall than coal for generating electricity (taking into account only the mean values of the two risk profiles and employing, to some extent controversial, "accounting" of total system risks).

On the surface, the procedure should be a strong one for not merely evaluating, but also encouraging, risk acceptance. However, increasingly often no practical alternative is deemed acceptable to the public or its spokesmen. They may demand some approach based on unproven or uneconomic technology, or the avoidance of the needed activity entirely (even at some unconsidered other risks). Nevertheless, this method, perhaps combined with procedures for determining the incremental benefits necessary to induce rational risk acceptance, may be the most suitable for hazardous materials transportation activities.

Balancing of risks and benefits

Quantitative procedures exist for expressing the risks of a hazardous activity, as well as its benefits, in common economic terms, e.g., present-value dollars. However, these procedures generally entail assuming or imputing a "value-of-a-life", and it has been difficult to obtain agreement on this feature of the analysis. If an agreement were possible, it could then be argued that a hazardous activity was acceptable if the potential loss induced by its risks were less than the dollar value (or some fraction of this value) of its potential benefits.

Evaluation of possible risk mitigation measures

Mitigation measures may reduce the risk by reducing the probability of occurrence of an accident or incident, or by reducing its consequences if it should occur. Mitigation measures may be procedural or technological. Procedural approaches may range from routing changes based on some predetermined criteria; new loading and unloading procedures; increased maintenance and inspection frequency, quality, and comprehensiveness; compliance with compatibility of materials guidelines that could specify the "forbidden" mix of commodities in a vehicle or the arrangement of cars in a train according to the hazards of the commodities; etc. Examples of technological approaches are flame arresters in transfer lines, thermal protection for tank cars, improved hot box detectors, and better containment of commodities for all transport modes.

For each mitigation measure considered, one must be very careful to assure that the risk reduced by the new approach or alternative does not result in an increase in risks elsewhere. One simple example is the consideration of having empty box cars separating hazardous material cars in a train. Although the resulting spacing can serve to reduce the probability of propagation of a fire or explosion to other cars carrying hazardous materials given that an accident occurs, spacer cars can, in some situations, have deleterious effects on the ability to properly "handle" the train, which in turn can increase the probability of an accident in the first place. Detailed analyses of alternatives and their true risk reduction potential must be carried out with extreme sensitivity to such risk transference possibilities.

It fault trees in sufficient detail could be successfully applied to transportation accident analysis, a straightforward procedure would be available for predicting the decrease in risks resulting from mitigating measures. It would only be necessary to recalculate the probability of a particular kind of accident, given that a mitigating measure has been applied to the elements of some of the "cutsets" describing the possible accident occurrence modes, thereby eliminating or decreasing the probabilities of such modes. However, as has been noted, this is not yet feasible, except for limited parts of an analysis, although new fault tree methods may make it possible to some extent in the future.

Cost-effectiveness and cost-benefit of alternatives

The effectiveness of a risk mitigating measure is quantified by the reduction in risk it provides. This reduction may be assessed in terms of an expected loss of lives averted, or in terms of more comprehensive differences between the relevant risk profiles, with and without the mitigating measure. The effectiveness of alternative measures which can be implemented within available financial and other resources can then be compared, and the alternative selected that provides the greatest effectiveness. Similarly, an alternative could be selected from all those considered to meet a given risk reduction requirement as the mitigating measure of lowest cost.

A related approach is the comparison of the cost of a risk reduction measure with the increase in longevity that would ensue in the population exposed to the risk. For example, Schwing constructs an index defined by the cost of a particular life-extending program divided by the longevity increase it provides [12]. The index (called an efficiency index) is then the cost in dollars to gain a year of longevity for the population affected. His rank ordering of 60 life-extending programs shows the efficiency index can vary by over five orders of magnitude, from $192 to $27.5 million per person-year of longevity extension. A scheme such as this for the evaluation of the cost-effectiveness of alternatives has the advantages that it not only places the costs of various mitigation measures in relationship to one another, but enables these costs to be put in perspective with safety expenditures in other sectors of society.

A complete implementation of a cost-effectiveness approach requires a realistic accounting of all costs (and other "dis-benefits"). In addition to the direct costs of an alternative, which includes capital, operation and maintenance costs, the costs of time delays and other indirect costs may also need to be incorporated. Still more broadly, considerations may be required of the loss of business by a carrier to another transport mode due to the increased costs, the loss of business by the shipper because of the reduced competitive position of the shipped goods relative to imports, and so on.

In addition to the estimation of the effectiveness of risk mitigations, as in the foregoing procedures, it is sometimes also important to estimate their benefits; that is, the translation into economic terms of the value of the reductions in risk they provide. This is required for many areas of federal safety regulations by Executive Order 12991 of 1981, for example. The purpose is to justify a mitigation by exhibiting that its cost is exceeded by its benefits expressed in common terms. Clearly, the value-of-a-life issue noted earlier again strongly arises and, as has been indicated, may with some difficulty be attacked directly; or perhaps in some instances it may be possible to employ indirect utility theory techniques [13].

Conclusions

Risk assessment is a potentially important tool in decision making and policy development for the assurance of safe hazardous materials transportation. Its main task areas are:

1. The structuring of the problem, which includes selecting a method of analysis that is consistent with answering the specific questions of concern. The techniques employed are determined by the character and complexity of the system being investigated, the availability of data, and the needs and resources of the sponsor or user of the analysis.
2. The estimation of the risks, i.e., the probabilities of the possible consequences or losses from undesired events.
3. The evaluation of the significance of the estimates, which may result in the acceptance of the risk or the recognition of a need for a risk mitigation measure.
4. The evaluation of the cost-effectiveness and cost-benefits of alternative mitigating measures, and the selection of a preferred measure from among them.

However, much must be done to enable risk assessment to be as useful as possible. It is clear that a primary impediment to the successful implementation of risk assessment for the transportation of hazardous materials, in particular, is the inadequacy of the data base — in both scope and detail. This inadequacy is reflected in the often questionable risk modelling assumptions and procedures employed to overcome it. Although extensive accident data are currently collected, the resulting records of numbers of accidents or incidents, their causes and associated conditions, are often incomplete, inaccurate and biased. Also lacking are good exposure data, e.g., quantities of materials shipped according to mode and container, box-car-miles, truck-miles, ton-miles, etc. Data acquisition and processing rules, procedures and systems need to be developed that are as responsive as possible to the needs of risk analyses.

Equipment failure rate data, needed for fault tree models especially, are also usually not adequate. Moreover, it is generally not possible to quantify the extent to which inadequate training, lack of experience or, possibly, inattention due to lack of motivation, of operating personnel, affects the accident rate or the consequences of an accident. The performance of people must be accounted for in risk estimates, and improved estimates of their failure rates is essential for meaningful risk analyses in many contexts.

The most controversial aspect of the implementation of risk assessment is the evaluation and interpretation of the estimated risks, and their implications to the need for, and justification of, risk mitigating measures. This inherently requires judgments based on factors that are difficult to quantify. They may include, in addition to a subject hazardous activity's risks, cost and benefits, associated business and political risks and ethical considerations and issues. Moreover, there is a lack of concurrence even on what attributes should be included among these factors. Much research, and education of the public and its leaders, on risks and risk evaluation concepts are evidently needed.

Glossary*

Acceptable risk

A level of risk from a hazardous activity deemed by some particular element of society to be sufficiently low to enable the activity to be instituted or continued. The judgment involved may or may not be similarly made by other elements of society. The process of development of the judgment is that of risk evaluation.

Accident

A random failure of a system due to which some harm results.

Basic event

The occurrence of a fault or failure in a system component, or of an external event, that can initiate, or participate in, an accident sequence (that is a sequence of events leading to a system accident).

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*Of terms employed herein, and also suggested as a basis for discussion and further development.

Consequence

A possible harmful outcome of an accident or incident.

Effect

A result of an accident such as the release and dispersion of a given quantity of a hazardous material.

Fault or failure

An undesired action, or lack of desired action, by a system or component, equipment or human.

Hazard

A set of internal and/or external conditions in a system's operation with the potential for initiating or exacerbating an accident. Hazards include dangerous energy sources, possible conditions that could lead to an undesired energy release, or possible conditions that could inhibit or prevent a desired energy release (such as power for safety equipment, or a control signal).

Incident

An inadvertent release of a hazardous material with some potential for harm. It may occur due to an accident, to mishandling of the material or its container, or to unusual stresses on a container during normal transportation operations.

Loss

An outcome or consequence of an accident or incident, expressed in terms such as the number of people killed, suffering a given severity of injury, a given loss of life expectancy, etc., or property damage; or an economic equivalent thereof.

Risk

The probability of occurrence, due to a fault or failure, or an external event, of a specific consequence or loss; e.g., the number of fatalities deriving from a given activity, such as the operation of a specified facility under specified conditions. Risk is often also used to mean the product of the probability and magnitude of a given deleterious consequence or loss, or the sum of such products over all possible consequences or losses, i.e., the expected consequence or loss. Individual risk is the probability of a given consequence (e.g., fatality) occurring to any member of the exposed population. Group or societal risk is the probability that a given number of individuals will suffer a given consequence.

Risk assessment

The integrated analysis of the risks of a system or facility and their significance in an appropriate context. It incorporates risk estimation and risk evaluation.

Risk estimation

The statistical, analytical and/or subjective modelling process leading to a quantitative estimate of a given risk.

Risk evaluation

The appraisal of the significance of a given quantitative (or, when adequate, qualitative) measure of risk, as for example, the comparison of the expected number of fatalities per year from a specified facility's operation, with that from a number of other, generally "accepted" causes; or the appraisal of the risk of such fatalities in relation to the socio-economic benefits of its acceptance.

Risk management

The process whereby decisions are made to accept a known risk or hazard or to eliminate or mitigate it. Trade-offs are made among increased cost, schedule requirements, and the effectiveness of redesign or retraining, installation of warning and safety devices, procedural changes, and contingency plans for emergency actions.

Safety

The condition of freedom from unacceptable risk (as evaluated by a responsible consensus of society).

Terminal event

The event to which an accident sequence leads, whose occurrence produces a particular consequence of concern. A terminal event could be a hazardous material tank rupture, a train collision at a given relative speed, etc.

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