Rational Risk/Benefit Decisions in the Use of Flame Retardants: an Analytical Approach

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Difficult trade-offs must be made in setting regulatory policy on the use of flame retardant chemicals. A rational policy is one that seeks a moderate middle ground, trading off toxic hazards against fire hazards to yield the minimum aggregated losses and costs to society.

DIFFICULT TRADE-OFFS are faced by society in the use of flame retardant chemicals. By their very design, such chemicals are intended to reduce fire losses, either through reducing the ignitability of treated materials or through reducing the rate and extent of flame spread when ignition does occur. But contrasting the reduction in fire losses, there is the possibility of adverse health effects. Use of flame retardants may also increase the cost of the treated materials. Thus, whereas there are certain benefits to be derived from the use of flame retardant chemicals, there are less certain yet potentially serious risks attendant on their use as well as increased costs to the consumer that must be weighed against the benefits.

Ideally, society expects nontoxic, fire-safe products and prefers not to have to pay extra for the peace of mind. However, it appears that this ideal is not technologically attainable, at least not now. Instead, in regulating the use of fire retardant chemicals, a trade-off must be made among the fire and toxicity-related losses, and the economic costs. On the one hand, society could opt for a policy that minimizes fire losses (i.e., require the use of the most effective fire retardant chemicals, regardless of toxicity), or at the other extreme, it could elect to minimize toxicity-related losses by forbidding the use of all flame retardant chemicals, regardless of the effect on fire

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losses. Of course, there are a wide variety of options in between these two extremes.

This paper is based on the premise that the most rational regulatory policy is that which minimizes total societal cost plus loss, where all fire and toxicity-related costs and losses are taken into account. Any other policy, regardless of how much it might reduce a single component of fire or toxicity-related death and morbidity, would result in more total cost to society in terms of the net losses and economic costs incurred.

Evaluating flame retardant regulation policy, then, becomes a problem of assessing and comparing the costs and losses that would occur under each of the possible regulatory alternatives. Unfortunately, whereas the principle of analyzing such policy is relatively straightforward, implementation is difficult. Several factors account for this difficulty. Foremost among them is the complexity of the underlying fire and toxicity problems. Uncertainty is also a major factor, as many of the underlying physical, chemical and biological relationships are poorly understood. Finally, even if the individual components of cost and loss could be assessed with certainty, difficult value judgments must be made in comparing the different outcome measures of burn injuries, disease, disability, death, and economic cost.

The purpose of this paper is to outline a decision analysis framework for evaluating alternative policies for the regulation of flame retardant chemicals. Decision analysis is a formal discipline for analyzing complex decision problems involving uncertainty. The methodology uses probabilistic models, especially developed for each application, to assess the performance of the decision alternatives in question, given current levels of uncertainty.

ILLUSTRATIVE EXAMPLE

The decision analysis approach is best demonstrated with the use of an example. For this purpose, the children's sleepwear problem has been chosen as a vehicle for demonstrating the approach. The example is by no means complete, but it is hoped that the analysis is sufficiently well structured and that the reader can appreciate the utility of the decision analysis approach in addressing explicitly the many issues that must be considered in setting policy regarding the use of flame retardants in children's sleepwear.

BACKGROUND

Flame retardant fabrics are used in children's sleepwear to prevent or reduce death and injury — estimated at about 3,000 severe burn injuries and 100 deaths annually — in small children, notably in the age range from newborn to those wearing up to size 6X.[1]* The most widely used flame retardant additive for children's pajamas is tris (2,3-dibromopropyl)

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* Superscript numbers refer to literature citations listed at the end of the paper.

phosphate — popularly known as tris BP, or simply "Tris."[2] While for some time there has been concern over the toxicity of fire retardant chemicals,[3,4] the issue first became one of broad public concern this year with the announcement that Tris was mutagenic according to Ames' salmonella/microsome test[1,2] and was possibly carcinogenic to humans.[5,6] The sale of garments treated with Tris was banned in April, but the ban was later overturned on technical grounds. In the meantime, suppliers of FRCs have made substitutions for Tris, such as Fyrol FR-2, but preliminary tests have raised similar questions about these substitutes.[7] Unsold inventories of sleepwear treated with Tris, Fyrol FR-2, and similar FRCs run into the hundreds of millions of dollars, creating a financial plight and disposal problem for manufacturers and retailers. This pales to insignificance, however, in comparison to the exposure of 60 million children to the risk of cancer, sterility, and genetic damage if this risk turns out to be genuine.

The heavy usage in fabrics of flame retardants such as Tris began in 1973 in response to stricter flammability regulations that followed the passage of the Flammable Fabrics Act of 1967 and the assumption of responsibility for its implementation by the Consumer Products Safety Commission (CPSC). As early as 1970, Myron Tribus,[8] then Assistant Secretary of Commerce for Science and Technology, laid out the framework of a decision analysis designed to determine the most cost-effective ways of satisfying the requirements of the Act and to guide the expenditure of the appropriations. Statistics on burn injuries were gathered to show the dimensions of the problem.[9] Subsequent priorities for implementation of the Act were based on the recognition that the young and the old are the most susceptible to burns from fabric fires and that these most often occur in the home when garments are exposed to bathroom heaters, kitchen stoves, and smoking materials, especially during the early morning hours. Children's sleepwear was first among the textile products singled out for stricter regulations. The longstanding favorite, cotton, lost out to polyesters mainly on the basis of the cost of treating it for flame retardancy. Tris was cheap, compatible with polyesters, effective as a flame retardant, and its combination with polyesters (introduced as an additive to the melt) could be counted on to pass the flammability tests that included a requirement that flame retardancy would survive 50 launderings. The inherently flame-resistive fibers lost out on a combination of economic and technical factors. Thus, through a combination of restrictive regulation and techno-economic realities, Tris became a 10 million-pound-per-year commodity.

The public, represented by its consumer advocates and regulatory agents, now has the problem of deciding whether the as-yet-unproven risk of cancer from flame retardant chemicals outweighs the better known risk of clothing-fire burns. Garment manufacturers, shaken by recent events and uncertain that the FRC industry can, under present circumstances, provide a technologic fix, are turning to inherently flame-resistive fabrics. CPSC is moving to assist a shift to these intrinsically safer fabrics through modification of the flammability standards to lessen dependency on chemical additives. The increased use of inherently fire-resistive fabrics is laudable, but the likely increase in cost may induce consumers to subvert the intent of CPSC's action, and any relaxation of the flammability standards that may again permit unsafe fabrics to be used must be carefully avoided. Clearly, the children's sleepwear dilemma is a good example of a public-safety problem whose regulation should be based on a rational, analytical decision-making process in which all reasonable alternatives are evaluated and compared.

ALTERNATIVE POLICIES

There are a number of possible regulatory policies for addressing the children's sleepwear problem, ranging from requiring flame retardant chemicals to be used in all children's sleepwear regardless of toxicity hazard, to disallowing the use of all flame retardant chemicals in children's sleepwear. Table 1 lists four representative courses of action. There are obviously many more possibilities, some of them being variations or combinations of the four listed and others being completely different approaches such as attempting to regulate the availability of ignition sources. Of the four alternatives listed in Table 1, two are primarily directed toward the toxicity problem and two mainly address the fire problem, but two alternatives do address both the fire- and toxicity-related losses.

ANALYTICAL APPROACH

In carrying out a full decision analysis of the children's sleepwear problem, the first step is to identify a reasonably comprehensive set of decision alternatives. The possible courses of action are developed from discussions with experts and decision makers. But for the purpose of this example, refer to the four alternatives listed in Table 1.

The second step of the analysis is to develop quantitative models for assessing the various costs and losses that would occur under each alternative. Separate models are built to assess the costs, toxicity-related and fire-related deaths and disabilities. The models are made probabilistic to account for the underlying uncertainty. It is important to recognize that the models are decision models for use in separating the clearly attractive alternatives from the less desirable ones. Thus, the models are not intended to give precise forecasts of how the alternatives might perform, but they are constructed with enough detail to compare and evaluate the different alternatives.

BURN-HAZARD TREE

Figure 1 gives a schematic of a probability tree that might be used to evaluate the fire losses under a possible policy alternative. The model — containing elements similar to Tribus' analytic framework (Reference 8) — is used to calculate the possible fire losses associated with a single garment during a given year. This result is then multiplied by the number of pieces of

TABLE 1. *Possible Alternatives for the Regulation of Flame Retardant Chemicals in Fabrics*

1. Disallow use of all FRCs and permit only inherently fire resistant fabrics that meet specified flammability criteria.
2. Disallow use of all FRCs but permit use of all fabrics regardless of flammability performance.
3. Allow all combinations of FRC and fabric that meet specified flammability criteria, but without regard for toxicity.
4. Allow only those combinations of FRC and fabric that meet both specified flammability and toxicity criteria.

sleepwear to determine the total annual losses due to children's sleepwear fires.

The principal model parameters are listed across the top of Figure 1. Given a fabric and treatment type, the model first considers whether the garment is exposed to an ignition source during the year in question. If there is exposure, the model gives the possible exposure sources and lengths of exposure. Depending on the type of exposure, the model then specifies whether a flaming ignition occurs. Given ignition, a probabilistic specification is then made on the extent of flame spread in the garment. Depending on the amount of garment burned, a specification is made on the extent of burn on the child, and from this the loss outcome is deduced.

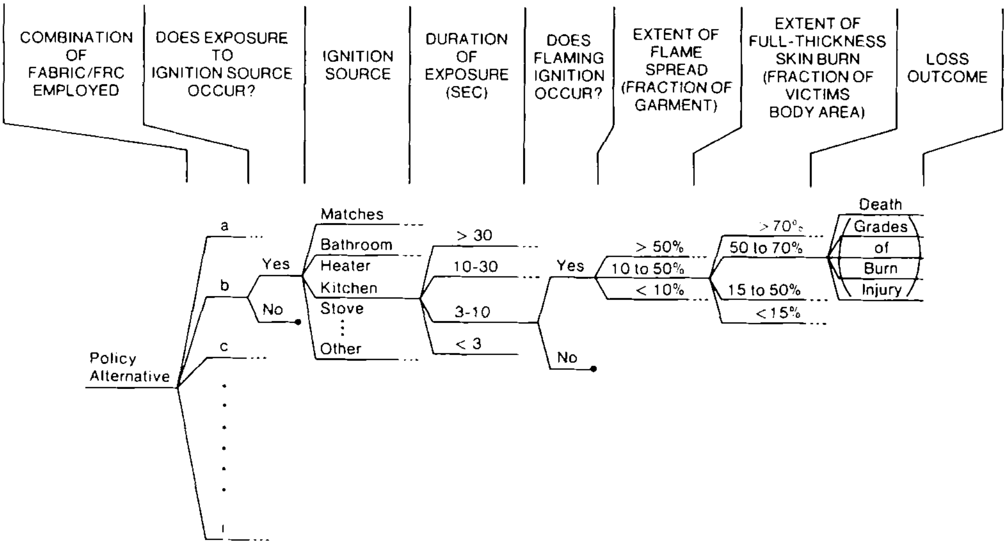

Figure 1. Schematic of probability tree for assessing burn hazards.

The first six parameters, from "is there an exposure?" to "extent of flame spread" are the independent or causal variables in the model. The last two parameters under "outcomes" are the dependent or output variables of the model. As shown, the losses are given in terms of death and severity of burn injury (if death does not occur). The logical and computation flow of the model is from left to right. The burn hazard model diagrammed in Figure 1 is only illustrative of the kind of model that would actually be built for this analysis. A complete analysis might include several additional variables.

The different branches under each of the parameters give the possible values that the parameters in question might take on. For example, under "ignition source" the possible sources of ignition are listed as "matches," "bathroom heater," "kitchen stove," and "other." The branch values are defined to encompass all possible values for the particular parameter.

The branches under the different parameters combine to produce a wide variety of events and settings under which children's sleepwear fires may occur. The tree of Figure 1 allows for over 500 different scenarios of such fires. With each path through the tree, or fire setting, there is a different degree and likelihood of fire loss. The probability tree therefore povides a visual device for representing the various children's sleepwear fires that may occur.

Probabilities are assigned to the different branches to indicate the likelihood of the particular parameter taking on the designated value. The probability of a particular path through the tree is calculated by multiplying the probabilities of the branches making up that path. The possible losses associated with each path are derived from fire incident data, adjusted by expert judgment where necessary. By combining the probability of each path with the corresponding losses and tracing all the paths of the tree, a probability distribution can be constructed on the possible losses associated with a single garment of children's sleepwear in a given year. Combining this distribution with the number of pieces of children's sleepwear then gives the probability distribution of total annual fire losses due to children's sleepwear fires.

TOXIC HAZARD TREES

Two probability trees are introduced to assist in assessing the possible toxicity-related losses associated with using flame retardant chemicals in children's sleepwear. Figure 2 gives a schematic of the probability tree used for assessing the toxic hazard to the wearer of the garment. Depending on the regulatory policy under consideration, the model first specifies the type of fabric of which the garment might be made and the flame retardant chemical treatment applied to it. Then, depending on whether the garment is prelaundered, the model specifies several levels of oral ingestion and skin uptake of the flame retardant chemical and corresponding probabilities that each of these will occur. Then, depending on the extent of exposure due to these two modes, the model makes probability assignments to the several possible levels of total accumulated dose that an individual could experience. Finally, depending on the total accumulated doses, an assessment is made of the final health consequence, ranging from no effect to death. As before, the probability tree lays out a wide variety of events and mechanisms which affect the ultimate health consequences resulting from use of flame retardant chemicals in children's sleepwear. By assigning probabilities to the different branches emanating from each point and loss outcomes to each of the paths through the tree. The range and likelihood of health effects resulting from the use of a particular flame retardant policy can be calculated.

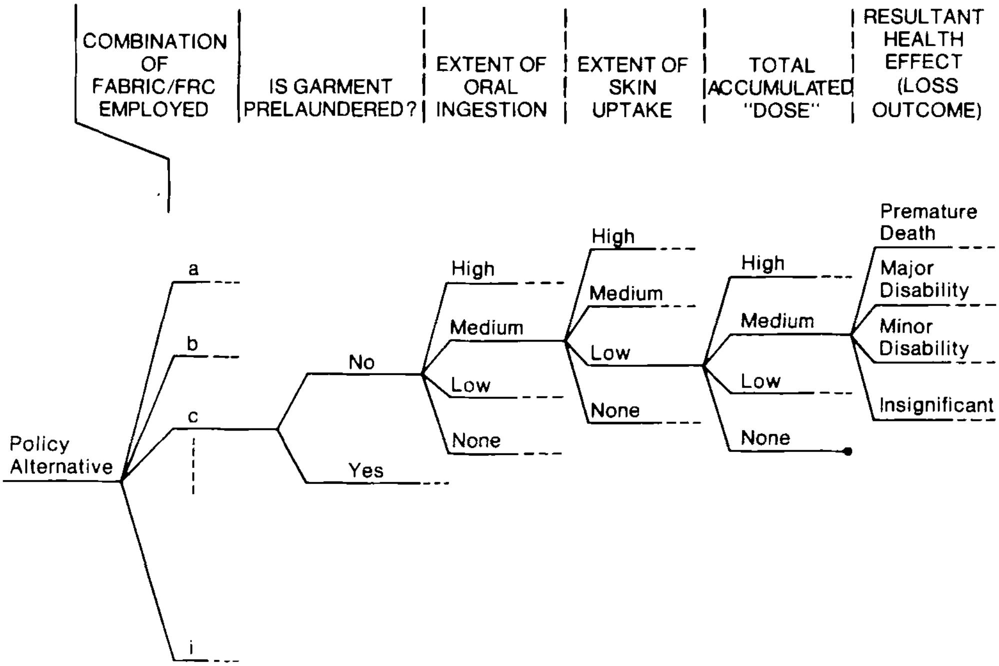

Figure 2. Schematic of toxic hazard tree (direct hazard to garment wearer).

Figure 3 gives a schematic of a probability tree that might be used to assess the toxicity-related hazard to the public at large resulting from the use of flame retardant chemicals in children's sleepwear. It is emphasized once again that the tree is only illustrative of the kinds of variables that might be included in a complete analysis. As with the probability tree for losses to the wearer of the garment, the model first considers the type of fabric and flame retardant chemical used and whether the garment has been prelaundered. The model then separately considers several possible methods of disposal for the garment and the residues contained in the waste water used to wash the garment during its lifetime. Then depending on the disposal mechanisms and the routes by which the chemicals can be transmitted to humans (air, water, or land), the model treats probabilistically the uptake levels that the population groups in question might incur. Finally, depending on the uptake rates, the model assigns probabilities to levels of accumulated human dose and evaluates the possible resultant health effects under each policy alternative.

ILLUSTRATIVE CALCULATIONS

To illustrate how the probability trees are used to assess the possible fire losses under a given regulatory strategy, consider a simplified version of the fire hazard tree, as shown in Figure 4. This simplified tree is limited to addressing the possible losses, given that an ignition has actually occurred. Data for the example are strictly illustrative, but are intended to approximate the case in which ordinary fabrics are used without any flame retardant chemicals (i.e., sleepwear fabric that existed prior to 1972 when the children's sleepwear regulations were passed).

Given that an ignition occurs in a garment made of ordinary, untreated fabric, the probability tree shows that there is a 20 percent chance that the flame spread in the garment will exceed 50 percent of the garment. There is a 40 percent chance that the flame spread will be between 10 and 50 percent of the garment and a 40 percent chance that the flame spread will be less than 10 percent of the garment. These probability assignments are strictly illustrative and are based on readily available judgment. In an actual application, empirical data to substantiate the probability assignments would be sought, or perhaps more modeling done to consider the individual events that combine to produce flame spread. Sensitivity analyses would also be performed to test how the ultimate loss outcomes change as a function of the probability assignments on flame spread. The sensitivity of the flame spread probabilities would be used as a guide in determining how much to refine the input probability assignments.

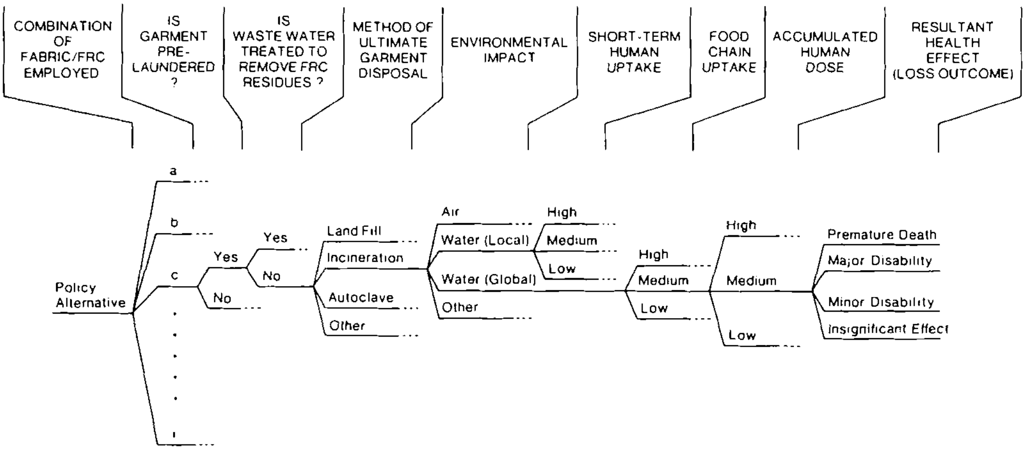

Figure 3. Schematic of environmental impact tree (hazard to public at large).

Given a particular level of flame spread in the garment, the model then discretizes the range and likelihood of resultant burn area on the child. Notice that the probability assignments on burn area are dependent on flame spread in the fabric. Thus, for example, if the fabric is more than 50 percent burned, the model allows for a burn injury of more than 50 percent. But if the fabric damage is limited to less than 10 percent, it is assumed that the maximum burn area of the child is 50 percent. The probability assignments shown in this part of the tree are also based on readily available judgment.

Probability assignments are also made on the actual loss outcomes. As shown, these assignments are made dependent on the extent of full thickness skin burn. The probability assignments are based on judgment, supported in part by data from a variety of clinical studies (Reference 10).

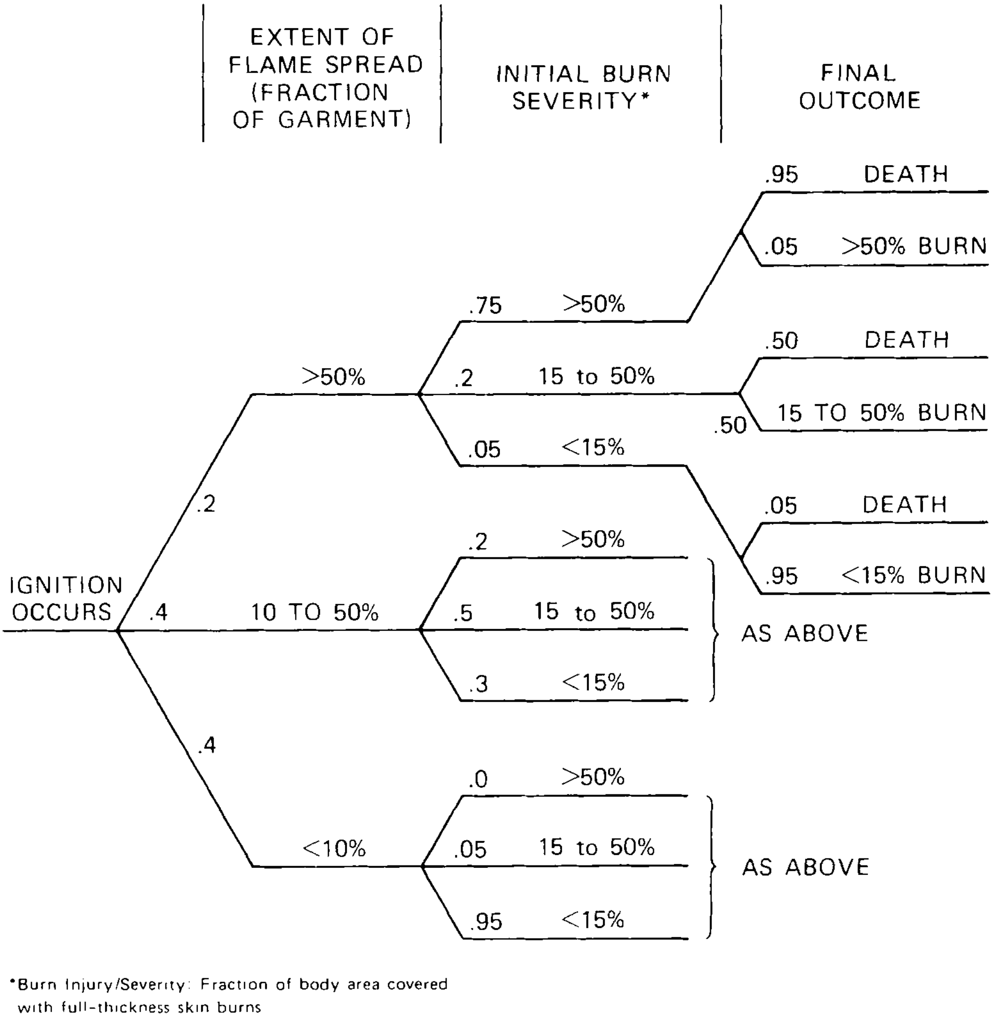

Figure 4. Simplified burn hazard tree for assessing losses given ignition (illustrative of pre-1972 fabrics).

The simplified tree in Figure 4 has 3 × 3 × 2 = 18 possible paths. Many of the paths in this simple example lead to the same outcomes, but they all have different likelihoods of occurrence. The probability of a particular path occurring is found by multiplying the probabilities making up the branches in the tree. By performing this multiplication for each path and then summing the results for the paths that lead to the same result, the probability of each of the outcomes occurring may be obtained. The resultant calculations are presented in Figure 5 as a discrete probability distribution. This distribution gives the range and likelihood of possible final outcomes once an ignition has occurred, given the uncertainties that were used to characterize the input events affecting loss. In this particular example, Figure 5 shows that there is a 37 percent chance that death will occur. Most of the survivors will sustain burn injuries over less than 15 percent of their body area. Only a small percentage of the surviving victims will suffer the more extensive burns (most victims having major burns do not survive their injuries). It is emphasized that the results in Figure 5 apply to the case where an ignition has occurred and that they are illustrative only, based on readily assembled judgment.

Economic Evaluation of Loss and Cost

In order to compare the possible fire losses with the potential toxicity losses and economic costs on a consistent basis, it is necessary to convert the different categories of fire loss to a common scale. The most convenient scale is a monetary one. Such a conversion requires that explicit value judgments be made on such factors as the amount society is willing to pay to prevent a single fire death. These judgments are difficult to make, but it is argued that such judgments are made explicitly or implicitly whenever a funding decision is made that affects public safety. Making the value judgments explicitly helps to ensure consistency from one safety decision to another. Sensitivity studies may also be performed to test the sensitivity of the decision to the value assignment used. Once the value assignments have been made, the probability distribution on physical losses to their economic equivalent can then be converted. An example of such a distribution is shown in Figure 6. The shape of this distribution has been modified somewhat to reflect the fact that in an actual application, there would be many more possible outcomes than the four considered in this example.

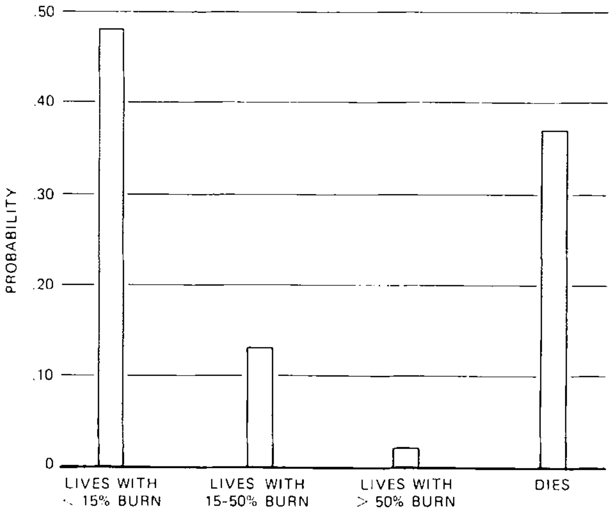

Figure 5. Output probability distribution for illustrative example.

Similar probability distributions would be calculated for the toxicity-related losses under each alternative. The individual distributions by category of loss would then be summed to obtain the range and likelihood of the dollar equivalent of the total fire- and toxicity-related losses occurring under the alternative in question.

As indicated, the set of possible alternatives must ultimately be compared on the basis of total societal cost plus loss. Thus, in addition to assessing the losses, work must be directed toward calculating the total economic cost associated with implementing the alternative in question. This assessment must take into account not only the increased consumer bill due to higher prices of the sleepwear, but also less tangible cost effects such as the consumer's loss of freedom of choice or denial of a place in the market for marginal consumers and producers because of higher prices. Also, if there are added costs such as bookkeeping, enforcement, or research and development that are not passed on in the form of higher prices, the cost effects must also be taken into account. In economic terminology, the cost assessment must address the total change in consumer and producer surplus.

If there are significant uncertainties on the values of variables entering into the cost calculation, then the calculations must be made in probabilistic terms, just as was done for the loss calculations. The probability distribution on cost is then added to the probability distribution on total loss to obtain the probability distribution on total cost plus loss for the alternative in question.

COMPARISON OF ALTERNATIVES

Probability distributions on total cost plus loss for two hypothetical alternatives are shown in Figure 7. The distributions give the range and likelihood of total cost plus loss that might result under the two alternatives, given the uncertainties that were used to characterize the input data in the analysis. In this example, the figure shows that Alternative A generally results in less cost plus loss than Alternative B, but there is a measurable probability that Alternative B will be more attractive. As long as there is uncertainty in the problem, it cannot be guaranteed that an analysis will definitely identify the option the would ultimately turn out to

Figure 6. Illustrative output probability distribution on total fire-related losses.

be the best. But a decision analysis such as outlined in this paper does provide the capability to address explicitly uncertainty and to show the implications of that uncertainty on the decision actually made.

In comparing two decision alternatives, it is often desirable to summarize the probability distributions on cost plus loss with a single number. In many applications, particularly where the assets of society are large compared to the possible losses, the expected value, or average, is a meaningful summary number of the probability distribution. The expected value is calculated by multiplying all of the possible outcome values by the likelihood of occurrence and then summing. If such a calculation was made for the two alternatives shown in Figure 7, it is clear that Alternative A would be the more attractive on an expected value basis.

SENSITIVITY ANALYSIS

It has already been mentioned how sensitivity analysis would be used to guide the extent to which probability and value assignments would be refined in carrying out a decision analysis. To demonstrate the output of a sensitivity analysis, Figure 8 is presented, which shows how the total expected cost plus loss of two hypothetical alternatives would vary with the underlying severity of the children's sleepwear fire problem, using number

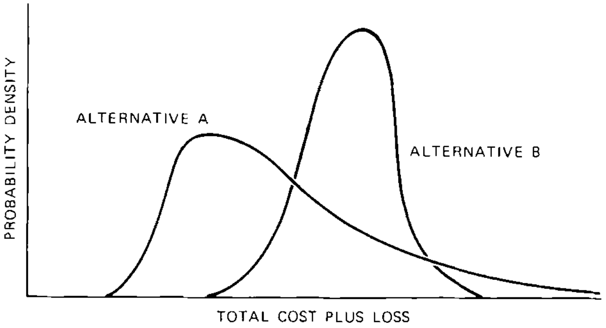

Figure 7. Illustrative output probability distributions on total fire- and toxicity-related cost plus loss for two alternatives.

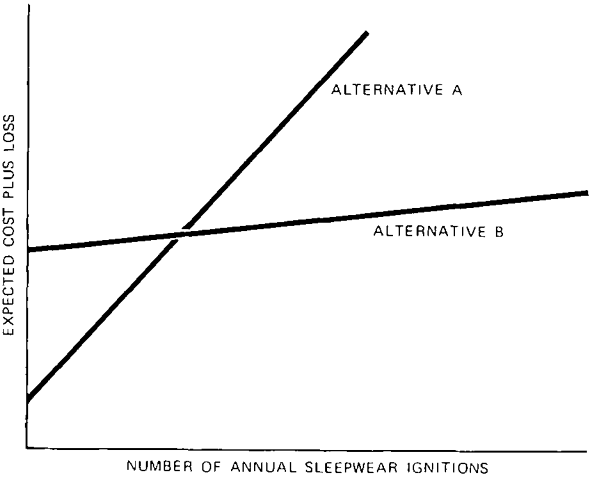

Figure 8. Illustrative sensitivity analysis on importance of number of annual sleepwear ignitions.

of ignitions as a measure of severity. The graph is constructed by holding all input variables in the analysis at their nominal values and then varying the number of ignitions. The graph shows that if there were not many sleepwear ignitions, then Alternative A, which does not use flame retardant chemicals, would be preferred. On the other hand, if the fire problem were severe, then Alternative B, which uses flame retardant chemicals, would be preferred. The graph provides an objective answer to the question: "How many accidental fire starts in children's sleepwear must occur in a year's time to make the potential reduction in injury and life loss due to clothing burns exceed the actual costs and health hazards, if any, of the flame retardant treatment?"

CONCLUDING REMARKS

The purpose of this paper has been to show how a decision analysis approach can be used to make rational decisions on the regulation of flame retardant chemicals. It has been argued that the criterion for setting such policy should be minimizing total societal cost plus loss, where all fire- and toxicity-related losses and costs as well as direct economic costs are taken into account. The underlying complexities and uncertainties of the risks and benefits attendant on the use of flame retardants make assessments of cost plus loss difficult. However, it has been shown that a decision analysis framework can be used to make these assessments and that there is a rational basis for making decisions in the face of uncertainty.

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