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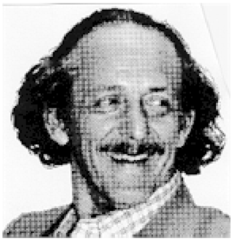


Current Comments

Risk Analysis, Part 1. How We Rate the Risks of New Technologies

Number 33 August 16, 1982

Modern science and technology provide many people with a higher standard of living than their ancestors ever enjoyed. Medical breakthroughs have reduced the threat of communicable diseases that decimated past generations. Agricultural improvements have increased crop yields and raised the quality of livestock. In fact, drugs and insecticides may be responsible for about half of the increase in life expectancy in the Third World since World War II.[1] Manufacturing industries provide what some believe are more convenient goods and services. There is also reason to believe that this overall, worldwide economic improvement is derived from the results of basic research and development.[2]

But modern technology can also confront us with hazards our ancestors never faced. These include increases in death due to accidents, toxic substances, disasters, and pollutants. Today, there is a high degree of public anxiety over what might happen if the new technologies backfire. Discussions of nuclear power inevitably take the Three Mile Island accident[3] as a point of departure. In 1976, concern over industrial safety increased after the explosion at the Icsema chemical plant in Seveso, Italy.[4] Twenty years ago, Rachel Carson's *Silent Spring* focused attention on the worldwide biological risks of pesticides.[5] In the 1960s, the thalidomide tragedy dominated debates on pharmaceutical risks.[6]

Inevitably, these events cause people to ask if the benefits of new technologies are worth the risks. It is not surprising, therefore, that a new scholarly discipline has developed around methods for analyzing the risks we're exposed to in modern society. Risk analysis is an important decision-making tool for government regulators and corporate planners. Its importance will surely increase in the years to come. Risk analysis already is a required activity in the chemical, pharmaceutical, and civil nuclear power industries. For example, the chemical industry now devotes about a fourth of its research and development costs to risk analysis.[7] The drug industry spends over half its research budget to this end.[7]

In this two-part essay, I'll discuss some of the premises and current methods of risk analysis. I'll also introduce the opinions of people in the risk analysis community to point out the strengths and weaknesses in its theories and calculations. The first part concentrates on risk analyses of new engineering technologies, such as nuclear power plants. The second part will be devoted to the analysis of biological risks from new chemicals and pharmaceuticals.

Of course, risk analysis is by no means limited to these problems. Insurance companies are also involved in risk analysis, for example. You might say that modern risk analysis is synonymous with "societal risk analysis." The subject of actuarial analysis, insofar as it relies on medical data of one kind or another, is a topic for future consideration.

Before beginning, it's helpful to define "risk." Norman Rasmussen, Massachusetts Institute of Technology, defines risk as the probability that some undesirable event will occur.[8] Chauncey Starr, Electric Power Research Institute, Palo Alto, California, defines risk in more mathematical terms as "the probability per unit time of the occurrence of a unit cost of burden."[9] That is, risk takes into account both the *chance* that some event will happen in a given time period, and the *magnitude* of its consequences. Usually, the time period is set at one year. The magnitude is expressed as whatever the possible consequences may be—death, injury, days of disability, man-hours of labor lost, property loss, incidence of cancer or birth defects, and so on.

Risk analysts are on firm ground when dealing with high probability events. For example, it's relatively simple to calculate the risk of motor vehicle death or injury. Auto accidents occur so frequently that detailed statistical records can be compiled. Unfortunately, risk analysts can't refer to historical records of new technologies. For example, nuclear power plants have a short "track record," and the kind of catastrophic accident that arouses the greatest concern—core meltdown—is a low probability event that presumably wouldn't be observed frequently even if nuclear reactors were in operation for several decades. Also, the adverse consequences of new pharmaceuticals, food additives, or pollutants are sometimes observed only years or decades after exposure. For obvious reasons, we can't afford to wait for detailed statistical records to be compiled on the risks of cancer, birth defects, or genetic damage from new pharmaceuticals or chemicals.

Instead, risk analysts have to anticipate consequences of new technologies *before* the public is exposed to them. To do this, risk analysts rely on mathematical models that predict how the new technology will perform under various conditions. Risk analysis of engineering structures is based on a systems analysis model.[7] This model asserts that the operation of a complex system depends on the relationships between its component parts. Rasmussen points out that the model is applied when "the system is made up of many parts and the failure rate of the parts is known."[8] Although nuclear power plants are a new technology, they are built with standard equipment used in other structures. The likelihood of an accident at a nuclear power plant can thus be inferred from the failure rates of its components.

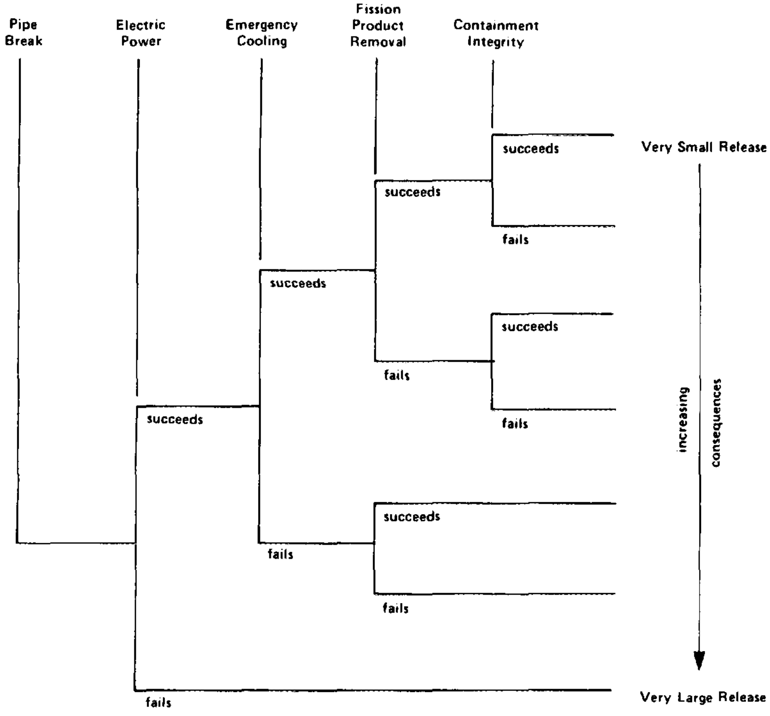
The 1975 Reactor Safety Study (RSS)[10] is regarded as perhaps the best-known example of risk analysis based on the systems analysis model.[7] RSS was initially sponsored by the US Atomic Energy Commission and completed by the US Nuclear Regulatory Commission (NRC). Incidentally, Rasmussen was the director of RSS, which is often referred to as the Rasmussen Report. HTGR Accident Initiation and Progression Analysis[11] is another major risk study which relies on the systems analysis model. It was conducted by the US General Atomic Company and released in 1978. Another prominent analysis of nuclear reactor risks is the 1979 German Risk Study, conducted by the Federal Republic of Germany's Gesellschaft für Reaktorsicherheit.[12]

These studies rely on "event tree/fault tree analysis" to determine the risk of nuclear reactor failures. Event trees and fault trees break down a nuclear accident into more simple, basic events. Garth Parry and Paul Winter, Atomic Energy Authority, Warrington, UK, explain that "the frequency of occurrence of the rare events (accident sequences with severe consequences) could [then] be estimated from the frequencies of basic events for which data were available."[13] Rasmussen notes that event tree/fault tree analysis is "probably the most widely used method for the quantitative prediction of system failure."[8]

Event trees are used to trace out virtually all possible accident sequences in a new technology that could result in undesirable consequences.[8] In the case of nuclear reactors, event trees outline the accidents leading to releases of radioactivity. The first step in event tree analysis is to define an "initiating event." The risk analyst then determines what parts of the system affect the progress of subsequent events. The object is to calculate the amount of radioactivity that would be released at the end of each accident sequence in the event tree.[10] (p. 42) Figure 1 shows an event tree diagram of a nuclear reactor accident sequence.

After these radioactivity amounts are estimated, the probability of occurrence for each branch in the event tree remains to be calculated. This is where fault tree analysis comes in, and its logic is almost the reverse of that of event trees.[8] It begins with the undesirable consequence. The risk analyst then determines what prior conditions could cause this event. The lowest events in the branching fault tree are called "primary

Figure 1: Simple event tree showing the sequence of events following a pipe break in a nuclear power reactor's cooling system. This initiating event could lead to core meltdown and a large release of radioactivity. If electric power is available, an "emergency cooling system" (ECS) is activated. In the event that the ECS fails, core meltdown will occur, but the "fission product removal system" reduces the amount of radioactivity released. If this option fails, the "containment integrity system" prevents most of the radioactivity from escaping.



faults." For example, Baruch Fischhoff and colleagues, Decision Research, Eugene, Oregon, identified 67 primary faults that could cause a car not to start. Figure 2 shows a fault tree that traces the branch of events involving only battery failure.[14]

After all the primary faults are identified, the probability of their occurrences is estimated. The estimate is based on past performance records for each component involved in the primary fault. Data on the individual failure probabilities are entered into a computer that calculates the probability of the top event. This information is then plugged into the appropriate branches of the event tree. The risk of very small or very large releases of radioactivity can now be calculated by multiplying the probabilities of failure along each branch of the event tree.[8]

When the event tree/fault tree analysis is completed, we know the probability of occurrence for various accident sequences and the amounts of radioactivity that are released at the end of each. The next task in the risk analysis is to determine the public consequences of exposure to radioactivity if it escapes the containment area. The Rasmussen Report states that this depends "upon how the radioactivity is dispersed in the environment, upon the number of people and amount of property exposed, and upon the effects of radiation exposure on people and contamination of property."[10] (p. 49)

The end result of risk analyses of nuclear reactor accidents is a series of graphs that relate the estimated annual frequency of accidents to their consequences. Typically, the graphs also show other types of human-caused and natural accidents to put the nuclear accidents in perspective. This information is presented in tabular form in Tables 1 and 2. Table 1 shows the statistical risk of any given individual in the US being killed in any one year in various human-caused and natural accidents. The Rasmussen Report estimates that there is one chance in five billion that someone living within 20 miles of a nuclear power plant will die in a nuclear accident. Table 2 shows the likelihood of larger numbers of fatalities resulting from human-caused and natural accidents. The probability of 100 or more (or 1,000 or more) people dying in a nuclear reac-

Figure 2: Simple fault tree diagram showing why a car may not start as a result of battery failure.

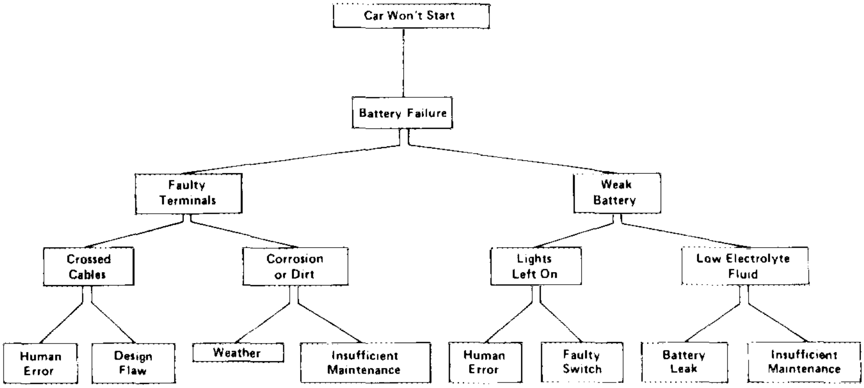


Table 1: Average risk of death to an individual from various human-caused and natural accidents.

Accident Type	Total Number	Individual Chance per Year
Motor Vehicle	55,791	1 in 4,000
Falls	17,827	1 in 10,000
Fires and Hot Substances	7,451	1 in 25,000
Drowning	6,181	1 in 30,000
Firearms	2,309	1 in 100,000
Air Travel	1,778	1 in 100,000
Falling Objects	1,271	1 in 160,000
Electrocution	1,148	1 in 160,000
Lightning	160	1 in 2,000,000
Tornadoes	91	1 in 2,500,000
Hurricanes	93	1 in 2,500,000
All Accidents	111,992	1 in 1,600
Nuclear Reactor Accidents (100 Plants)	——	1 in 5 billion

Source: **US Nuclear Regulatory Commission.** *Reactor safety study: an assessment of accident risks in US commercial nuclear power plants.* October 1975, NRC Report WASH-1400 (NUREG-75/014). p. 3.

Table 2: Average risk of death from various human-caused and natural accidents.

Type of Event	Probability of 100 or More Fatalities	Probability of 1,000 or More Fatalities
Human-Caused		
Airplane Crash	1 in 2 yrs.	1 in 2,000 yrs.
Fire	1 in 7 yrs.	1 in 200 yrs.
Explosion	1 in 16 yrs.	1 in 120 yrs.
Toxic Gas	1 in 100 yrs.	1 in 1,000 yrs.
Natural		
Tornado	1 in 5 yrs.	very small
Hurricane	1 in 5 yrs.	1 in 25 yrs.
Earthquake	1 in 20 yrs.	1 in 50 yrs.
Meteorite Impact	1 in 100,000 yrs.	1 in 1 million yrs.
Reactors		
100 Plants	1 in 100,000 yrs.	1 in 1 million yrs.

Source: **US Nuclear Regulatory Commission.** *Reactor safety study: an assessment of accident risks in US commercial nuclear power plants.* October 1975, NRC Report WASH-1400 (NUREG-75/014). p. 10.

tor accident is about the same as the probability of the same number of fatalities due to meteorite impact.

Of course, these calculations and figures and tables should be interpreted very carefully. Lennart Sjöberg, University of Gothenburg, Sweden, says, "Risk analysis has...been widely cited in the public debate on nuclear power as an argument for the alleged extreme safety of nuclear power plants, in spite of the well known fact that uncertainties in the absolute level of probability of risk are quite large.... The very fact that a figure is cited in a report easily lends itself to tremendous overconfidence in this particular figure."[15]

A review of the Rasmussen Report, sponsored by the NRC, also focused on this point. It stated, "The Executive Summary to [RSS], which is by far the most widely read part of the report among the public and policy makers, does not adequately indicate the full extent of the consequences of reactor accidents; and does not sufficiently emphasize the uncertainties involved in the calculation of their probability. It has therefore lent itself to misuse in the discussion of reactor risk."[16]

Starr says that risk analyses are subject to "hypothetical uncertainty."[9] That is, there is always the chance that some occurrence has been overlooked in a complex system that has a *multitude* of potential failure paths. Rasmussen acknowledges that it is difficult to account for *all* possible initiating events and *all* possible consequences. But risk analysts assume that the occurrences they haven't thought of or experienced are rare. Thus, they believe that omitting the unanticipated probably doesn't affect the overall estimate of failure probability.[8]

More important, there is considerable "experimental uncertainty"[9] attached to risk estimates. Remember that overall failure rates of nuclear reactors are derived by combining the probabilities of failure for each component. The performance records of these components are limited, and there is some amount of statistical variation in their operation. This statistical uncertainty can be small or large, depending on how much is known about the component.[9] More-over, the risk analyst has to take into account the likelihood of *human* error. The uncertainty here is almost always large because we don't have enough "good data" to predict human performance in new technologies, such as nuclear power.

Rasmussen admits that "one can expect an uncertainty of plus or minus a factor of ten"[8] in risk estimates of complex system failure. He also notes that this "is about the same as the uncertainty of the most poorly known of equipment failure rates."[8] Parry and Winter aren't certain it is even possible to "construct a rigid statistical framework in which all sources of uncertainty are quantified."[13] Fischhoff says that, as a result, critics question whether event tree/fault tree analysis is "methodologically sound enough to be used as a basis for decisions of great importance."[14]

Recently, the Oak Ridge National Laboratory was commissioned by the NRC to reevaluate the risks of nuclear power plant accidents. The Oak Ridge study examined over 19,000 failures at nuclear power plants from 1969 through 1979. They concluded that the chance of an accident involving damage to the core is almost one in 1,000 years of the plant's operation. The Rasmussen Report estimated this probability to be only one in 20,000 years of operation. There are now 74 operating nuclear power plants in the US, so "an accident as bad as the one at Three Mile Island, or worse, could be expected every 10 to 15 years."[17] However, Oak Ridge officials feel this new estimate is still too pessimistic because they didn't take into account safety improvements ordered after the Three Mile Island accident in March 1979.[17]

Another controversy in risk analysis centers on how the expert's analysis of technological risks compares with the public's perception of them. The expert objectively rates risks according to how many fatalities are likely to result in a given year of some technology's operation. But the public might evaluate risks more subjectively.

A recent study by Fischhoff and colleagues illuminates this point.[18] Their survey results showed that a layperson's perception of fatal risk bears little relation to the actual fatality rates of a given technology. The authors found that laypeople tend to regard as risky any technology that is new, imposed upon them, unfamiliar, and beyond their control. Also regarded as risky are those technologies, such as nuclear power, in which disaster brings delayed, rather than immediate, effects.

Risk analysts have suggested ways to include the public's qualitative evaluations in their quantitative calculations. They propose assigning "risk conversion factors" to those qualities the public associates with high risk. For example, Starr states, "The public is willing to accept 'voluntary' risks roughly 1000 times greater than 'involuntary' risks."[19] Also, William Rowe, American University, Washington, DC, has assigned risk conversion factors to voluntary/involuntary, delayed/immediate, control/uncontrol, and other qualities of technology.[20] These risk conversion factors would be used when the risks of various technologies are compared.

For example, Rasmussen took into account two qualities of nuclear power that make it riskier than other technologies in the public's mind: its newness and delayed effects. When nuclear power was "penalized" for this and again compared to the frequency of human-caused events involving early fatalities, he found that nuclear power "no longer appears to be as insignificant a risk as was shown in the original [RSS] comparison."[8] This shows how important it is to carefully interpret risk estimates. The analyst's calculations can be significantly inflated or deflated by the public's more subjective evaluation of a new technology's risks. When we ask how risky an activity or technology is, we should specify who is judging it.

As you can see, risk analysis is a multidisciplinary research area involving statisticians, engineers, systems analysts, social psychologists, policy makers, and many other professionals. It is surprising that only one journal specifically devoted to modern risk analysis has emerged from this new and still developing field. *Risk Analysis* is a quarterly journal that only started publication in 1981. It is issued by the Society for Risk Analysis, and published by Plenum Press. Subscriptions to this journal cost $60 per year, but a subscription is included in the society's $30 membership fee.

The Society for Risk Analysis was incorporated late in 1980 as a nonprofit organization. Robert Cumming, editor-in-chief and past president of the society, says the society was founded mainly to ensure that its journal would be unbiased, international, and multidisciplinary.[21] The current president of the society is Chris Whipple, Electric Power Research Institute.

The society expanded its functions to include sponsoring workshops on risk analysis. The first "International Workshop on the Analysis of Actual Versus Perceived Risks" was held in June 1981. It was cosponsored by the society, the World Health Organization, and the National Academy of Science's Assembly of Social Sciences and Board of Toxicology and Health Hazards. The society recently sponsored another workshop, entitled "Low Probability/High Consequence Risk Analysis," with the NRC, Environmental Protection Agency, and Department of Energy. Proceedings will be available early next autumn.

The Society for Risk Analysis also is planning a book series on contemporary issues in risk analysis. In addition, a newsletter on the society's activities is available. Cumming says there are about

Figure 3: *ISI/CompuMath*™ research fronts relevant to risk analysis and systems modeling. Numbers in parentheses refer to core/citing articles included in each research front.

Code Number	Research Front Name
80-0065	Fault trees and algebraic manipulation of probability expressions of network reliability evaluations (7/72)
80-0102	Boolean difference techniques in fault trees and combinational logic networks (2/20)
80-0918	Fault trees for symbolic reliability analysis for a complex network (9/71)
80-2066	Systems engineering methodology, unified program planning, decision-making, and worth-assessment (2/13)

Figure 4: Core documents for research front #80-0065: Fault trees and algebraic manipulation of probability expressions of network reliability evaluations.

Aggarwal K K, Misra K B & Gupta J S. A fast algorithm for reliability evaluation. *IEEE Trans. Rel.* 24:83-5, 1975.

Bennetts R G. On the analysis of fault trees. *IEEE Trans. Rel.* 24:175-85, 1975.

Fussell J B, Powers G J & Bennetts R G. Fault trees—a state of the art discussion. *IEEE Trans. Rel.* 23:51-5, 1974.

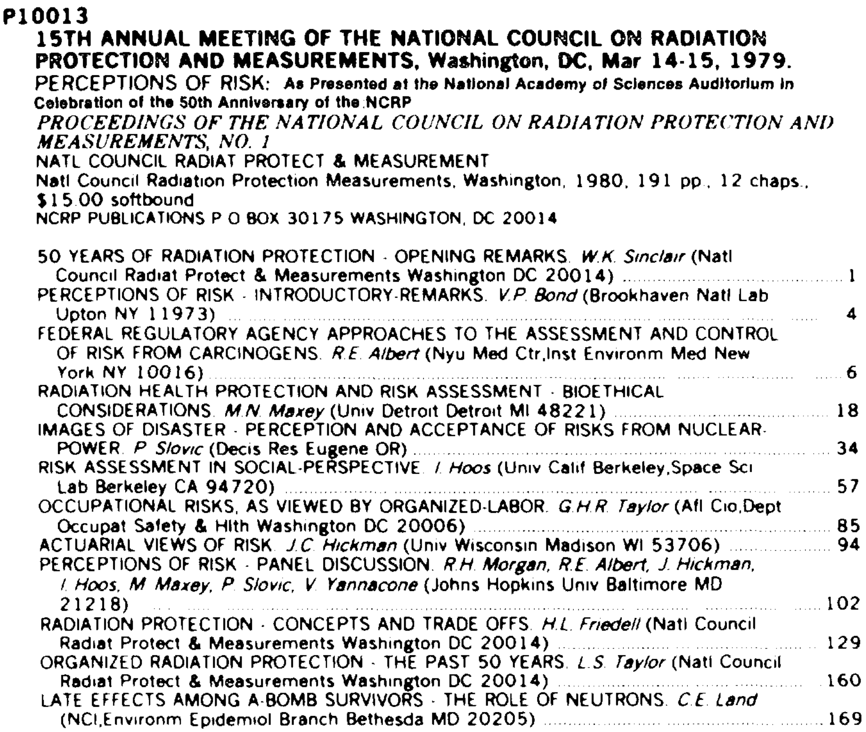
Kim Y H, Case K E & Ghare P M. A method for computing complex system reliability. *IEEE Trans. Rel.* 21:215-9, 1972.

Krishnamurthy E V & Komissar G. Computer-aided reliability analysis of complicated networks. *IEEE Trans. Rel.* 21:86-9, 1972.

Lin P M, Leon B J & Huang T C. A new algorithm for symbolic system reliability analysis. *IEEE Trans. Rel.* 25:2-14, 1976.

Satyanarayana A & Prabhakar A. New topological formula and rapid algorithm for reliability analysis of complex networks. *IEEE Trans. Rel.* 27:82-100, 1978.

Figure 5: Example of proceedings listing in *Index to Scientific & Technical Proceedings*®.



P10013
15TH ANNUAL MEETING OF THE NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS, Washington, DC, Mar 14-15, 1979.
PERCEPTIONS OF RISK: **As Presented at the National Academy of Sciences Auditorium in Celebration of the 50th Anniversary of the NCRP**
PROCEEDINGS OF THE NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS, NO. 1
NATL COUNCIL RADIAT PROTECT & MEASUREMENT
Natl Council Radiation Protection Measurements, Washington, 1980, 191 pp., 12 chaps., $15.00 softbound
NCRP PUBLICATIONS P O BOX 30175 WASHINGTON, DC 20014

50 YEARS OF RADIATION PROTECTION - OPENING REMARKS. *W.K. Sinclair* (Natl Council Radiat Protect & Measurements Washington DC 20014) 1
PERCEPTIONS OF RISK - INTRODUCTORY-REMARKS. *V.P. Bond* (Brookhaven Natl Lab Upton NY 11973) 4
FEDERAL REGULATORY AGENCY APPROACHES TO THE ASSESSMENT AND CONTROL OF RISK FROM CARCINOGENS. *R.E. Albert* (Nyu Med Ctr,Inst Environm Med New York NY 10016) 6
RADIATION HEALTH PROTECTION AND RISK ASSESSMENT - BIOETHICAL CONSIDERATIONS. *M.N. Maxey* (Univ Detroit Detroit MI 48221) 18
IMAGES OF DISASTER - PERCEPTION AND ACCEPTANCE OF RISKS FROM NUCLEAR-POWER. *P. Slovic* (Decis Res Eugene OR) 34
RISK ASSESSMENT IN SOCIAL-PERSPECTIVE. *I. Hoos* (Univ Calif Berkeley,Space Sci Lab Berkeley CA 94720) 57
OCCUPATIONAL RISKS, AS VIEWED BY ORGANIZED-LABOR. *G.H.R. Taylor* (Afl Cio,Dept Occupat Safety & Hlth Washington DC 20006) 85
ACTUARIAL VIEWS OF RISK. *J.C. Hickman* (Univ Wisconsin Madison WI 53706) 94
PERCEPTIONS OF RISK - PANEL DISCUSSION. *R.H. Morgan, R.E. Albert, J. Hickman, I. Hoos, M. Maxey, P. Slovic, V. Yannacone* (Johns Hopkins Univ Baltimore MD 21218) 102
RADIATION PROTECTION - CONCEPTS AND TRADE OFFS. *H.L. Friedell* (Natl Council Radiat Protect & Measurements Washington DC 20014) 129
ORGANIZED RADIATION PROTECTION - THE PAST 50 YEARS. *L.S. Taylor* (Natl Council Radiat Protect & Measurements Washington DC 20014) 160
LATE EFFECTS AMONG A-BOMB SURVIVORS - THE ROLE OF NEUTRONS. *C.E. Land* (NCI,Environm Epidemiol Branch Bethesda MD 20205) 169

1,000 members in 14 countries, and he expects that number to double within a year.[21] For more information on membership, publications, and workshops, write to: Society for Risk Analysis, P.O. Box 531, Oak Ridge, Tennessee 37830.

ISI®'s multidisciplinary data bases help to retrieve risk analysis research published in a wide variety of journals. In particular, our unique research front specialty searches are an effective way of locating research in new specialties, such as risk analysis. We identified four research fronts in our *ISI/CompuMath*™ [22] data base that are relevant to event tree/fault tree analysis and systems modeling. They are listed in Figure 3, and the number of core/citing articles in the research front is shown.

Figure 4 lists the seven core papers in the research front entitled "Fault trees and algebraic manipulation of probability expressions of network reliability evaluations." As you can see, all of these papers were published in *IEEE Transactions on Reliability*. Most of the 72 "current" papers assigned to this research front have also been published in this journal. But other relevant journals include *Microelectronics and Reliability*, *International Journal of Systems Science*, *Operations Research*, *Advances in Applied Probability*, *Networks*, and several more. It is also noteworthy that much of this research has been done in India.

ISI's *Index to Scientific & Technical Proceedings*® (*ISTP*®)[23] lists scores of published proceedings on risk analysis issues. This data base is especially useful since risk analysis is a new specialty whose research results are communicated in various meetings, workshops, and proceedings. Figure 5 presents an example of how proceedings appear in *ISTP*. The online version of *ISTP* includes multiauthored book series as well as proceedings—hence the designation *Index to Scientific & Technical Proceedings & Books* (*ISTP&B*™).[24]

In the second part of this essay, I'll discuss how medical researchers analyze the biological risks from exposure to chemicals, pharmaceuticals, pollutants, and toxic substances in the environment.

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