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THE APPLICATION OF PROBABILISTIC RISK ASSESSMENT TO NUCLEAR FUEL REPROCESSING AT THE SAVANNAH RIVER PLANT

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Introduction

The Savannah River Laboratory has developed an integrated risk assessment methodology that has been applied to systems in the nuclear fuel reprocessing facilities at the Savannah River Plant. The methodology can be applied to several types of design and operational problems.

The overall methodology is illustrated in Figure 1. Basically, the analysis is subdivided into individual modules that can be either utilized separately or integrated into an overall risk analysis. Computer codes and computer data banks are utilized extensively to minimize the manual effort. The flow of information begins with a definition of the system to be analyzed followed by an evaluation of sources of fault information, storage of this information in data banks, design analysis and data treatment, risk calculations, and end product options.

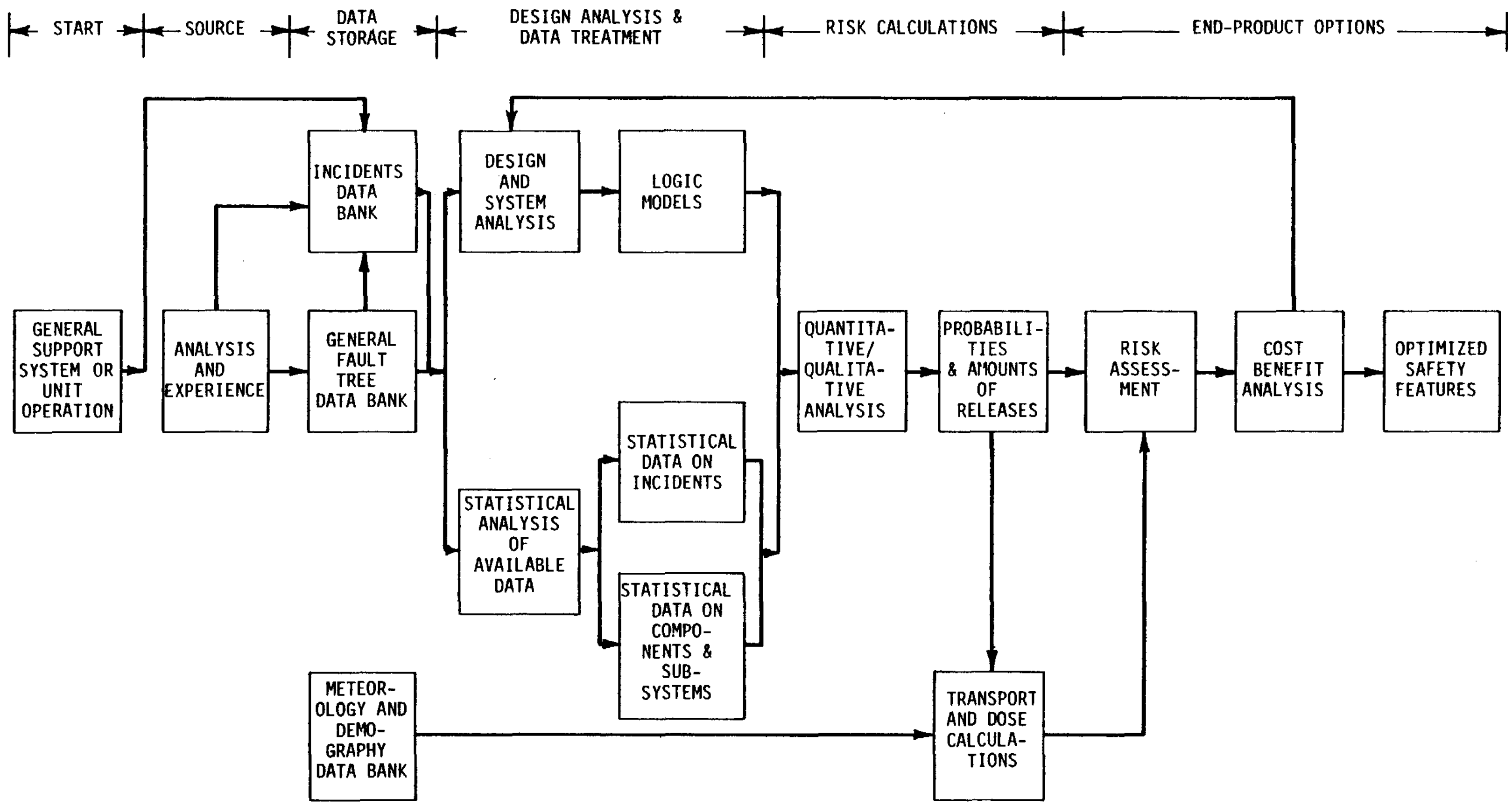

FIGURE 1. Integrated Risk Assessment Plan

Fuel reprocessing plants are best treated as unit operations. Such a treatment is a reasonable optimization of computer code capability, manpower, and calculational precision. Although each case must be considered individually, equipment or operations may generally be grouped under a single analysis if: 1) the physical form of the radioactivity and the matrix is the same, 2) the ratio of the nuclides of interest does not vary significantly, 3) the pathways for transport of radioactivity through protective barriers correspond, and 4) the stresses to which the equipment is subjected are similar.

Sources of Data

Sources of raw data for risk assessment include published data from DOE reprocessing sites, environmental impact statements, safety analysis reports, license applications, theoretical and experimental studies, waste management alternative reports, journal articles, and risk assessments by industrial engineering firms on existing or proposed commercial reprocessing plants. Several types of information have been extracted from these reports, including actual incidents, potential incidents, consequences, and engineered safety features designed to prevent, detect, or mitigate such incidents.

Data Storage

These data have been stored in several data banks in a manner suitable for sorting and retrieval of the information for use with other modules of the assessment. The data banks include an incident data bank that contains known potential incidents that could occur in each of the unit operations associated with fuel reprocessing.[1] Also included are causes of these incidents, consequences in general terms, and engineered safety features.

The fault-tree data bank contains published, actual incidents, including the dates of occurrence. These incidents are coded by site location, facility, unit operation, and keyword so that they can be recalled by a wide variety of specifications compatible with qualitative fault tree construction. In addition, the incidents may be recalled and analyzed with a computer code called STATPAC that fits times between occurrence to five standard distributions. The code calculates the mean and median times between occurrences, the standard deviation, and the parameters required to determine error bounds by the SAMPLE computer code. A chi-square test is also run as an aid in determining the best distribution equation. The parameters thus calculated are stored in a failure data library for automatic retrieval by the fault tree quantification codes.

The meteorological data banks contain one year of weather information on all areas of the United States. The Savannah River Plant has a similar bank with two years of information. Meteorological averages or probability distributions can be constructed from these banks.

The population data bank contains the 1970 census data. Population is enumerated by census districts for the total

United States. These can be updated to reflect the present population or projected by regional population growth.

Design Analysis and Data Treatment

The design and systems analysis phase includes review and evaluation of the process, the physical location of the operation, and the specific items that could affect either the magnitude of release, the type of releases, or the frequency of a consequence. This is a key area for considering the effect of additional safety features. Information used in this module is derived largely from design documents and from the data banks previously discussed. The system is studied to determine that it is both functional and reliable. The effects of equipment location changes and process modifications are evaluated. Desirable design changes and engineered safety features can be incorporated into the basic design to serve as a model for further analysis.

Risk Analysis

The logic models normally involve the use of event trees and fault trees. Fault trees are generated based on information from five steps: experience with the unit operation being analyzed, experience with related unit operations, published studies of potential incidents, judgment of the technical analyst, and discussions with production personnel. Several combinations of fault tree quantification codes have been used successfully at Savannah River including PREP-KITT, MOCUS-SUPERPOCUS, and FTAP-IMPORTANCE. The SAMPLE code has been used to calculate distributions in both frequency and consequence data. Report quality copies of fault trees are generated by the TREDRA computer code.

Presently, onsite and offsite atmospheric transport and doses are calculated by a computer code. The code considers the internal dose from inhalation and the external dose from immersion in the cloud (cloud shine) and from exposure to surface deposition (ground shine). In addition, the effect of aqueous releases on offsite populations through the consumption of drinking water is determined by simple calculations.

End Product Option

The integrated risk assessment calculations can produce three end product options: calculation of risk, cost-benefit analysis, or optimized safety features. The calculation of risk is the primary end product. Risk is defined as the expected consequences (man-rem/event). The expected frequency is obtained from the KITT, IMPORTANCE, or SUPERPOCUS computer codes. The consequence is the product of the dose per unit curie for a specific isotopic composition and the curies released per event.

A cost-benefit analysis may be either the end product or an intermediate step for optimization of the safety features. As an end product, the cost-benefit analysis may show that a new design is not feasible because of excessive costs to achieve the desired safety. In this case, no further analysis is warranted. Normally, for new designs, the cost-benefit analysis serves as the decision point for recycling the analysis back to the design and systems stage so that risks and costs for alternative solutions can be compared. Benefits of a safety feature are measured by the reduction in risk as a result of either reducing the frequency of an event or by mitigating the consequence.

The third end product of an integrated risk assessment is a set of optimized safety features. Such features are obtained by employing an optimization loop between the cost benefit analysis and the design and systems analysis. In such a loop, a base case system is established and analyzed. Desirable design changes are made and/or safety features are added or deleted until the risk of the system is reduced to as low as reasonably achievable at an acceptable cost.

Application

The integrated risk assessment methodology has been applied at the Savannah River Plant to calculate risks for each of the reprocessing facilities, to reduce specific operating errors, to specify engineered safety features for new facilities, and to optimize control systems. Four of these studies are discussed.

Reprocessing at Savannah River is conducted in a number of separate facilities. Included in these are the canyon operations in which reactor fuel is dissolved and separated into various product and waste solutions. Primary unit operations include: fuel receipt, fuel storage, dissolving, centrifugation, solvent extraction, evaporation, and waste disposal. Incidents that could potentially affect these operations were identified, such as transfer errors, overflows, chemical addition errors, fires, uncontrolled chemical reactions, natural phenomena, nuclear criticality, impact, leakage, pluggage, siphoning, suckback, and coil failure. Frequencies, consequencies, distributions, transport parameters, and population doses were determined by the methods previously discussed. The results are summarized in Table 1 as a function of the potential incident in decreasing order of risk. Based on these studies, the risks of reprocessing were compared to those of reactor operation:

- In general, the dominant incidents in nuclear reactors can be described by only two conditions: loss of coolant and power increase. In reprocessing plants, a large number of incidents are possible that can result in loss of small amounts of radioactivity if features to detect, prevent, or mitigate the incidents are not provided.
- Incidents resulting in small releases of radioactivity from primary containment can be expected to be more frequent for a reprocessing plant because the materials are mobile and continually move between operations.
- The potential energy in reprocessing systems is much less, and significant penetration of protective barriers is more difficult; the frequency of significant penetration per initiating event is therefore less.
- The consequences of reprocessing incidents are lower because the integrity of the barriers can be maintained even under severe conditions.

TABLE 1

Risk of Incidents in Canyon Operations

Accident	Population Dose, man-rem		Risk, man-rem/yr		
	Onsite	Offsite	Onsite	Offsite	Total
Fire in Ion Exchange	4	20	0.2	0.8	1
Sudden Spill from Waste Header	-	100	-	0.09	0.09
Slow Leak from Waste Header	-	10	-	0.09	0.09
Criticality in Solvent Extraction	20	1	0.002	0.007	0.009
Fire in First Cycle Solvent Extraction	0.7	4	0.001	0.008	0.009
Coil Failure in Evaporation	-	0.7	-	0.004	0.004
Criticality in Head End	0.06	1	1×10^{-4}	0.002	0.002
Criticality in Dissolving	0.06	1	5×10^{-5}	9×10^{-4}	0.001
Transfer Error from Evaporation (HHW)	-	4000	-	0.002	0.002
Coil Failure in Ion Exchange	-	2	-	0.001	0.001
Criticality in Ion Exchange	0.06	1	4×10^{-5}	7×10^{-4}	7×10^{-4}
Transfer Error from Head End	-	300	-	5×10^{-4}	5×10^{-4}
Criticality in Materials Receipt, Handling, and Storage	0.01	0.2	9×10^{-6}	2×10^{-4}	2×10^{-4}
Fire in Second Metal Cycle Solvent Extraction	0.04	0.2	4×10^{-5}	2×10^{-4}	2×10^{-4}
Transfer Error from Ion Exchange	-	40	-	2×10^{-4}	2×10^{-4}
Coil Failure in Dissolving	-	0.5	-	3×10^{-4}	3×10^{-4}
Coil Failure in Head End	-	0.5	-	3×10^{-4}	3×10^{-4}
Transfer Error from Solvent Extraction 1A Bank	-	0.04	-	2×10^{-4}	2×10^{-4}
Fire in Second Cycle Solvent Extraction	0.008	0.05	7×10^{-6}	5×10^{-5}	6×10^{-5}
Transfer Error from Dissolving	-	0.03	-	5×10^{-5}	5×10^{-5}
Transfer Error from Solvent Extraction 1B and 1C Banks	-	0.5	-	3×10^{-7}	3×10^{-7}
Transfer Error from Evaporation (LHW)	-	1	-	4×10^{-7}	4×10^{-7}
Transfer Error from Solvent Extraction 1D Bank	-	1	-	2×10^{-7}	2×10^{-7}
Transfer Error from Solvent Extraction 2A Bank	-	0.1	-	2×10^{-7}	2×10^{-7}
All Other Accidents Studied	-	-	-	4×10^{-8}	4×10^{-8}
TOTAL			0.20	1.01	1.21

- The inventory of short-lived isotopes in reprocessing systems is significantly less than in a reactor system.

An example of the second use of the methodology was in resolving a relatively minor but recurring problem of adding liquid to the wrong vessel. Mean time between occurrences was ten months. The data best fit a log normal distribution; the 90% error range was one month to three and one half years. The primary cause was that of failure to verify valve settings. A logic model was constructed to confirm the original conditions that led to the errors. The model was then adjusted to reflect improved communications between the control room operator and the field operator such that the calculated mean time between occurrences was four years. Further reduction in the frequency was not considered to be cost effective and was therefore not initiated. In the two and one half years since the study, the changes appear to have been effective.

Portions of the methodology have been used effectively in performing preliminary hazards analyses of new and upgraded facilities. For example, a facility is being designed for the conversion of the high-level liquid waste at the Savannah River Plant into borosilicate glass. Many of the unit operations and support facilities will be quite similar to those already in operation, e.g., evaporation, centrifugation, ion exchange, ventilation, and electrical. The incidents affecting these operations are stored in the incident data bank. These data provided the nuclear safety analyst with most of the information required for the qualitative portion of the safety analysis. The data provided the design groups with an extensive list of engineered safety features to be considered for the prevention, detection, or mitigation of the consequences of these incidents. The data are not a complete package for other applications because some considerations were specific to the Savannah River system.

The final example for the use of the integrated risk assessment methodology was in optimizing the control system for two ventilation systems in series. The systems consisted of two fans in parallel exhausting a satellite facility and discharging into the exhaust air tunnel of the parent facility upstream of its fans. The parent facility exhaust consists of four fans in parallel. If the parent facility fans were to fail while the satellite facility fans continued to operate, air pressure in the parent facility would be positive which could result in the release of airborne radioactivity into personnel areas.

One solution would be to interlock the satellite fans with the parent fans such that failure of the parent fans would shut down the satellite fans. Results from quantification of the logic trees, as shown in Table 2, showed that the electrical systems for the two sets of fans were so interconnected that the frequency of failure of the parent fans without causing failure of the satellite fans is negligible. Installation of an automatic interlock would decrease the overall reliability of the system.

TABLE 2

Failure Intervals Calculated for Series Fan Systems

System Failure	Mean Time Between Failures, yr	90% Error Range
Independent failure of satellite fans	10	3 to 60
Common cause failure of both fan systems	950	330 to 6,700
Independent failure of parent fans	800,000	220,000 to 40,000,000

In summary, the integrated risk assessment methodology has many varied uses in safety and design studies of nuclear fuel reprocessing plants. Also the methodology and data banks are continually being updated by the Savannah River Laboratory.

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