RISK METHODOLOGY OVERVIEW

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Figure 1 gives the agenda for the risk methodology overview. Before talking specifically about the carbon fiber risk methodology, I'd like to talk about risk methodology in general. We'll talk about some considerations of risk estimation, how risk is measured, and how risk analysis decisions are made. We'll then turn to the specific problem of carbon fiber release where I will review the objective, describe the main elements, and give an example of the risk logic and outputs.

RISK ANALYSIS CONTENT

- GENERAL
  - ESTIMATION
  - MEASUREMENT
  - DECISION
- SPECIFIC
  - OBJECTIVE
  - ELEMENTS
  - EXAMPLE
    - LOGIC
    - OUTPUTS

Figure 1

Risk estimation involves a number of considerations, as outlined in figure 2. Among these are the objective, the elements of the individual problem, the methods that are used, and how those methods are chosen and tested. Another consideration is whether the methods used are analytic or approximate; under "approximate" we're particularly interested in whether simulation is used. We are also concerned with what assumptions are made. For example, are all filters properly installed? How much carbon fiber is carried and by what types of planes? What kind of electronics will be used in 1993? Another component of risk estimation is scope. Under scope we are interested in both micro and macro

RISK ESTIMATION

- OBJECTIVE
- ELEMENTS
- METHODS
- ASSUMPTIONS
- SCOPE: MICRO, MACRO, LIMITS
- ERRORS
- SENSITIVITY STUDIES
- WORST CASES

Figure 2

analysis. "Micro" and "macro" are used here as economic terms and mean "bottom up" and "top down," respectively. Micro refers to the details of the problem whereas macro refers more to an overview. Mr. Ansel Butterfield gave a good example of a micro analysis when he talked about the costing of industrial plants. An example of a macro analysis would be trying to cost a power outage resulting from the carbon fiber problem by using costs of power outages resulting from non carbon-fiber problems. Part of scope are the limits of the risk analysis. Limits are closely tied with assumptions. Two limits, for example, in the carbon fiber study are restriction to just the commercial part of civil aviation and to just single fibers.

A major consideration in risk estimation is errors. Errors are involved in the elements, methods, assumptions, and scope. How these errors are defined and presented are two important parts of the problem. Sensitivity studies show how variations in the elements affect the risk; in particular, they indicate which of the elements are the main contributors to the risk. A sensitivity study is done by varying only one parameter, or perhaps one group of the parameters, while holding all other elements fixed and recalculating the risk for each variation of the parameter. Worst cases are usually important to present. Furthermore, if, as in most risk analyses concerning rare events, simulation forms the basis of the methodology, the worst cases might not be obtained among the simulated cases and, hence, must be calculated separately.

Figure 3 gives the units and format for risk measurement. The usual units are fatalities, injuries, dollars and complaints. As Mr. Heldenfels noted in his talk, fatalities and injuries are usually the most important units. However, as he also pointed out, they don't seem to be an issue in this problem. Complaints can't be ignored even though the dollars are small, and there are no fatalities or injuries. Because nearly all risk analyses involve probabilities which range from 0 to 1, the main output is in terms of a curve instead of a point. Two types of curves that are commonly used are what are called density and cumulative curves and I will be giving examples of these later. Even though the main result is a curve it is usually important to have one or more summary measures. Some of the typical types of summary measures are means, medians, modes, extremes, and various combinations of these four. Again, error bounds are usually important in any type of risk analysis, and they can be shown in various ways.

RISK MEASUREMENT

UNITS:

FATALITIES

INJURIES

DOLLARS

COMPLAINTS

FORMAT:

CURVE: DENSITY, CUMULATIVE

POINT: MEAN, MEDIAN, MODE, EXTREME, OTHERS

ERROR BOUNDS

Figure 3

The main elements of risk decision are given in figure 4. The first job in decision making is defining the decision maker. Sometimes he is not specifically defined. Sometimes the decision maker is a body of people. The second job is determining the measures that are important to the decision maker. These measures, or acceptability criteria, vary with the problem and with the decision maker. The first acceptability criterion usually concerns the actual values. If the risk curves have many extremely large values or all very small values, the remaining acceptability criteria may not be important. Under "actual value" one is concerned with whether the value is direct or indirect. An example of a direct cost in the carbon fiber problem is equipment replacement and repair. An example of an indirect cost would be product loss, as Mr. Butterfield illustrated, resulting from equipment that has malfunctioned because of the carbon fiber problem.

RISK DECISION

- DECISION MAKER
- ACCEPTABILITY CRITERIA (VARIES WITH PROBLEM AND DECISION MAKER)
  - ACTUAL VALUE
    - DIRECT VERSUS INDIRECT
  - COMPARISON WITH OTHER RISKS
    - VOLUNTARY VERSUS INVOLUNTARY
  - COMPARISON WITH BENEFITS

Figure 4

Once we have analyzed the actual risk values, we are then interested in comparing these values with those from other types of risk. For example, how does the probability of failure to a stereo from the carbon fiber problem compare with the probability of failure to a stereo from all other causes. How does the carbon-fiber risk compare with other types of risk, for example, risks from floods, tornadoes, driving, and private flying. In making risk comparisons, two concerns are voluntary risk versus involuntary risk. Voluntary risk is risk a person imposes upon himself. Involuntary risk is risk imposed upon the person. Examples of voluntary risk are flying a private plane and driving an automobile. Involuntary risk is exampled by being a passenger in a commercial airplane. Needless to say, people are much more willing to accept voluntary risk than they are involuntary risk. We are also interested in comparing risk with benefits in terms of the curves and summary statistics. If the benefits greatly outweigh the risks, then the decision maker leans toward acceptance of the risk. However, a benefit-risk comparison is never the sole criterion for decision making. If, for example, a program would have huge benefits but is such that there would be a high probability of destroying two cities, the program would not be accepted.

Figure 5 gives an example of a risk comparison. This figure, which is called a risk profile, comes from a risk analysis of the operation of water-cooled nuclear power plants in the United States. This nuclear reactor safety study was commissioned by the United States Atomic Energy Commission and directed by Dr. Norman C. Rasmussen of M.I.T. The vertical axis gives the number of events per year exceeding various dollar damages that are shown on the horizontal axis. The curve for natural events is dominated by hurricanes. The second main contributor is tornadoes. The main component of the man-caused events is huge fires. Among other events are mine disasters and industrial explosions. The "100

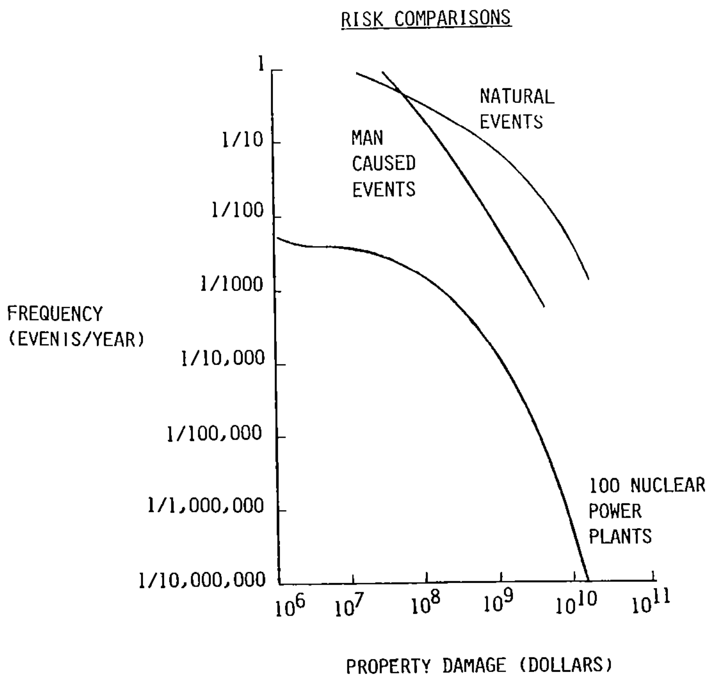

Figure 5

nuclear power plants" means that the nuclear-plant population considered consists of 100 plants, rather than just one plant. That is, if the probability of one accident at one plant is "x", then the probability of one accident out of a population of 100 plants is 100 times "x".

The plot indicates that the damage from both at least one natural event, such as a hurricane, and one man-caused event, such as a large fire, can be expected to exceed $10 million once every year and $10 billion once every 1000 years. Equivalent damage from nuclear reactor accidents occurring within a population of 100 nuclear plants is expected to happen much less frequently. Note that automobile accidents, which had about $15 billion in property damage when the three curves were constructed, were not included in the man-caused events. In a subsequent talk Dr. Joseph Fiksel of Arthur D. Little will compare the current risk profile for the carbon-fiber problem with the risk profiles shown in figure 5.

As you heard previously, and as shown in figure 6, the first objective of the carbon fiber risk analysis is to estimate the risk to the nation over the next 15 years from the use of carbon fiber in civil aircraft. The methodology is a logical, systematic analysis that strives to reduce the subjectivity of the risk

<u>CARBON FIBER RISK ANALYSIS OBJECTIVES</u>

- ESTIMATE RISK TO NATION OVER NEXT 15 YEARS FROM USE OF CARBON FIBER IN CIVIL AIRCRAFT
  - REDUCE SUBJECTIVITY (ESTIMATE, ERRORS)
- PROVIDE FRAMEWORK FOR DECISION MAKING ON MATERIAL USAGE, MODIFICATION, AND PROTECTION SCHEMES

<u>NOTE:</u> OTHER RISK ANALYSIS:

- AUTOMOBILES: SEAT BELT USAGE
- LIQUIFIED NATURAL GAS (LNG): TRANSPORTATION,STORAGE
- NUCLEAR POWER PLANTS (WATER-COOLED): OPERATION
- OIL (SPILLS): TRANSPORTATION
- VACCINATIONS: SMALL POX, SWINE FLU

Figure 6

estimate and of the errors associated with that estimate. The second objective is to provide a framework for decision making on material usage, material modification, and protection schemes. Note that other risk analyses have parallel objectives. Some of the more recent risk analyses are usage of seat belts in automobiles, transportation and storage of liquified natural gas (LNG), operation of water-cooled nuclear power plants - the study we just discussed for figure 5, comparison of transportation methods for oil so that spills are minimized, and mass vaccinations for the public; smallpox and swine flu being two examples.

As shown in figure 7, the carbon-fiber risk-analysis elements can be described in terms of three levels. The first is the local level, which is some type of geographic subdivision of the United States. The second is the national level, given that you have an estimate of the risk on the local levels. The third level involves extrapolating the risk estimate from the national level into the future. As noted in a previous paper, we're using the next fifteen years 1978-1993 as the future. As you also heard previously, some of the main elements on the local level are aircraft accident probability, dispersion of carbon fiber, transfer function, vulnerability, and costing. On the national level some of the main elements are number of accidents per year and the location of these accidents. Among considerations for location are whether the accident sites are near mountains or large bodies of water and

CARBON FIBER RISK ANALYSIS ELEMENTS

LOCAL:

- AIRCRAFT ACCIDENT PROBABILITY
- DISPERSION OF CARBON FIBER
- TRANSFER FUNCTION
- VULNERABILITY
- COSTING

NATIONAL:

- NUMBER OF ACCIDENTS PER YEAR
- LOCATION OF ACCIDENTS

FUTURE (1978-1993):

- CARBON-FIBER USAGE PROJECTIONS
- ACCIDENT STATISTICS CHANGES
- TECHNOLOGY CHANGES

Figure 7

what the population and electronic densities are. Some of the main elements on the future level are carbon fiber usage projections, accident statistics changes, and technology changes.

The next three figures are sequential illustrations of the logic for generating damage from an accident involving fire. This logic is an example of what is called an event tree or a decision tree. All our risk methodologists use some type of event tree like this one, although of much greater complexity and not necessarily in the sequence shown. Although this is a very simplified tree compared to what is actually used, at least one representation of each of the main elements of the carbon-fiber problem is included. The elements of the risk assessment under evaluation are identified across the bottom of the next three figures, that is: accident probability, source, dispersion transfer function, vulnerability, and costing. Across the top of the three figures are the data sources for these various elements: operation rates, accident records, weather records, census maps, experiments, surveys, and pathfinder studies. Calculations are made at each of the nodes. Some calculations involve analytic models; others, random selections.

The first node, shown in figure 8, represents the occurrence of an accident involving fire. The second node represents the choice of the location for the accident. Air traffic in the United States can be represented by the traffic at the 26 large

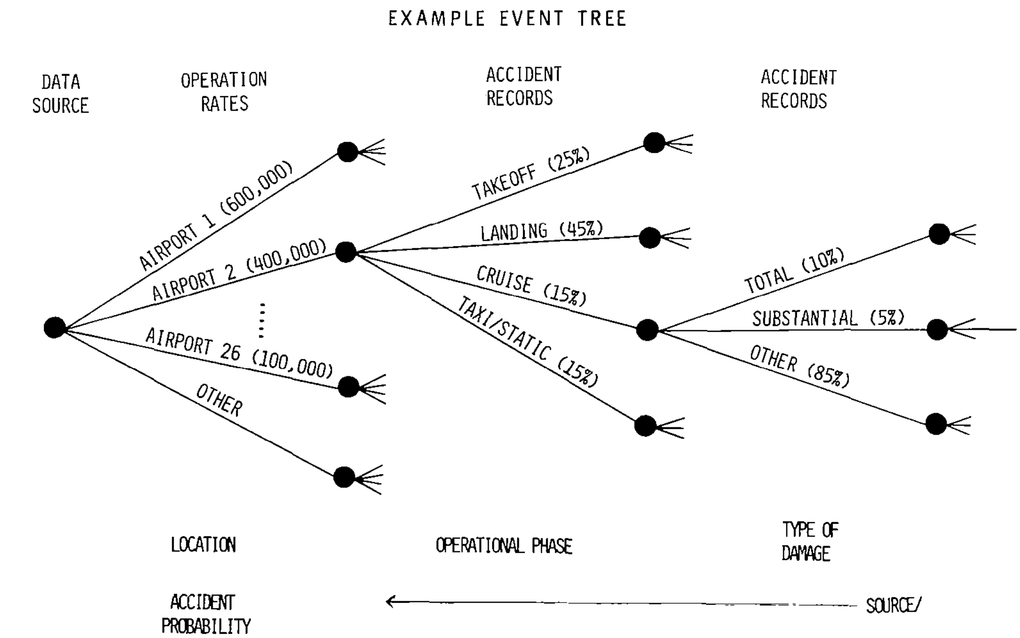

Figure 8

hub airports with everything else lumped into all "other." The number in parenthesis approximately gives the number of operations per airport. The airport selection is made by a random selection process. This selection process can be illustrated in the choice of the operational phase. Accident records show that fire accidents occur 25% of the time in take-off; 45%, in landing; 15%, in cruise; and 15% in static or taxi operation. The selection of the operational phase can be illustrated by use of a roulette wheel. Moving clockwise, assign the first 25% of the roulette wheel to take-off; assign the next 45% to landing; the next 15% to cruise; and the last 15% to taxi/static. The roulette wheel is therefore divided into four areas with proportions corresponding to the probability of an accident in take-off, landing, cruise, and static or taxi operation. For this example, a spin of the roulette wheel selects "cruise" as the operational phase. Although this is a very simple example, all random simulations are performed in a similar manner. The next node selects the type of damage. The type of damage determines, in part, the amount of fiber released. In this example "substantial" is selected using the random process based on statistics from accident records.

A similar random selection process is used to select the size of an aircraft, which affects source. The three aircraft size categories are shown in figure 9. The probability of an explosion

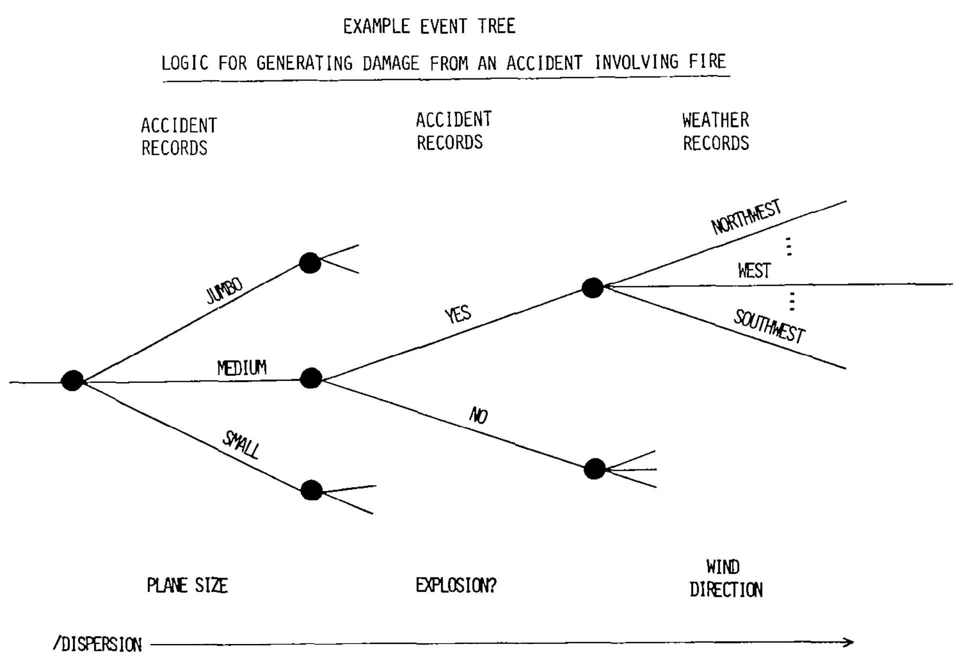

Figure 9

is also determined by random selection. The presence of an explosion determines not only how much material is released, but how far it disperses. If there is an explosion, most of the material is likely to be contained within a 10-mile area. If there is not an explosion, much of the material can be dispersed as far away as 100 kilometers or more. One of the two explosion paths is chosen using the random process. The wind direction is determined by random selection from weather records for the location chosen in the first step. At this point, the use of the random selection processes is completed. The dispersion of released carbon fibers can now be calculated based on an accident scenario constructed from probabilities derived from accident records, operational experience, and projections of the amount of carbon fiber to be used on aircraft in the future. The dispersion footprints, or isopleths of constant exposure, are related to specific geographical locations.

As illustrated in figure 10, by using a census map, with the various exposure isopleths superimposed, the areas of the city and countryside affected can be identified. The example in figure 10 shows only three such areas: commercial, public (which could be post offices, hospitals, and fire stations), and residential. Given the areas affected, the next step is to determine transfer functions into the building types within each of these areas and the vulnerability of the various equipment types within each build ing type. Equipment examples are: computers in the commercial

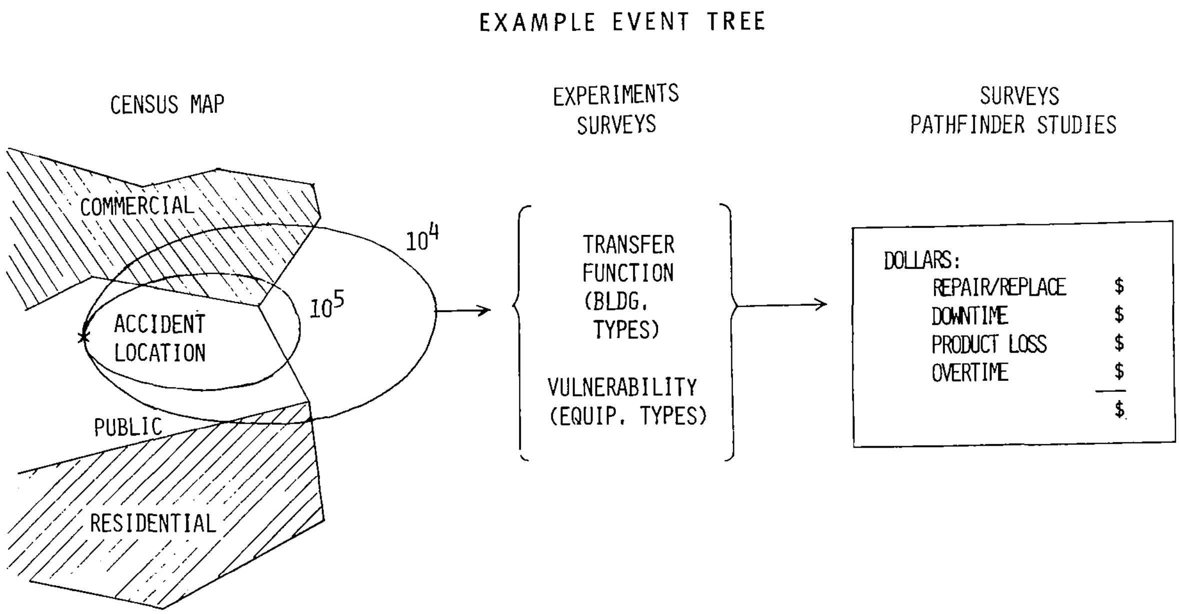

Figure 10

districts, stereos and televisions in the residential areas, and telephone exchanges in the public area. Finally, the dollar loss is determined using impact surveys and pathfinder studies. Four examples of impact costs are repair or replacement of equipment, overtime, downtime, and product losses. The sum of these costs gives the cost impact from one accident. By using the historical five or six accidents a year involving fire, the random selection of nodes in the event tree and the cost calculation is repeated five or six times and the cost summed to obtain one estimate of the national risk. However, one estimate is not enough to obtain a statistical distribution of estimates and, therefore, the calculations of the national risk must be repeated a large number of times.

Suppose we repeat these calculations 1,000 times and that they give the results shown in figure 11. The first two columns of figure 11 give dollar values for a year's national costs, or damages, and the number of the 1,000 trials that had those dollar values. For example, the first line of the first two columns gives that 50 of these 1,000 trials had zero costs. Perhaps very little fiber was released or perhaps all that was released went over the water or into the countryside. The last line gives one case that had a very high cost. Perhaps this case resulted from use of a jumbo plane and carbon-fiber release over highly industrialized areas.

EXAMPLE

DENSITY AND CUMULATIVE TABLE

NATIONAL COSTS

TRIALS THAT HAVE $ VALUE OF $X	YEARLY NATIONAL COSTS, $(X)	X	DENSITY PROBABILITY	=	PRODUCT	TRIALS THAT HAVE $ VALUE OF ≥ $X	CUMULATIVE PROBABILITY
50	0		.05		0	1000	1.00
200	$ 1,000		.20		$ 200	950	.95
100	10,000		.10		1,000	750	.75
400	100,000		.40		40,000	650	.65
246	200,000		.246		49,200	250	.25
3	1,000,000		.003		3,000	4	.004
1	10,000,000		.001		10,000	1	.001
1000				$\sum$ =	103,400		

EXPECTED NATIONAL VALUE $103,400

Figure 11

From the first two columns of numbers, we calculate a density function, with values given in the third column, by simply taking the number of trials that have a certain yearly national cost and dividing that number by 1,000. Note that, to simplify the example, all numbers in figure 11 are rounded off and grouped into only seven categories; in reality, of course, there are hundreds, perhaps thousands, of categories. The fourth column gives the product of the second and third columns. This column weighs the dollar costs by the frequency with which they occur. Summing up these dollar costs gives the expected value, which is the most common summary statistic used in risk analyses. The expected national value of $103,400 in this example is very small, especially with respect to the extreme of $10 million. In this example, there is a very high frequency of middle and small costs that tend to drown out the very large costs.

Some of the other types of summary risk measurements are the median cost, which is $100,000, and the extremes, which are $0 and $10 million. A particular interest is the frequency with which the upper extreme occurs. One way of looking at this .001 frequency is to say that roughly every one in a thousand years a $10 million national cost can be expected. The last column gives the cumulative probability, which is the basis of the most frequently used type of curve in risk analyses. This column is obtained by simply cumulating the probability given in the third column. For example, the bottom values of 0.001 are the same. The next-to-bottom cumulative probability is obtained by adding the two bottom density probabilities of 0.001 and 0.003.

In figure 12, these cumulative probabilities have been plotted to give a risk profile. The ordinate gives the values from the last column of figure 11. The abscissa gives property damage in dollars. Note that the curve is plotted on a log scale. The error bounds in this illustrative problem are equally weighed except when they're bounded by one.

Figure 13 gives several summary points about the capability of risk analysis methodology. First, risk methodology integrates the data and engineering judgment into a logical framework. Second, it combines both deterministic and probabilistic models. Third, it permits sensitivity analyses of key assessments. Two examples are the carbon fiber usage projections and the nature of released fiber; in particular, the fall rate. For example, what are the effects from single fibers versus those from lint or clumps. Finally, risk methodology permits evaluation for alternative sources, where alternative sources might be exampled by general aviation or helicopters in civil aircraft or by other types of sources such as automobiles.

EXAMPLE

ONE-YEAR RISK PROFILE

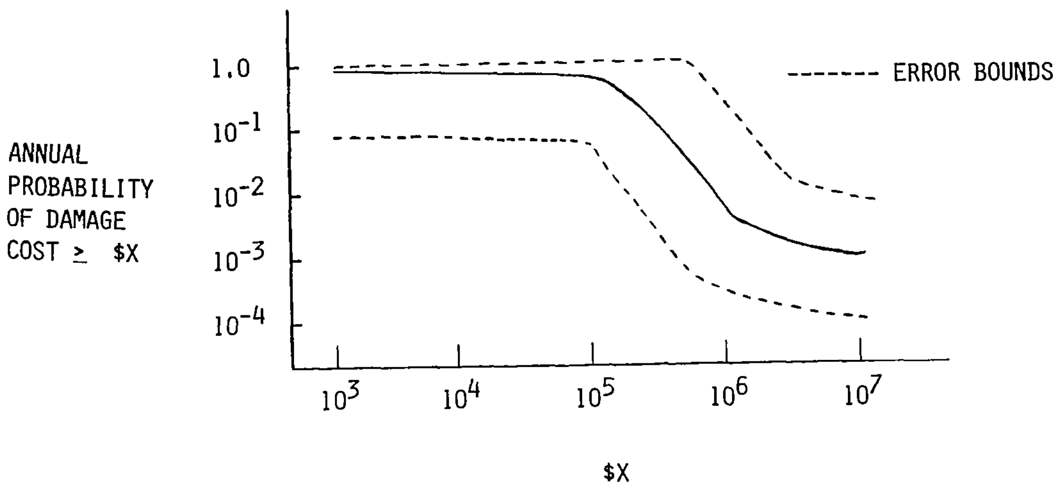

Figure 12

SUMMARY

CAPABILITY OF RISK ANALYSIS METHODOLOGY

- INTEGRATES DATA AND ENGINEERING JUDGEMENTS IN A LOGICAL FRAMEWORK
- COMBINES BOTH DETERMINISTIC AND PROBABILISTIC MODELS
- PERMITS SENSITIVITY ANALYSIS OF KEY ASSESSMENTS
  - CARBON FIBER USE PROJECTIONS
  - NATURE OF RELEASED FIBER
- PERMITS EVALUATION FOR ALTERNATE SOURCES

Figure 13