the state or local authorities subject to the approval of DOT. In any event, DOT should develop the criteria (relating to population density, industrial characteristics, road conditions, or the like) on which the restrictive zones would be designated. Under this scheme, a carrier planning a route could determine the most restrictive zone through which the carrier would travel, and thereby learn precisely what level of restriction would be imposed on that carrier's activities.

DOT Might Establish Criteria for Non-Federal Jurisdictions Seeking to Impose Specific Requirements

DOT might allow non-federal jurisdictions to impose requirements that are different from those promulgated by DOT if they fall within certain specific, federally developed guidelines. Under this scheme DOT would first initiate rulemaking proceedings to establish the criteria against which non-federal requirements would be measured and to develop a process whereby such requirements would be submitted to DOT for its approval. The criteria might allow for the establishment of region-specific hazardous materials routing plans by non-federal authorities, developed according to guidelines that would require consideration of the concerns of neighboring jurisdictions and of the affected industry. DOT, in fact, might require such plans to be developed by the state and localities on a regional, rather than on a purely local, basis.

DOT could also develop criteria allowing state and local jurisdictions to impose more or less restrictive controls along the course of such regional routes. However, such controls would have to be developed in coordination with the other jurisdictions in the region and could not unreasonably interfere with interstate commerce. In this manner, controls that might otherwise interfere with the smooth flow of commerce (such as absolute bans in limited areas, time restrictions, permit requirements, and operating controls) by subjecting a carrier to a multiplicity of conflicting regulations could be developed and imposed without confusion.

DOT CAN ENACT GUIDELINES TO MINIMIZE CONFUSION IN THE FIELD OF PREEMPTION

Regardless of how DOT goes forth to promulgate its substantive regulations, it can act to minimize administrative and judicial litigation by providing some clear guidance to state and local authorities as to what types of activities it views as permissible under the HMTA. DOT might undertake a detailed analysis of its regulations and decide for itself what sort of state or local activities are circumscribed. It might then publish informational guidance documents, or might even commence formal rulemaking proceedings to establish criteria against which non-federal activities would be measured.

Interested parties may, of course, now be guided by the views expressed in DOT's inconsistency rulings. Yet this piecemeal approach to the problem is not very efficient, and since we can expect non-federal actions to multiply in this climate of public concern, DOT may soon find itself flooded with inconsistency petitions.

DOT would therefore be well advised to face the difficult questions in a general, threshold proceeding, and thereby clear the air at the outset.

CONCLUSION

DOT is faced with the very delicate task of balancing the need for uniformity in the area of hazardous materials regulation against the need to address local safety concerns adequately. If it succeeds in striking the correct balance and in establishing a viable mechanism for including local considerations in its federal regulations, the issues surrounding preemption will be of little importance to the field. However, if DOT fails to meet its challenge, interjurisdictional conflict will proliferate, and the legal issues involved with preemption will be considered by the courts for years.

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Hazardous Materials Transportation Risk Assessment

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A glossary of terms useful to the reader precedes part 1 of this paper, which describes various risk estimation methodologies along with their strengths and weaknesses. Approaches to risk evaluation and acceptance are also discussed. Part 2 considers some of the ethical and philosophical aspects of risk assessment. The meaning of "safety" and the concept of the justifiability of harm are tested. A plea is made for the use of systemic risk analysis in contrast to the current piecemeal application of risk analysis. Part 3 raises questions for consideration by conference participants. It is intended that recommendations for improvements in methodologies and implementation approaches will result.

GLOSSARY OF SOME RISK ASSESSMENT TERMINOLOGY

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 failure of a system due to which damage results.

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

Consequence--A result of an accident such as the release and dispersion of a given quantity of a hazardous material, a given level of damage to a rail car, or a given number of people injured.

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

Harm--The likelihood of a reduction in life expectance (longevity) or likelihood of damage to the environment or property.

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, mishandling of the material or its container, or to unusual stresses on a container during normal transportation operations.

Loss--An outcome of an accident, 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.

Risk--The probability of occurrence, due to a fault of 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 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 and/or analytical modeling 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 appraisal of the risk of such fatalities in relation to the socioeconomic 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, 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 given a relative speed.

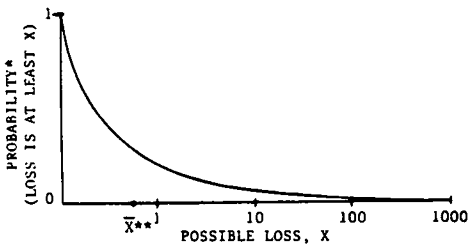
PART 1: METHODOLOGY OF RISK ASSESSMENT
INTRODUCTORY CONCEPTS

The basis for discussion of the important aspects of risk assessment for hazardous material transportation is established in part 1. It considers the needs for risk assessment in its present and potential applications. It outlines the general character of the risk assessment methodology and the several approaches to particular areas of its application. It emphasizes the strengths and weaknesses of these approaches and motivates considerations of means for their improvement for various classes of users. It is intended that the outcome of these considerations at the National Strategies Conference, in particular, will be (a) specific research and development recommendations for establishing these improvements through enhanced data development procedures and risk modeling techniques and (b) increased facility in the application of risk assessment at all levels of its use.

Concept and Goals

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 (a) the acquisition and application of appropriate data to the estimation of the probabilities of occurrence of the possible deleterious consequences or losses that may result from a subject hazardous activity and (b) the combination of 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 and the expected number of fatalities per exposed person (equivalent to the probability of death per person) per year. To avoid the loss in perspective of low probability/high consequence events that the simple expected value measure entails, however, a complete "risk profile" may be developed (see Figure 1). [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

Figure 1. Illustrative risk profile.



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

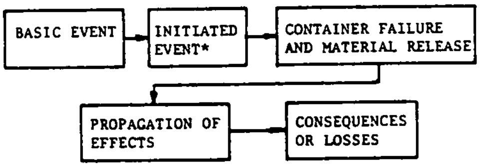
**$\overline{X}$ is the expected loss (per year, etc.), the mean of the distribution from which the risk profile derives

greatest importance to decisionmakers, 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 small 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.] It 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 0 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 loss that are possible, such as fatalities, injuries of different severities, and property damage in dollars. Each of these consequences must be broken down 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.

The risk evaluation activity consists of assessing the significance of the estimate risk with respect to its acceptability, as feasible; the risks of alternatives to the subject hazardous activity; or the worth and cost of means for mitigating it to a lower level. The problem of defining criteria for acceptable levels of risk for given hazardous activities in our contentious society has so far been unsolvable, 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 used on comparatively more objective considerations; first, of the relative risks of hazardous activities providing the same benefit, and, second, of the balancing of the cost of a risk mitigation with the value of the risk reduction. (This latter process may still get into trouble as arguments arise about such things as the "value of a life", or about what characteristics should be included as benefits.)

Figure 2. General risk estimation model.



*or Accident Occurrence

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

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 Figure 2, for the case of a transportation accident, they may generally be considered to be the occurrence of a basic event such as equipment failure that leads to an initiated event (the occurrence of a particular accident) such as a derailment. A container such as a tank car then fails and releases its contents all or in part, and thereby generates one or more possible effects (e.g., a fire, explosion, BLEVE, toxic cloud, and flammable cloud). When they impinge on some target structure (adjacent people and buildings, etc.), these effects induce certain consequences or losses (number of injuries, etc.). The effects and consequence or loss events may occur with a range of possible magnitudes. A distinction between consequences or loss is not usually required. It may be helpful, however, when consequences take several forms, but a single loss measure (e.g., equivalent dollars) is desired.

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 Equation 1 (assuming 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:

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

The circled asterisk signifies a given unit of exposure from 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 Figure 1.

The profile expression (Equation 1) will change somewhat 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, and so on.

Risk Evaluation and 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, perhaps, of ways to mitigate the risk where this is deemed 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:

1. How safe is a particular hazardous activity?
2. How does this safety compare with the safety of other activities?
3. How much additional safety could be attained for a given cost, through some set of alternative modifications?
4. How much would it cost to attain some required level of safety, through some set of alternative modifications?
5. 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)?
6. How much added risk would be imposed on 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, etc.)?
7. Is the estimated (perceived?) risk "acceptable"? What are ways of appraising this central sociopolitical issue?

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

Techniques Applicable to Several Phases of Risk Estimation

Four general types of risk estimation methodologies have so far evolved and been applied to hazardous materials transportation risk analysis. The four methodologies are statistical inference, fault-tree modeling, analytical-simulation modeling, and 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: (a) estimation of the probability of occurrence of an accident and/or incident, (b) determination of the nature and probabilities of occurrence of possible effects (hazardous material tank rupture, spill and fire, explosion, etc.), (c) determination of the possible consequences, and (d) determination of the possible losses that derive from these effects (e.g., number of public fatalities, injuries, property damage, worker injuries, etc.).

Procedures related, but not necessarily identical, to the basic risk estimation procedure are also needed to identify and analyze (or 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 or risk estimation is discussed in this section. Data and methodological problems, their implications to uncertainties of concern to the user, and possible approaches to improvements are noted in particular.

Statistical Inference

The most regularly employed procedure for estimating accident of incident occurrence probabilities is that of statistical inference. However, it is directly usable only if an adequate 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, the methodology of statistical inference assumes that a system's accidents or incidents occur independently and with constant probabilities and 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, for instance, the frequency per year that is then extrapolated to future years. For example, if the frequency per shipment, per mile, or per ton mile 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, for instance, given as the ratio of the frequency of accidents or incidents to the frequency of shipments. 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 are kept and accessible on shipments of the hazardous material. Such records are not generally available. Thus, estimates must usually be made by 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 the accident-incident occurrences. This is always the case for the rare, catastrophic events that are usually of greatest interest. If the record of exposure (e.g., number of shipments) is great enough, it may be possible to nevertheless estimate credible upper bounds on the probabilities of such events, but these are often too conservative (that is, too large) to support practical decisionmaking on the control of future shipments with just as large or larger rates of exposure.

Instead of generating such upper bounds on the probabilities of accident-incident occurrence, 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 liquid natural gas (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 in a particular mode is extended by incorporating all accidents-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 the nationwide modal accident statistics, on a per mile basis, to inferences of the probabilities of accident occurrences on 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 or incidents. That is, it must be assumed that the past record also represents the future (or 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. 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 DOT. 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 by using regression analysis, analysis of variance, or contingency table analysis methods.

Overcoming fully the problems that have been noted and others that could also be brought forward (2) is not possible. But the situation for the user could be improved by, first, making the uncertainties that the inference procedure gives rise to as explicit as possible so that the user can incorporate them in his or her decision process. Second, steps for improving the accident-incident and exposure recordkeeping procedures should be defined comprehensively, and carried out. 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 developments of the inferences, including the assumptions of stationarity and independence.

Fault-Tree Modeling

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 will have been tracked back through all possible event sequences to their initiating basic events. To realize the full power of fault-tree modeling, 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 magnitude of the consequences accurately predicted. If these requirements are met, a series of combinatorial probability calculations results in assessments of the probabilities of occurrence of specified consequences with given magnitudes, i.e., the risks deriving from the hazards under analysis.

The principal difficulties with the fault-tree procedures are the uncertainty that all significant event sequences have been considered and the acquisition of sufficiently precise data necessary for predicting, with reasonable accuracy, the initiating and related action event probabilities. These difficulties are central to the controversies on the application of logic tree methods in nuclear power plants and other fixed-facility risk assessments and their generally complete failure in transportation accident probability determinations. Because there are so many possible kinds of accidents and because interactions of possible accident causal factors exist in the dynamic operations environment of transportation systems, descriptions in terms suitable for probability analysis of all important sequences of events culminating in transportation accidents are not able to be meaningfully accomplished. However, fault trees, in particular, have been effectively applied to post-accident events analysis--most notably in analyses of nuclear material container failure 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 very recently been developed for nuclear and chemical processing plants.

Certainly, if fault-tree methods can be applied to transportation accident occurrence modeling, 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 basic event probability data generally still require statistical methods (and perhaps some subjectivity) to develop properly. What is emphasized here is that large enough sample sizes, even for different sets of conditions, are clearly much more easily and correctly developed for basic events than for actual accident occurrences. While certainly not trivial, this problem is at least possible to be solved with appropriate recordkeeping systems, experimentation, simulation, and testing.

Second, fault trees conveniently lend themselves to the evaluation of the effectiveness of given mitigating measures. Any such measures should be able to be assessed through the changes that they would induce in the original fault tree describing the accident occurrence that it is intended to prevent or decrease its probability. The evaluation of the effectiveness of mitigating measures by using statistical models 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 importance of such modes if at least relative basic-event data can be provided, such as the relative likelihood of occurrence of one equipment's failure compared with that of another.

To gain these advantages, fault-tree modeling 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 or failures, and control action time delays. Comprehensive testing, experimentation, and simulation programs will be needed for this.

Analytical and Simulation Modeling

Analytical and simulation modeling approaches to risk analysis begin with functional descriptions of the system under study. The operations of the system are then expressed in terms of appropriate performance parameters that express the functions and the interaction of the functions, systems components (human and 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 formulas (if analytical models) through numerical accumulations from repeated runs of system operation "scenarios" (in simulation models), or by combinations of both procedures.

The main problems with analytical models are the need for acceptable simplifying assumptions that the derivation of their formulations usually require and of the related departure of their modeled factors from direct physical significance. Simulations are better in these regards in that they usually tend to replicate real-world factors in a fairly recognizable way. However, to the extent that they avoid arbitrariness of their simplifications, their complexity and computational requirements increase. The need to repeat many runs of simulated 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, especially in the marine mode. Simulations have been used, but without great success, for estimating marine-mode accident probabilities. It is not believed that analytical-simulation modeling of accident occurrences is worth further consideration.

Subjective Estimation

When all else fails, an approach to augmenting sparse data in developing statistical inference 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 that they can meaningfully extrapolate their experience to new conditions, employing only their individual judgments in combination with those of the other experts (3).

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 sulfide transport as extrapolations from general experience with the material and from a "baseline" set of specific 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 likelihoods of possible causative events as these rankings derived from the experience of 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 Delphi are considered. The objective of this improvement effort would be to enhance the selection, control, and input information development of expert panels.

Estimation Considerations of Consequences and Losses

In risk evaluation one generally is concerned with determining both the probability of an event occurring and the consequences of that event. However, there are situations when determining only one of these factors is necessary. Determining the most probable cause of an undesired event and its associated probability of occurrence in some cases is more important than understanding in detail the consequences if the event occurred. An example of this is the evaluation of an innovative method of transportation such as a "ground-effects" machine or a new concept for a rail-train system. There are other circumstances when understanding the details of the consequences of an undesired event is of prime importance. This is often the case when there is a potential for severe impact on the public in terms of majority property damage and injuries.

The determination of the losses resulting from an accident consists of several steps: (1) Generally, the material leaves the container; (2) the material disperses into the environment (if flammable, it may be ignited immediately on emerging from its container or it might find an ignition source at some time and distance from its origin); (3) exceptions to steps 1 and 2 are the small class of materials where ignition can occur spontaneously within the container and the case where external events such as fires from hot boxes can cause a reaction in the commodity in the car; and (4) depending on the characteristics of the material being released, there may be damaging effects, or the potential for losses, due to fires, explosions, toxic effects on people and vegetation, contamination of ground water, etc.

Container Failure and Release

Container failure and the subsequent release of the hazardous material to the environment are common results of an accident sequence, especially for the case of liquified gases or liquid commodities. Containers can fail from a large number of "external" causes, such as the result of an accident (e.g., a train derailment), or "internal" causes, such as an undetected structural defect (e.g., crack) in the container or the vehicle. Containers of hazardous materials can also be adversely affected by events such as fires occuring in adjacent non-hazardous material containers. (Containers, as used here, can range from relatively small packages of materials as may be found in some air shipments to rail tank cars or barges.)

Analyses to understand the response of a container and its contents to an accident situation are usually performed by structural engineers assisted by someone skilled in heat transfer and thermodynamics. The reason for the requirement for the latter skills is that the material may be cryogenic and/or pressurized, or the container may be subjected to an external fire.

The possible scenarios for analysis are limited by the ingenuity and experience of the analyst. The selections of situations to be analyzed can often be guided by a fault-tree analysis. Even when quantitative data are not available for the fault tree, qualitative estimations are of value in selecting problems for consequence analysis.

In practice, we either focus our analyses on a specific situation or else on a small number of credible situations, including worst-case scenarios. The level of detail of the analysis is guided, for the most part, by the "level of effort" that is decided on before the analysis is begun. There are seldom technological constraints to carrying out the analysis on the response of a container and its contents to a postulated accident of incident.

The analysis frequently involves comparing the loads and forces of the postulated accident situation with the strength of the container. For external causes of accidents, we are normally dealing with a dynamic situation and the loads tend to be impact induced. Some examples are the impact of one vehicle into another, leading to rupture of the container due to direct impact or overturning; or a coupler impacting and penetrating the head shield 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 released.

"Internal" causes of releases of the commodity may be due to failures of pressure relief valves or valves that connect to a product transfer line. One can also postulate structural defects such as cracks in the undercarriage of the vehicle and/or cracks in the container, which can lead to structural failure and the subsequent release of the commodity being shipped.

These defects can be due to design defects, manufacturing defects such as inadequate welds coupled with poor inspection, or defects that arise with age and are not observed by inspection or not corrected.

Although the science and 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 desirable because often it is not cost-effective to construct the most sophisticated analytical model possible, other times we do not have the material properties data required for analysis. Even when there are no constraints on the analysis, testing serves to validate the analysis. Testing can range from small-scale laboratory experiments, to full-size testing of a component in the laboratory (e.g., head-shield/coupler interaction or brake-system behavior under load), all the way to full-scale testing of the actual vehicle with a simulated commodity on a test track. One must be carefull in designing laboratory tests because often parameters of interest in understanding the response of containers to certain types of accidents do not scale.

Testing can take the form of nondestructive, instrumented tests for the purpose of measuring physical parameters such as stress, and temperature in the container or its supporting structure, for various input parameters related to normal and abnormal operating conditions. Other testing methods are destructive tests that simulate an accident situation or an "internal" failure. These tests are also instrumented so that one knows the actual test parameters (the input loads), such as speed, angle of impact, force-time relationships at various locations, etc. It is important to instrument these tests, so that comparisons can be made with the analysis of the same situation, or predictions made for situations not analyzed. Further, if there is disagreement between analysis and test results one can ascertain the source of those differences from the test data.

There are some situations where testing (without 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 a volatile liquid, the escaping material will spread, evaporate, mix, and move downward, with the air surrounding the spill forming a cloud. (If flammable, the air-fuel mixture will burn if a suitable ignition source is present.)

The details of the spreading and cloud formation, among other things, depend on the rate of release of the material, its density, vaporization rate and buoyancy, meteorological conditions, and terrain. 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 have been developed that attempt to describe these complex events. The models differ significantly from one another in sophistication, because of their approximations and assumptions, in characterization of the source (point or area source, instantaneous or continuous release), or in the manner of spreading and air entrainment. For the majority of materials, input data on material properties are lacking and data for similar materials are used, which give rise to errors of uncertain magnitude.

For liquefied natural gas (LNG), these models generally agree for small spills, but not for large spills. This is due to the fact that the models were calibrated for the only data available, which were 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 the different models' predictions for such parameters as downwind distance. The differences depend on the simplifying assumptions used by the analyst.

Adequately instrumented tests involving large spills are needed to verify the mathematical models, since reliable observations are lacking from the few accidents where large quantities were spilled. Relatively small spill tests of LNG, liquid ammonia, and several light hydrocarbons on land and water have been conducted by using limited instrumentation. Larger tests are planned, but they will still be small compared with potential accident spill sizes.

The problem of modeling spreading and dissipation of soluble and insoluble liquids in water is in some ways as complex as spills on land since both physical and chemical effects must be accounted for.

Wind-tunnel simulations of LNG spills have been carried out by Meroney (4) of Colorado State University to better understand the effects of terrain features and obstructions on the dispersion and concentration of vapors in air.

Concentration measurements of materials dispersed in water are simpler to make than measurements in air. Still there is a paucity of data. Such measurements can be made in large laboratory tanks and there are several facilities that have the capability of making meaningful measurements. Currently studies of dispersion and mixing of a variety of soluble and insoluble liquids in water, to simulating flowing streams, is in progress. Much more experimental work is required to understand the behavior of the broad spectrum of materials being transported.

Characterizing Effects of Released Material

The dispersed material can lead to a number of undesired effects. Volatile liquids and liquefied gases when dispersed in air can cover an area several orders of magnitude larger than they were contained. A material in this state may be flammable, explosive, or toxic (to people, vegetation, fish, etc.).

In order for a material in its vapor phase to burn or explode, it needs to be at the proper concentration (i.e., within its flammable limits), and it needs an ignition source. A fire and/or explosion gives rise to thermal radiation, and/or overpressure and impulsive forces, which can have adverse effects on people and property. The flammable limits of many commonly shipped materials are known. The explosion effects in terms of energy release, i.e., its TNT equivalency, can be estimated from the heat of combustion of the material, if this property is known. The maximum possible energy release is never realized in accident situations because optimum conditions are never met. For maximum energy to be released in an explosion, one needs to have all the material within the explosion limits when it encounters an ignition source. Accidents tend to yield about 10 percent 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 cloud can give rise to enchanced blast in one direction. Predictions of fire and explosion effects tend to be conservative since calculations generally consider the worst case. Any other approach cannot be readily supported, except to draw on past accident experience to "establish" a credible energy release.

For the case of toxic materials, the effect of various concentrations, on people, vegetation, etc., is known for a fraction of the materials being shipped. Moreover, much of this information was developed for occupational exposures, i.e., for people exposed on an 8-h/day basis. Except for very few materials, we do not know how large a concentration is acceptable for a single exposure resulting from an accident.

To better understand how toxic and flammable materials behave in actual incidents, the National Transportation Safety Board 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 can thus show events that are time dependent, such as the growth of the dispersion pattern. In this way the sequence of events and the effects are readily visualized. The following information is to be displayed on the maps (5):

(1) The relationship between the dispersion pattern(s) formed by materials releases, and the size and nature of the hazardous material container.
(2) The relationship between the environmental conditions and the hazardous materials dispersion patterns.
(3) The relationship between the dispersion pattern, the location of casualties, and the degree of injury or harm.
(4) The relationship between the times associated with the dispersion patterns and injuries.

This approach has promise of aiding in understanding exceedingly complex phenomena. It will also help support and validate aspects of risk analysis consequnce estimates.

Accidents When the Container Is Not Breached

Fires, explosions, and releases of toxic materials can occur due to external causes. In the case of trains, for example, box car 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 strength properties of the container and the subsequent release of the hazardous material, be it flammable or toxic. 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 or materials not known to be sensitized by a small amount of contaminants. An example of the former 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 within a pile. We do not know if the hazard is size dependent and if it occurs only in large bulk cargo ships. This problem is currently being studied.

We expect that in the future more of these exotic materials will be transported as nonhazardous wastes. We must develop a protocol for evaluating the hazards of these materials.

Chronic Exposure Risks

Chronic exposures could occur from the following kinds of accident scenarios:

1. A spill of toxic liquid that migrates through the soil and contaminates the ground water;
2. A spill of a material into a body of water that cannot assimilate the material (the contamination that persists may have adverse effects on the ecosystem and/or the recreational use of the water); and
3. Extremely toxic materials can contaminate the soil, buildings, roads, etc., which may be impossible to fully decontaminate (an example of this

type of contamination is the release of a dioxin from a chemical plant explosion in Seveso, Italy, in 1976); there has never been a comparable transportation accident; however, the continuous low-level exposure of transportation workers to toxic materials may also become a matter of growing concern.

Such chronic risks will need to be considered in future risk assessment studies.

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 and the effectiveness of the attempt, the system's vulnerability along with the performance of its security capabilities, if any, and then assessed quantitatively in relation to this attempt.

Fault-tree methods, for instance, can be applied to develop the conditional probability (given the attempt) of any particular outcome. The methodological and initiating and associated event data needs for a sabotage risk analysis for a transportation system give rise to the same kinds of development requirements as for transportation accident risks. Experiments and simulations are possible basic approaches to meeting these requirements.

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: comparision with "ambient"/historical risks, comparisons with risks of equibenefit alternatives, and balancing of risks and benefits.

Comparisons with Ambient/Historical Risks

In 1969, Chauncey Starr (6) published the first of many articles on public risk acceptance in relation to benefits as revealed by historical data. Expected fatalities per year per individual in various groups exposed to accidents and other deleterious factors due to voluntary or involuntary hazardous activities were estimated from past data and compared with assessments of the benefits accruing from these activities. Starr found that historical levels of risk acceptance increased proportionate 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.

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

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, a risk measure based on expected, average, or mean losses, while convenient, obviates the 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 decisionmakers. The "disutility" of accidents appears clearly to be nonlinear as accident magnitude increases. The utility functions to express this have been discussed, but they have not yet been meaningfully developed. 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 very difficult to resolve.

The second of these philosophical problems noted above is the only one that has been so far meaningfully attacked. This was in the well-known attempt at risk acceptability evaluation (albeit not presented in those 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 with 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 distribution functions developed) is its neglect of the fact that, even if the incremental risk of the hazardous activity is small compared with the total ambient risk, the proposed involuntary risk takers do not often happily accede to even a small addition. The overcoming of 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). Any means for enhancing the credibility to them of risk estimates would be helpful, but probably not decisive.

Risk Comparisons of Equibenefit Alternatives

A second risk acceptability evaluation approach is the standard operations research technique of assuming 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 nuclear power has been argued to be safer overall than coal for generating electricity, for example (taking into account only the mean values of the risk profile 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 their spokespersons. 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 some "value of a life", and this has been a difficult feature of the analysis to agree on. If it could be agreed to, it could then be argued that a hazardous activity was acceptable if its potential loss (mean, or full risk profile) induced by its risks were less than the dollar value (or a given fraction of this value) of its benefits.

A similar argument has been employed in cost-benefit analyses of the value of safety programs. (The potential saving of n lives per year was worth at least nv dollars, where v was the value of a life in dollars, and so a safety program cost per year of less than nv dollars was justified.) The direct argument has also been put forward in the United Kingdom. Its use in the United States remains questionable, nevertheless. An extension to the use of merely the value of an incremental risk avoided or accepted appears to be more practicable.

Evaluation of Possible Mitigation Measures

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

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 somewhere else. One simple example is the consideration of having empty box cars separating hazardous material cars on a train. Although the spacing can serve to reduce the probability of the propagation of a fire or explosion to other cars carrying hazardous materials, spacer cars can, in some situations, have deleterious effects on the ability to properly "handle" the train, which in turn could increase the probability of an accident. Detailed analyses of alternatives and their "true" risk reduction potential must be carried out with extreme sensitivity to the possible opportunity to increase risks elsewhere.

If fault trees in sufficient detail could be successfully applied to transportation accident analysis, a straightforward procedure would be available for predicting the decrease in a risk resulting from a mitigating measure. It would only be necessary to recalculate the reduced 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, although new fault-tree methods may make it possible to some extent in the future.

Cost-Effectiveness of Alternatives

When evaluating alternatives for risk mitigation one first compares their effectiveness in terms of the the reduction in estimated risk. Effectiveness can be measured in a variety of ways, such as the expected number of lives saved, reduction in expected property damage, or other measures that may be selected. However, in order to make a reasonable decision as to whether one should implement an alternative strategy that has shown to be effective (i.e., the risk was reduced), the cost of the alternative should be determined. Although these costs cannot usually be estimated with the degree of precision desired, nonetheless their estimation is necessary for an orderly decisionmaking process. In view of uncertainties, the rank ordering of the cost of alternatives for a "unit" reduction in risk is a possible approach for making decisions.

An interesting rank ordering approach is to compare the cost of the risk reduction measure with the increase in longevity that would ensue. To make this comparison one must first determine the relationship between the crude mortality rate (deaths/100 000 population) and increased longevity. Schwing (7) has shown that the relationship is approximately as follows: increased longevity (Δ years) = 0.02 x crude rate. Next he constructed an index, which was the cost of a particular life extending program divided by the longevity increase it provided. The index (called an efficiency index) is expressed as the cost in dollars to gain a year of longevity for the population affected. His rank ordering of 60 life-extending programs showed the efficiency index differed by more than five orders of magnitude, from $192 to $27.5 million per person year of longevity extension. A scheme such as this for evaluation of cost-effectiveness of alternatives has the advantages that it would not only place the costs of various mitigation measures in relationship to one another, but would enable one to put these costs in perspective when compared to the safety expenditures in other sectors of society.

The implementation of any cost-effective approach requires a realistic counting of all costs. In practice this is not readily achievable. One needs to include the direct costs of an alternative that includes capital, operation, and maintenance costs. The costs of time delays and other indirect costs also need to be included. On a broader perspective are considerations of the loss of business of the carrier, to another transport mode due to the increased costs and/or loss of business of the shipper because of a reduced competitive position of goods relative to imports, etc.

If after all these factors are considered the cost of a mitigation measure to reduce risks is shown to be less than the cost of the existing method of operation, then the decision in favor of implementation is clear. However, as is usually the case, if the cost of an effective mitigation measure is higher, by any amount, than the cost of the existing method of operation, then the decision for implementation of a mitigation is not so obvious.

Evaluation of Cost-Benefit of Alternatives

For meaningful decisions to be made as to where to allocate resources, to decide where the greatest gains can and should be made, one should go a step beyond cost-effectiveness determinations and attempt to also characterize the cost and benefits (in monetary terms) of a given mitigation measure. Although estimations of cost-effectiveness contain uncertainties due to our inability to ascertain some of the desired costs and effectiveness information, evaluating the cost and derived benefits of a given mitigation measure is even more difficult, being fraught with uncertainties, unknowns, and the likelihood of omissions and controversies.

From the simplest viewpoint, if the cost of the mitigation measure is less than the benefits derived (measured in dollars), then the mitigation measure should be implemented. In practice, this is not so simple or straightforward a decision to make. The reasons are numerous. The data, to support the magnitude of the risk reduction estimates and the cost of implementation of a mitigation measure, often contain large uncertainties.

Extreme caution must be exercised when considering whether to make a decision based on data with a high degree of uncertainty. This is especially true when the decision to implement a risk reduction measure may affect the competitive position of the carrier and/or the shipper and/or the availability of the commodity in a timely manner. Even if there were no uncertainties, can business risks be accounted for and somehow be balanced against the risk reduction of the hazard? It is not always clear that society as a whole benefits by implementing a risk reduction measure. One can create an extreme scenario where the cost of reducing the hazard risk results in a cost that makes a given mode of transportation uneconomic and another mode is used. Those people put out of work temporarily, or permanently, will suffer psychological pain and anguish that can be compared with the suffering of victims of an evacuation when a toxic material is released in a transportation accident. The cost to the economy of the unemployed transportation employee needs to be compared with the cost of such things as the evacuation just cited, and so on. The "simple" case just envisioned is not simple at all; all the benefits and all the harms are not always feasible to account for or to estimate their impacts. The effects of risk reduction measures whose economic impacts are even more subtle are subject to even greater difficulty in their proper assessment.

The approaches described are not sharply discontinuous, there are similarities and overlaps between them. They all face the same question, how are decisions to be made so that the greatest benefits can be achieved per dollar expended? Spending money on suboptimum activities results in lives sacrificed because of lack of funding of more efficient endeavors. One of our problems in reaching equitable decisions include deciding what attributes both direct and indirect benefits should have, such as longevity, lack of psychological suffering and anguish, availability of goods at a competitive price, a viable transportation network encompassing all modes (a national security benefit), etc. Even if we did agree to the attributes to be considered, we are faced with the formidable problem of placing a dollar value, or some other index, on each type of benefit. The same concerns apply to identifying and quantifying the direct and indirect costs of mitigation measures.

Approaches to Facilitating the Use of Risk Assessment

Validation Techniques for Risk Analyses

The controversies and lack of acceptance of risk analysis primarily involve its quantification. The consequences part of the risk equation is subject to direct validation by full-scale or small-scale field tests. Validation is possible because we are concerned with deterministic physical phenomena. However, estimates of the probability of undesired events or an accident stemming from various failure modes or basic events are not as readily validated. There are a number of reasons for this. The accuracy and completeness of the logic trees or other approaches directly affect the validity of the results. Incompleteness may be due to not fully understanding how the system works, either by oversight or by a simple lack of thoroughness by the analyst. An analogy is a computer program that can be incorrect due to errors, omissions, or poor logic in programming. In programming, however, these errors, etc., are almost always eventually discovered by the failure of the program to run to completion or by nonsense results. The corresponding problems with respect to risk analysis are not so readily detected and may only be overcome by a validation procedure that requires an independent analysis. There is a regulatory precedent for third-party verification in the design of off-shore oil and gas platforms.

If one tries to compare a predicted value from a fault tree, for example, with an historical value for the same top undesired event, one can encounter a number of problems. Most events are of low probability, so there is not enough experience for the existence of a statistically valid set of data. Sometimes there is enough experience but the data have simply not been collected. To overcome the data availability and adequacy problem, it is sometimes possible to obtain data from a wide range of sources and to compare results as a function of the data base used. Some examples are data acquired by U.S. government agencies, industry data either acquired by an individual company or by a trade association, insurance company data on claims (U.S. and worldwide), and data collected in foreign countries. Some of the data may be for situations or environments that are of a different severity than the problem being analyzed--but this can be accounted for in a qualitative way.

Some approaches to validation for a given problem are to (a) use more than one method; (b) have the analysis done by two people, independently of one another; and (c) use as many data bases as it is feasible to acquire. If consistent results are obtained, one can gain confidence in the validity of the methodology and the quantitative results. The above approach has been used by one of the authors for a risk analysis that was subject to public scrutiny at a nuclear power plant licensing proceeding.

A "true" validation of the currently used methods of risk estimation would be to (a) identify an activity for which there is a statistically valid data base, (b) exercise risk analysis methods that are intended to predict causes and probabilities of accidents, and (c) compare the predictions in (b) with accident experience of (a). It is also possible to consider special experiments and tests that could produce data that could be used to validate at least the lower elements of a risk model (e.g., at an intermediate level of a fault tree).

Applications for Potential Users

The requirements for risk assessment vary widely among different kinds of present and potential users. One federal regulatory office may need a methodology for assessing the risks of a given hazardous material transport operation under generic conditions that express representative nationwide factors. Another may need a detailed capability for modeling the risks of specific alternative shipment routes, modes, or containers for a given material. A third may need to be able to assess in detail the effectiveness of some possible risk mitigating measures. State and local government agencies may need to assess the risks of shipments of one or all hazardous materials into or through their areas, as specifically as possible to the conditions on their present routes and possible alternatives to them. Shippers and carriers may require similar assessment capabilities to support their cost-safety optimization decisionmaking, which may in the future become increasingly explicit.

While the basic concepts and general techniques must be common to all such applications, it is evident that considerable variability is possible in the particular form and specific details of risk analyses appropriate to different users' needs. The main trade-off is between risk modeling precision and simplicity in applications. Of course, as has been discussed in this paper, precision is always inherently limited by the quality of available data and modeling assumptions that are made in major part because of data shortcomings. To enable simplified uses of risk assessment incorporating still more generic data and broader assumptions, a yet greater sacrifice of precision will generally be required, but if the effects of this sacrifice on the decision process using the risk assessment are understood and accounted for, the less precise but simpler-to-apply methodology will nevertheless be worthwhile.

A study therefore appears to be warranted that would define the several kinds of users of hazardous materials transportation risk assessment, the circumstances in which they could or should use it, the data available and their costs, and, finally, the specific characteristics of the methodologies that best fit the different users' needs and resources. It can be envisioned that these latter characteristics will range from full-scope modeling and data acquisition and analysis approaches to, say, simple cumulations of some scores that for given circumstances are associated with a set of risk factors provided in a predefined list and employing, to the extent feasible, a common data base. The role of the federal government, most especially, in the development and standardization of such simplified approaches and common data bases should also be defined in the suggested study. It is also suggested that an important function of the national strategies conference is the initial definition of such a study, a fuller delineation of its utility, and a determination of its potential sponsors.

PART 2: ETHICAL AND PHILOSOPHICAL ASPECTS OF RISK ASSESSMENT

The parameters of the risk assessment problem have been succinctly stated in a report of the Transportation Task Force of the Urban Consortium for Technology Initiatives (8):

> The transportation of hazardous materials is an essential activity in the twentieth century, one upon which all sectors of the economy are highly dependent. The transportation of these materials cannot be discontinued, or their flow impeded to to the extent that their use becomes prohibitive, without a return to a primitive civilization in which the hazards of life and health would far exceed the dangers inherent in their transportation.

The needs and issues being raised by hazardous material transport could not be summarized more clearly.

As this citation suggests, mounting public awareness and attention to the transport of hazardous materials will be seriously counterproductive if it results in a general failure to develop and apply a method of managing not only the materials in question, but also public perceptions of their threat to public safety. Risk assessment methodologies have been developed as tools for this managerial task. However, their adequacy and application in our current institutional framework have been questioned from a moral and ethical perspective. At least three reasons may account for the fact that the evaluation aspect of risk assessment methods is being challenged.

In the first place, as a concept as well as a goal of social policy and standard-setting, the quest for "safety"--interpreted as "absence of risk"--has grown increasingly problematic. Access to a higher standard of living enjoyed by increasing numbers of citizens is accompanied by rising expectations for acquiring those goods and services that promote a sense of "security and safety". With the attainment of first-order, basic goods essential for survival, individual pursuit of safety becomes expressed as a vital need to protect and preserve nonsubtractive, second-order or "buffer" goods. These take virtually limitless form to the extent that moral responsibility for providing such good shifts from the individual citizen to social institutions. Institutions are then expected to monitor and deliver "safety"--perceived and conceptualized as an identifiable commodity or intrinsic property possessed by a given product or process. An unrealistic expectation derives from public misconceptions of what can and cannot be delivered by social institutions. "Safety expectations" are at the root of objections to the judgment and decisions derived from risk assessment methodologies. As Max Singer (9) observes:

> Safety is one of the reasons it is better to be wealthy than poor. But as we get wealthier and safer, we become more concerned about safety.... Like most social problems, the death toll from hazards requires a complex, balanced and limited response. We cannot give ourselves up to eliminating or even reducing hazards. As individuals and a society we must not become cowardly, fearful or hypochondriacal. The weakening of our character can do us more harm than all the auto accidents and all the fires.

In the second place, there is general failure to recognize and accept what Lapham terms, "the Law of Conservation of Risk" (10). He states that, like energy, risk can neither be created nor destroyed. Unless we are careful, all we may do is cause its displacement either in time from one generation to another, or in space from one location to another. A spatial displacement of risk is exhibited by those who refuse to allow repositories for municipal, commercial or industrial waste, or transport of hazardous materials in their vicinity. We hear citizens today join in with the general clamor and exclaim "not in my backyard." We must be wary of the potential for displacement, least risks to our health and safety do not disappear but reappear in another guise. Consequently, it is sophistry to form public policy or set safety standards on the basis of considering only incremental risks and incremental benefits of one or another technological activity, as if these were simple additions to a current risk background. To the contrary, bioethics requires consideration of systemic risks--that is, risk and venefit accounting for an entire social system--as a consequence of hazardous material transportation methods. The failure to conduct systemic risk assessment induces the possibility of a risk of far greater magnitude.

In the third place, despite their good intentions, purposes, and promises, risk assessment studies for the purpose of increasing safety have been applied within traditional institutional frameworks in ways that force them to be piecemeal, ad hoc, haphazard, isolated for one-at-a-time consideration. In the public domain, one hazard is spotlighted for a time, giving way to another in unending succession.

Moreover, each regulatory agency or branch within agencies has its own mandate to control one category of hazards. For this category it conducts ongoing research, thereby making a case for more federal funds to do more research and impose more regulatory requirements in the name of further risk reduction. Not only does piecemeal, selective concentration increase the visibility of certain hazards, but the public is often led to believe that the more studied risks are, by that fact, the more dangerous to public health and safety. But this is clearly not the case.

Philosophical Framework for Risk Evaluation

Contrary to a popular misconception, "hazards" have neither a bare factuality nor an intrinsic morality predetermining how human beings should behave in relation to them. Hazards are not baldly "there" in nature or in human transactions with it. What people regard as hazardous in any given era reflects what they have come to know about their environment, and what they value as essential or desirable on a scale of real possibilities. In short, human beings structure hazards; they are, in that sense, human artifacts. A hazard is not by definition "toxicity of substance" or "violence of event" or "magnitude of consequences" that can be known, classified, and predicted. A hazard exists only when, and to the degree that, harmful exposure of and assimilation by the human body or other valued living systems becomes a genuine and not merely an imaginable possibility. That possibility exists only when there is an inability or failure to devise and maintain controlling actions or safeguards.

Because there are vast uncertainties about "how the world works," it serves no human purpose to bewail our "legacy of risks to future generations," and then make the fraudulent claim that the goal of hazard management should be to assure centuries of control over toxic elements or to make predictions about future adverse events. Clark states that the primary goal of hazard management is "to increase our ability to tolerate error and to take productive risks" (11). His statement stands in contrast to a popular yet unexamined notion, observed by Häfele, that "we are locked in a world of untested hypotheses (of unimplemented trials) because we dare not let experience prove us wrong. The costs of failure have grown too great" (12). Not only does this notion reflect the New Pessimism, spawning defeatism and pseudoscientific dire predictions that now pervade our cultural climate, but it also constitutes in itself the ultimate hazard--the failure to design and maintain structures of social resiliency. It is the social ideal of resiliency that has been a major driving force behind the emergence of highly complex and technologically advanced societies. The social ideal of resiliency accounts for the development of the burgeoning art of risk analysis.

Because of the identification of risks with hazards by a small but vocal group of people, they have perceived a false antithesis between risks and benefits--as if there were a way to have one without the other. The trouble with the phrase, "risk-benefit analysis" is twofold: It fails to express a proper symmetry and it tends to obscure the primary motivating force of human activity, i.e., the foreseen and intended benefit that can be gained or lost. In concrete decisions, what is often "at risk" is the possibility that the intended benefit may not materialize and, instead, harm may occur. On the other hand, both benefit and harm may result, but to different groups. When harm results, it is clearly unwanted and unintended. Risks and benefits are inseparable, not antithetical.

A major problem about the growing dispute over hazardous materials transportation is the inadequacy, not of risk analysis, but of harm-benefit analysis. Some refinement in the notion of benefit is essential. Okrent and Whipple suggest three qualitative distinctions in benefits, namely those goods essential to society (e.g., food, water, energy) or basic goods; advantageous to society (e.g., most manufacturing); and of peripheral, if any, value to society (e.g., aerosol deodorants having substitutes at lower cost and likelihood of harm) (12). Each qualitative benefit has corresponding levels of harm. Basic harms may result from being deprived of goods essential to subsistence and material well-being. Justice and equity require a society to provide access to basic goods and avoid basic harms. As for second-level benefits, the total outcomes any social policy toward these improvements will have an unclear mix of benefits and harms. Automobile and airplane manufacture afford major economic benefits to employees, capital investors, travelers, and the general health of international economies. Yet, each time someone drives or enables an airplane to take off, the benefits pursued may entail the possibility of unintentionally causing the death or serious impairment of a fellow human being. Any society must, at some point, deliberately decide how we ought to balance economic benefits and costs against possible harm or loss of life.

According to critics of such balancing, a human life is of infinite value, and its loss or impairment cannot be put in a class with other "negative consequences," much less be given a finite monetary value. To do so indicates the moral bankruptcy of our materialistic, consumerized, decadent society. Cost-risk-benefit quantifications, say its critics, manifest a loss of respect for the sacredness of human life. Those who defend this conceptual tool have often used simple observations, such as "there are necessary trade-offs in any public policy decision" or "everyone puts a finite, monetary value on one's life when buying life insurance, installing safety mechanisms in a home or automobile, taking hazardous jobs because they pay higher wages". Although true, such analogies are not sufficient. The public must be confronted with the fact that any society has but a finite amount of resources to spend on health protection and safety, and that the ethical problem is to get the most protection for the most people from this finite amount.

As a conceptual tool that attempts to enhance informed consent, cost-risk-benefit quantifications are simply one tool among many others whereby policymakers endeavor to allocate finite amounts of money in a just and equitable manner. They are not tools for putting some callous dollar value on human life or injury as a moral judgment or individual worth, much less of using economic losses to society as a measure of personal expendability. We are in fact maximizing the value we place on human life when we endeavor to allocate limited amounts of money in such a way as to reduce widespread hazards, thereby preventing as much loss of life and providing as much protection from injury as possible.

The fact that our tools for balancing economic costs against risk to human life are not morally or ethically objectionable does not amount to saying that they are easy and acceptable to the public. Far from it. The task of public education in this matter is monumental. Moreover, as Pickering observes: "We are going to have to do more than find some level of acceptable risk; we are going to have to come to terms with the question of justifiable harm. There are, after all, some kinds of harm which cannot be avoided; but there are other kinds of harm which any society should not allow and against which it should adopt protective or remedial measures to the best of its ability" (13). Which is which becomes the policy question.

Means for Enhancing Credibility of Diverse Stakeholds

If policymakers, regulators, and managers of risks from hazardous materials transport are to merit public credibility, some method should be found to demonstrate that decisions about policy and standards have been made in the context of an adequate ethical framework--one structured primarily around a fundamental bioethical principle. This formulation is suggested:

> Social justice and equity require an equitable management of sources of basic harms, that is, potential hazards that might have adverse health effects and unjustifiable social consequences.

By "equitable management" is meant that policymakers should first be comprehensively informed about the broad spectrum of both natural and ordinary manmade hazards that may have health effects for large segments of the population; then make comparisons of the actual risks as well as costs per capita (or per person affected) to reduce these effects; and only then make policies and set safety standards that will get the most public health protection for the many out of a finite amount of money. Potential hazard management is ethically equitable only if it is proportional in relation to actual basic harm that can be identified and reduced by expenditures of human effort, time, and money.

In view of this principle, one approach is to determine what society has already decided it is willing to pay to avoid the statistical occurrence of a death, an injury, or an undesirable environmental impact. Protection of society from risks due to hazardous material transport should not require greater expenditure of resources than a society has generally shown willingness to pay for equivalent protection from risks due to other potential biohazards. The inconsistency that exists in social decisions does not invalidate the approach but rather calls attention to the need for its more rigorous application.

PART 3: CONCLUSIONS AND QUESTIONS FOR DISCUSSION

Assessing the risk of hazardous materials transportation involves (a) the selection of the most appropriate method for the problem at hand and the acquisition of the data required for that method; (b) the application and implementation of risk assessment results; and (c) consideration of the ethical issues governing risk acceptability, the meaning of "safety", and the use of systemic risk analysis versus piecemeal application of risk analysis.

In order to stimulate discussion and assist in the formulation of recommendations for specific research and development programs, a series of questions are posed for consideration by workshop participants. These questions are to serve as the starting points for discussion. It is expected that a consensus will be arrived at concerning approaches and recommended programs to enhance the usefulness of risk analysis.

Methodological and Data Needs and Issues

Risk assessment involves a number of tasks. They are

1. The structuring of the problem that includes selecting the method of analysis that is consistent with answering specific questions and providing output of a specific predetermined nature; the techniques employed are suggested by the magnitude and complexity of the system being investigated, and availability of data, and the needs and resources of the sponsor/user of the analysis;
2. The determination, or estimation, of risk (i.e., probabilities and consequences of undesired events with and without mitigation measures); and
3. Evaluation and interpretation of the predicted outcomes that may result in the introduction of risk reduction measures or the acceptance of the risk.

It is clear that one of the impediments to the successful implementation of risk assessment (items 1 and 2 above) for the problems of transporting hazardous materials is the inadequacy of the data base--in both scope and detail. Data on numbers of accidents, their causes, their location, etc., are incomplete or spotty in scope. Also lacking are population data, e.g., quantities of materials shipped according to mode of shipment, box car miles, truck miles, ton miles, etc., for hazardous materials and all commodities.

Failure rate data on safety-related hardware are generally not available. Although not specifically discussed in this paper there also is the need for properly trained, experienced, and motivated personnel. We currently cannot quantify the extent to which inadequate training or lack of experience affects the accident rate or how inattention due to lack of motivation increases the consequence of an accident. The performance of people must be accounted for in risk estimations and a quantitative estimate of the failure rates is necessary input to several of the risk analysis methods.

Although extensive accident data are currently collected, their limitations are numerous. The data-collection system should be strengthened so that the data that are reported are of the type that can be used to support the various risk assessment methods.

The most controversial aspect of the implementation of risk assessment is the evaluation and interpretation of the predicted risks (item 3 above). This aspect of the problem involves judgments based on factors that are difficult to quantify. They include the hazard's risks, costs, and benefits; business and political risks; and ethical considerations and issues. There is the lack of concurrence as to what attributes should be included in these factors. Even if all the attributes could be defined and agreed to, their quantification is not readily achieved. Much research and education of the public are needed in this area.

The following questions for discussion may be helpful:

1. What approaches should be taken to improving

exposure (shipment) data bases and their reporting systems?

2. What approaches should be taken to improving accident/incident occurrence data bases and their reporting systems? Are data bases capable of supporting multivariate statistical analyses (to delineate causative factors and their associations) practicable?

3. What improvements in statistical inference, fault-tree, analytical, and subjective estimation-simulating modeling procedures would be desirable, and what approaches should be followed to investigate their feasibility and to implement them if they are feasible?

4. What are the main problems in modeling the probabilities of accident/incident occurrence, container failure and release probabilities, effects and their propagation, and consequences and losses? What are approaches to overcoming these problems? What about sabotage and chronic risk modeling? How do these approaches relate to those in items 1-3, above?

5. How might numerical risk acceptability criteria be best established? Consider both analytical and sociopolitical issues.

6. Can economics-based risk-cost-benefit calculations be used in hazardous materials transportation risk analysis? What are approaches to its best development?

7. How can the effectiveness, in the future, of risk mitigation measures best be predicted? What testing and experimentation would be practical to provide data in support of such predictions?

Application Needs and Issues

To enhance the application of risk analysis one must be convinced of its validity, understand how a specific risk compares with other societal risks or a predetermined safety goal, and effectively balance the role that risk analysis should play along with other tools and approaches available to the decisionmaker.

The following questions for discussion may be helpful:

1. What approaches should be investigated for the development of effective means for validating risk assessments? Consider, for example, internal procedures for estimating and/or overcoming uncertainties, and external procedures such as replicated analyses and special experimentation/test data (at the system level if feasible or, perhaps, at intermediate risk modeling levels).

2. How can existing risk assessment methodologies, if diligently applied, lead to improved safety?

3. How can risk/hazards assessment be made a simple, inexpensive, and practical tool for the regulator and others for everyday operational use? Is it every going to be possible?

4. Are current methods and approaches useful for comparing risks? Can and should comparative risk assessment be used separately by the regulator of each transportation mode? Should there be a DOT systemic approach or only a comprehensive comparative assessment for all hazardous activities throughout our society? Should risk analysis be required of shippers and/or carriers by regulation?

5. Can and should risk assessments be used as a guide for setting priorities and for implementation of safety measures, within a given mode and between modes?

6. Should a safety goal be set and should risk assessment methods be used to see if the goal is met?

7. Instead of a safety goal, should best available and safest technology (BAST) criteria be used or should as low as reasonable achievable (ALARA) criteria be used? Can risk assessments tell you whether BAST has been achieved?

8. Should there be standardization of risk assessment methods?

Ethical Issues

A profound misconception of "safety" dominates the controversy over hazardous materials. The working assumption has been that safety is an intrinsic, measurable, absolute property that a given system or product or activity can and should possess. Our society has institutionalized and appointed the regulators to measure approximations to that elusive property. The mandate of the regulator is to make ever more stringent regulations, presumably to come ever closer to that property by reducing risks. But the only risks the regulator is expected to monitor and minimize are a small percentage of the total spectrum of risks tolerated by members of society as a whole. Intent on making a set of risks publicly "acceptable" as an index of "safety", the professional regulator must continue to propose risk-reduction with inadequate knowledge of costs or social impacts of ever-changing regulations. Presumably he or she is "only giving the public what it wants", namely safety. This spiral is likely to continue unless or until the public comprehends the fact that safety is not an intrinsic property measured by approaching zero-risk. Safety is an evolving, relational value judgment derived from current personal or social priorities. Whereas risks can be measured, quantified, and predicted, safety cannot be measured, much less predetermined by the presence or absence of risks.

Judgments of safety are judgments about the justifiability or unjustifiability of harm. The process of reasoning for ethical safety-policy decisions should be dictated--not by risk avoidance, an impossible ideal--but by comprehensive risk estimations and cost-risk-benefit evaluations. When these comparisons make it clear that a point of diminishing returns on allocations of money, time, and effort has been reached by comparison with other potential hazards in a society, then the product or process under scrutiny is "safe enough". If indeed unintended and unwanted harm should occur, then such harm can be judged justifiable because it is unavoidable or negligible by comparison with other harms and essential benefits.

What is needed is a whole new field of numbers. We need to know, with the most comprehensive overview, how much public money is spent to reduce ordinary diseases and accidents and hazards that afflict major segments of the population, the cost per capita to reduce them, and precisely at what point vast amounts of money may be pouring into budgets that can assure only minor gains in the status of public health. We have a surfeit of statistics on public health, but those data are not arranged by any responsible public institution so as to look at risks to the entire population relatively, to make comparisons, to maximize cost-effectiveness so as to get the most public health for the many out of the expenditure of public money. Comparable risk analysis is talked about, but it is not acted on or used responsibly at a comprehensive level by those state and federal agencies empowered to do it.

The following questions for discussion may be helpful:

1. What are the paramount ethical issues in the use of risk-cost-benefit analysis and how can they

be best responded to at different government and industry levels?

2. Is the concept of "justifiability of harm" likely to enhance the utility of risk assessment?

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How-to-Do-It Regulations Inhibit Research

William C. Jennings

DOT's Materials Transportation Bureau issues safety regulations for the transportation of hazardous materials in interstate commerce by all modes of transportation. These regulations are published in 49 CFR Parts 100-199.

Most of MTB's regulations relating to hardware are specific how-to-do-it requirements. This is particularly true of the requirements for designing, making, and testing containers such as drums, tank cars, tank trucks, and pipelines. These how-to-do-it requirements inhibit the development and use of new products and procedures.

The how-to-do-it language in the regulations is usually the result of MTB's adapting or adopting consensus standards as regulatory requirements. While our concern is with the whole range of specifically stated requirements, this paper will focus on the practice of adopting consensus standards as regulatory requirements.

DESCRIPTION OF CONSENSUS STANDARDS

Consensus standards are written by committees composed of representatives from (a) industry sources such as operators of facilities, manufacturers of products, and contractors who build facilities, and (b) non-industry sources such as college faculties, research institutions, and government agencies. The committee members bring to committee deliberations a wealth of technical knowledge and operational experience. They develop standards to advise the various segments of industry as to the products and procedures that experience has shown to be acceptable for general use.

Consensus standards are advisory, not mandatory. Most companies follow the recommendations because they are good. However, any company is free to experiment with new products and procedures. As a result of this experimentation, the industry is able to accumulate operating experience with new products and procedures. When there is enough operating experience with something new to show that it is acceptable for industrywide use, the committee incorporates it into the standard. Thus the consensus standard process recognizes and recommends what experience has shown to be good, while permitting experimentation and innovation.

The merit of the continuing consensus standard process is that it is self-renewing. The committee continually reviews operating experience and gives its approval to new products and procedures when industry's cumulative operating experience has shown their worth. The committee bases its recommendation on experience with yesterday's technology, but it does not foreclose use of tomorrow's technological developments. As each consensus standard is periodically updated, the new version marks another milestone in the continuing development of industrial products and procedures.

DESCRIPTION OF REGULATIONS

Regulations differ markedly from consensus standards. Regulations are mandatory, not advisory. Industry is required to use the products and follow the procedures prescribed in the regulations. Companies are not free to experiment with new products and procedures, except through the cumbersome process of getting a waiver of compliance from MTB.

When MTB adopts a consensus standard as a regulation, it decrees that industry must operate in the future on products and procedures that were already in use at the time the standard was published. The regulation does not accommodate the use of new products and procedures, except by waiver. There is little opportunity to gain operational experience with new products and procedures. As a result, the consensus committee does not get the kind of information on which it relies to update the standard. The consensus standard milestone, a mark of progress, thus becomes a regulatory milestone, inhibiting progress. By this process, industry's products and procedures are slowly fossilized by fiat.

The federal safety standards for the transportation of natural gas by pipeline are in Part 192. The requirements for pipeline materials are in Subpart B--Materials, which consists of Sections 192.51-192.65. The following provisions of Subpart B are pertinent to this discussion:

1. S.192.51 states the scope, "This subpart prescribes requirements for the selection and quali-