Quantifying the Risk of Nuclear Fuel Recycling Facilities

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Introduction

Quantitative risk assessment (QRA) as a method of safety analysis of nuclear facilities is most strongly identified with probabilistic risk assessment (PRA) of nuclear power plants. The last safety analysis (Nuclear Fuel Services, 1962) of a commercial U.S. nuclear fuel recycling plant that actually went into operation was performed in 1962 to support the license application of the West Valley Spent Fuel Processing Plant under Title 10, Part 50, "Domestic Licensing of Production and Utilization Facilities," of the *Code of Federal Regulations* (10 CFR Part 50). This, of course, was some 13 years before the publication of the famous Reactor Safety Study (USNRC, 1975). Meanwhile, QRA (QRA and PRA have the same meaning in this paper) has become the foundational approach for comprehensively implementing the concept of risk-informed safety analysis. This does not mean that QRA has been universally accepted in the safety analysis world, although it pretty much has when it comes to such high profile facilities as nuclear power plants and nuclear waste repositories. As renewed interest develops in the U.S. for recycling nuclear fuel, it is prudent to examine the progress that has been made in nuclear facility safety analysis and how risk-informed safety analysis might be applied to nuclear fuel recycling facilities. Thus, it is the purpose of this paper to consider how QRA might be applied to a nuclear fuel recycling plant.

Any decision to apply QRA to nuclear fuel recycling must be accompanied with the decision of which QRA approach best serves the needs of the particular problem. In this case we adopt what is referred to in the literature (Garrick, et al., 2008) as the scenario approach to risk assessment based on the triplet definition of risk discussed later. In the absence of an actual QRA of a nuclear fuel recycling plant, the approach will be to highlight the methodology and illustrate how selected QRA algorithms might be applied, including the type and form of the results.

Why Quantitative Risk Assessment

The primary advantages of a QRA are completeness, context, and realism; completeness, in the sense that all of the scenarios that can threaten the performance of the system are in principle considered, and context in the sense that the likelihood of the scenario, including its consequence, is part of the answer. Of course, it may not be possible to manifest all of the scenarios that represent a threat to the system, but it is usually possible to account for the important ones. Similarly, it may not be possible to calculate absolute likelihoods (e.g., probabilities), but by embracing the concept of uncertainty in the likelihood functions the confidence in the likelihoods can be manifested. The concept of likelihoods and scenarios allows for the systematic importance ranking of the contributors to risk and a scientific basis for effective risk management. It also allows for the aggregation of the risk of individual scenarios into the total risk of the system. Finally, one of the important drivers for QRA was to have a method of safety analysis that targeted realistic results, as opposed to bounding analyses, that tend to leave the reader wondering what the experts believe is the real risk.

Fundamentals of Quantitative Risk Assessment

The fundamentals of the QRA approach that are advocated here involve the following basic steps:

> *Step 1.* Define the system being analyzed in terms of what constitutes normal operation to serve as a baseline reference point.
>
> *Step 2.* Identify and characterize the sources of danger, that is, the hazards (e.g., stored energy, toxic substances, hazardous materials, acts of nature, sabotage, terrorism, equipment failure, combinations of each, etc.).
>
> *Step 3.* Develop “what can go wrong” scenarios to establish levels of damage (consequences) while identifying points of vulnerability.
>
> *Step 4.* Quantify the likelihoods of the different scenarios and their attendant levels of damage based on the totality of relevant evidence available.
>
> *Step 5.* Assemble the scenarios according to damage levels, and cast the results into the appropriate risk curves and risk priorities.
>
> *Step 6.* Interpret the results to guide the risk management process.

Steps 1 through 4 are founded on five basic principles and conditions, (1) the triplet definition of risk, (2) scenarios linking threats to consequences, (3) the quantification of uncertainties, (4) the *credibility* definition of probability, and (5) Bayesian inferential reasoning.

Definition of Risk

The general framework for QRA is the "set of triplets" definition of risk.

$$R = \{<S_i, L_i, X_i>\}_c,$$

In this format, the inner brackets enclose the triplet, the outer brackets denote "the set of", and the subscript c implies that the set is complete. The risk ("R") is a comprehensive answer to the following questions:

- "What can go wrong?" This question is answered by describing a structured, organized, and complete set of possible damage scenarios ("S").
- "What is the likelihood of each scenario?" This question is answered by performing detailed analyses of each risk scenario, using the best available data and engineering knowledge of the relevant processes, and explicitly accounting for all sources of uncertainty that contribute to the scenario likelihood ("L").
- "What are the consequences?" This question is answered by systematically describing the possible end states, including the damage states, such as different radiation dose levels that may be received by a member of the public ("X").

Structuring the Scenarios

The process of structuring “what can go wrong” scenarios involves three major activities. The first is the development of the so called success scenario for the system being analyzed. The success scenario usually involves linearizing the system to the extent possible into different stages, phases or functions that must perform in sequence in order for the total system to perform its intended function. The success scenario must be structured such that any significant threat to the system can be represented as a disturbance to one or more of the function boxes in the success scenario. This suggests the second activity and that is the performance of a threat assessment. The threat assessment is the process of analyzing each function in the success scenario in terms of the types of events that could disturb the function. In many respects the threat analysis is the most important and creative part of risk modeling because it is the key to the completeness of the process. The location and operating conditions are major factors in determining the threats to any facility. Some threats may cause a direct release of radioactive materials from the facility, while others may initiate a sequence of events that unless mitigated will result in such releases. Some threats may alter the site in ways that increase its vulnerability to other threats: e.g., loss of essential support services or events that could alter natural protective barriers of the site. Potential conditions that may affect the site are often grouped into two general categories.

- **Disruptive Events**. These are unexpected events that may cause an immediate change to the site or the facility. They are typically characterized by an event occurrence frequency and by directly measurable immediate consequences. Examples are severe storms, tornadoes, earthquakes, fires, and airplane crashes.

- **Nominal Events and Processes**. These are expected events and processes that evolve continuously over the life of the facility. They are typically characterized by a rate, which may be constant or changing over time. The potential consequences from these processes depend on the duration of the exposure period. Examples are the aging and degradation of engineered systems.

The scope of potential threats should be as complete as reasonably possible and include a broad range of natural phenomena and processes, equipment degradation, and human-caused events. Generally, risk assessments do not include intentional acts of destruction, war, terrorism, or sabotage, although the QRA methodology can be effectively applied to such threats (Garrick, et al., 2004). For security reasons, it is prudent to do such QRAs separately. Threats can be screened out when there is evidence that they do not compete with the threats driving the risk. In the table below are examples of the types of threats that might be considered for a nuclear fuel recycling plant.

Internal Threats: Fires, Explosions, Equipment Failure including Safety Equipment, Operator Error, Instrument Malfunction, Criticality Events, Process Malfunctions, Power Disruptions, Building Failure, Deliberate Human Acts, Failure to Follow Procedures or Believe Instrument Readings

External Threats: Fires, Loss of External Power Supplies, Loss of Other Utilities, Severe Storms, Sitewide Pipeline and Utility Accidents, Seismic Events, Hurricanes, Tornadoes, Nearby Facility Accidents, Site Intrusions, Toxic Gas Releases, Transportation Accidents, Volcanoes, Surface Geology, Lightning, Flooding Events

Each threat must be considered and its disposition determined in order to decide how much analysis it deserves.

Finally, the third activity of structuring scenarios is given the events or conditions that could disturb any of the functions necessary for system success (usually labeled *initiating events or initial conditions*), what is the sequence of events to the final damage states of the individual scenarios, another very creative part of risk assessment. The damage states may take many forms from radiation release mechanisms to radiation dose and from physical damage to the plant to human injuries and fatalities. The total process is illustrated in Figure 1.

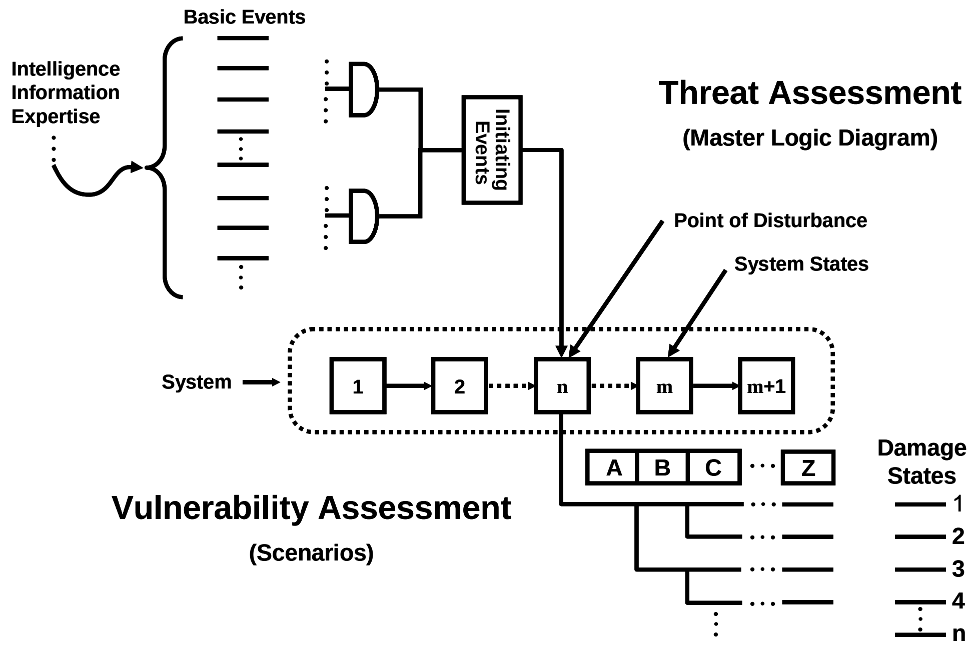

Figure 1. The Concept of Linking System Disturbances to System Damage States

Quantification, Probability, and Bayes Theorem

Given that we know what the scenarios are, the question now is, how do we go about quantifying their consequences and converting the results into a statement of risk. The answer lies in the parameter chosen to measure risk, the manner in which uncertainties are quantified, and the interpretation given to *probability*. The parameter chosen to measure risk is the frequency of occurrence of different states of damage (consequences). Quantification is recognizing that the damage state frequencies are uncertain and must be quantified. Frequency uncertainty is communicated by a probability distribution (probability of frequency concept). Two types of uncertainty that dominate the quantification process are information uncertainty and modeling uncertainty. Both have to be addressed.

We define probability as synonymous with *credibility*, as in the credibility of a hypothesis based on all the available evidence. It is a positive number ranging from zero to one that obeys Bayes theorem. The probability curves for the frequency of different damage states are inferred from all of the available evidence, using the fundamental mathematical principle of logical inference, known as Bayes theorem. In particular, Bayes theorem answers the question, how does the probability of a given hypothesis change with new information.

The actual quantification process is done with the aid of an event tree, a decision type diagram first used in the nuclear field in the Reactor Safety Study. The event tree traces the sequence of events following any abnormal disturbance of the system and is illustrated in Figure 2.

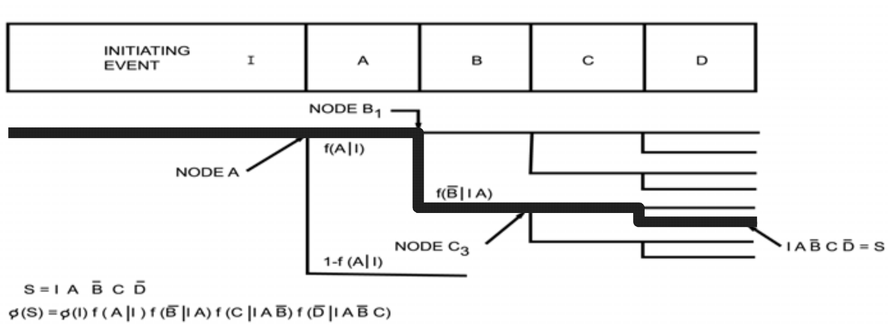

Figure 2. Quantification of a Scenario Using an Event Tree

The boxes A, B, C, and D represent intervening events, such as a backup system, that can alter the course of the scenario. The likelihood of a scenario depends on the quantification of the split fractions at the branch points in the scenario. All branch points that are logically relevant are considered. Each scenario is represented by a Boolean equation combining branch point events. The form of each term in the Boolean equation is a probability density function and the risk of a scenario is the convolution of the various terms in equations of the type shown in Figure 2. The convolution process is illustrated for the highlighted scenario in Figure 3.

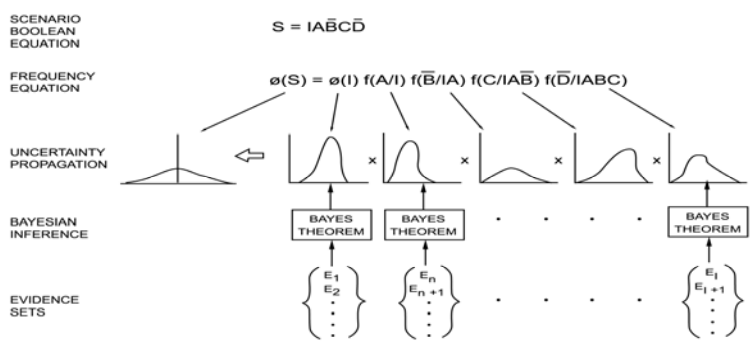

Figure 3. Bayes Theorem Used to Process Parameters

Assembling the Scenarios

A QRA of a complex system such as a nuclear fuel recycling plant may end up having hundreds, thousands, or possibly even millions of individual scenarios, each scenario represented by a probability of frequency curve of the form of Figure 4.

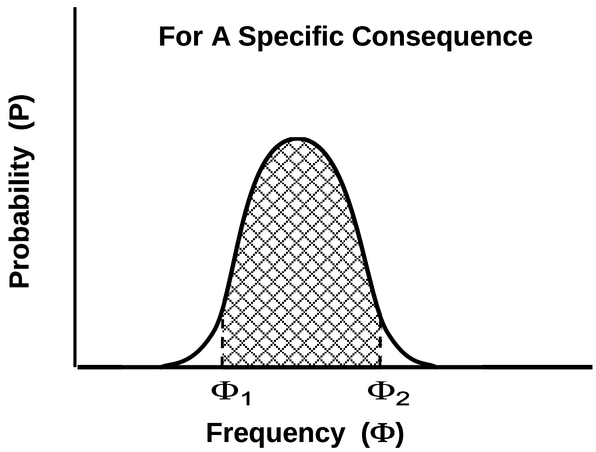

Figure 4. Probability of Frequency Curve

Figure 4 is a very convenient form for representing the risk of an individual scenario. Suppose the shaded area is 90% of the total area under the curve. What this curve tells us is that we are 90% confident that the frequency range of this consequence is between φ_1 and φ_2.

The question is: how do we assemble the individual scenarios into a form that represents the risk of the total system? The most common form of such a representation is to construct from the individual scenarios, using probability arithmetic, frequency-of-exceedance curves, also known as complementary-cumulative-distribution-functions. In particular, such curves are obtained by ordering the scenarios by increasing levels of damage and cumulating the probabilities from the bottom up in the ordered set against the different damage levels and plotting the results in a log-log format. The result is a curve of the form of Figure 5.

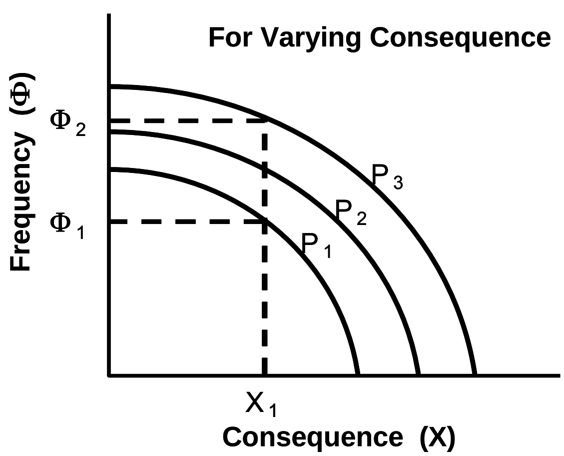

Figure 5. Risk Curves for Varying Consequences

Suppose in Figure 5 that P_1 and P_3 are the 5^{th} and 95^{th} percentile curves. The total risk of the system under consideration would be described in the following manner: we are 90% confident that the frequency of occurrence of X_1 level of damage, or greater, is in the range of φ_1 to φ_2.

Interpreting the Results

While it is a major achievement to obtain results of the above forms, the most important result from a QRA is full exposure of the contributors to the risk and their relative importance. The above method of assembling the results provides the information necessary to deconstruct the results into different types of contributors and their relative importance. This is the information that is most valuable in making decisions for controlling the risk, the primary reason for doing a QRA.

Safety Experience of Nuclear Fuel Recycling Plants

As a preamble to how the above methodology might be applied to a nuclear fuel recycling plant, it is appropriate to make a few observations on what the safety experience has been with such plants. Currently there are no operating nuclear fuel recycling plants in the U.S. The major recycling plants operating worldwide are in France, the United Kingdom, Japan, and Russia. India has three plants, but little is known about their safety experience.

The past U.S. experience includes large Government-owned plants located in Richland, Washington, and Savannah River, South Carolina, for plutonium production and a plant in Idaho to recover spent naval reactor and other highly enriched fuels (USNRC, 2008). The only commercial nuclear fuel recycling plant to operate in the U.S. was the Nuclear Fuel Services' West Valley plant, which is now shutdown and being decommissioned. The West Valley plant differed from the government facilities in that it processed high burnup oxide fuels. It was a multi-purpose plant designed to reprocess a wide range of fuel types. Its product was uranyl nitrate and plutonium nitrate in the form of concentrated aqueous solutions.

There have been no known accidents in recycling plants that involved large numbers of fatalities. There have been criticality accidents that resulted in deaths and major radiation exposure injuries at Tomsk in Russia (fuel reprocessing plant) and Tokaimura in Japan (nuclear fuel plant). In both cases, plant operators were performing manual transfers that had not been properly reviewed and moved nuclear material into geometrically unsafe (for criticality control) vessels. Such experiences have been used to design fuel reprocessing and fuel fabrication facilities so that nuclear criticality is prevented by physical controls that cannot be bypassed except after a safety review.

Over the several decades of operation of the U.S. government plants there were incidents of fires, leaks and spills, chemical and resin explosions, and temporary failures of offgas treatment systems. The most high profile events have been the so called "red oil incidents" that have occurred in government plants in the U.S., Russia and Canada (USNRC, 2008). Red oil is formed when tributyl phosphate (TBP) comes in contact with concentrated nitric acid at temperatures above 130°C. Under these conditions the TBP undergoes decomposition and nitration reactions causing formation of nitrated organic compounds that give the organic phase an amber color, hence the name "red oil". If the temperature is above 130°C the red oil can undergo rapid decomposition generating gases and overpressure. These gases can also detonate or decompose explosively. Studies of red oil explosions recommend a maximum process temperature of 120^{o} C to provide a safety margin where TBP may be present.

Red oil incidents have occurred in the Hanford reprocessing plant in 1953 and at the Savannah River plant in 1953 and 1957. There were no major personnel injuries associated with any of these incidents. Red oil explosions have also occurred in reprocessing plants in Russia and Canada. The exact nature of the damage or injuries outside of the U.S. from reprocessing plant accidents is not known, but is not believed to have been extensive, especially with respect to radiological consequences. It should be noted that in each red oil incident a major cost consequence was the downtime to evaluate the incident and define requirements for safely resuming operation. The French plant has not experienced the red oil phenomenon.

As to the safety experience of the West Valley commercial plant which operated from 1966 to 1972 by Nuclear Fuel Services, Inc., there were no accidents where the radiological consequences resulted in any fatalities. However, there were several incidents involving the release of radioactivity (Mellon, 2008). While the number of leaks and spills was quite high for such a short operating period, most were inconsequential from a worker and public safety standpoint because of the design of the process cells to accommodate limited leaks and spills. Two incidents are noted that did go beyond the ability of the design to provide full containment. One occurred in 1967 and involved a leak of about 200 gallons of recovered nitric acid from one of the lines in the offgas operating aisle. The leak traveled from the breached line down the walls of the offgas cell and the adjacent southwest stairwell below and under the Main Process Building through a floor expansion joint. This turned out to be the dominant contributor to what was later identified as the North Plateau groundwater plume. ^{90}Sr and its decay product ^{90}Y are the principal radionuclides of health concern in this plume.

The second incident of some radiological consequence was an uncontrolled airborne release in 1968. This leak occurred when a high-efficiency particulate air filter in the main ventilation system failed and part of the filter media was drawn into the blower, cut into pieces, and discharged out the main stack. While no excessive doses of radiation were received by members of the public, this event did have offsite radiological consequences.

During the operating period of the plant there were numerous leaks, spills, small fires, and operating errors involving radioactive liquids (E.R. Johnson, 1980). While the safety risk was generally limited, some of the events had serious operational risk consequences. For example, there was a leak of high activity waste from a line rupture between the general purpose evaporator and the high-level waste tank that required operations to be halted for some 2 months to decontaminate the affected area and replace equipment.

The U.S. experience with nuclear fuel recycling while limited is still sufficient to support meaningful risk analysis and management. In combination with the international experience, there exists a reasonably robust data and information base on the safety of operations to support very meaningful quantitative risk assessments providing the uncertainties become part of the results of the assessment.

Structuring a QRA Model for Recycling Facilities

As previously indicated, a QRA was not available to the authors to illustrate the six-step QRA process noted earlier. We will discuss how each step might be implemented for a recycling plant and in some cases illustrate the QRA modeling algorithms.

Step 1. Define the system being analyzed in terms of what constitutes normal operation

For a fuel recycling facility the sequence processing steps needed for successful operation can be derived from the process flow diagram. For example, Figure 6 is a simplified process flow diagram or block flow diagram showing the major processing steps in a typical nuclear fuel recycling plant based on the PUREX technology.

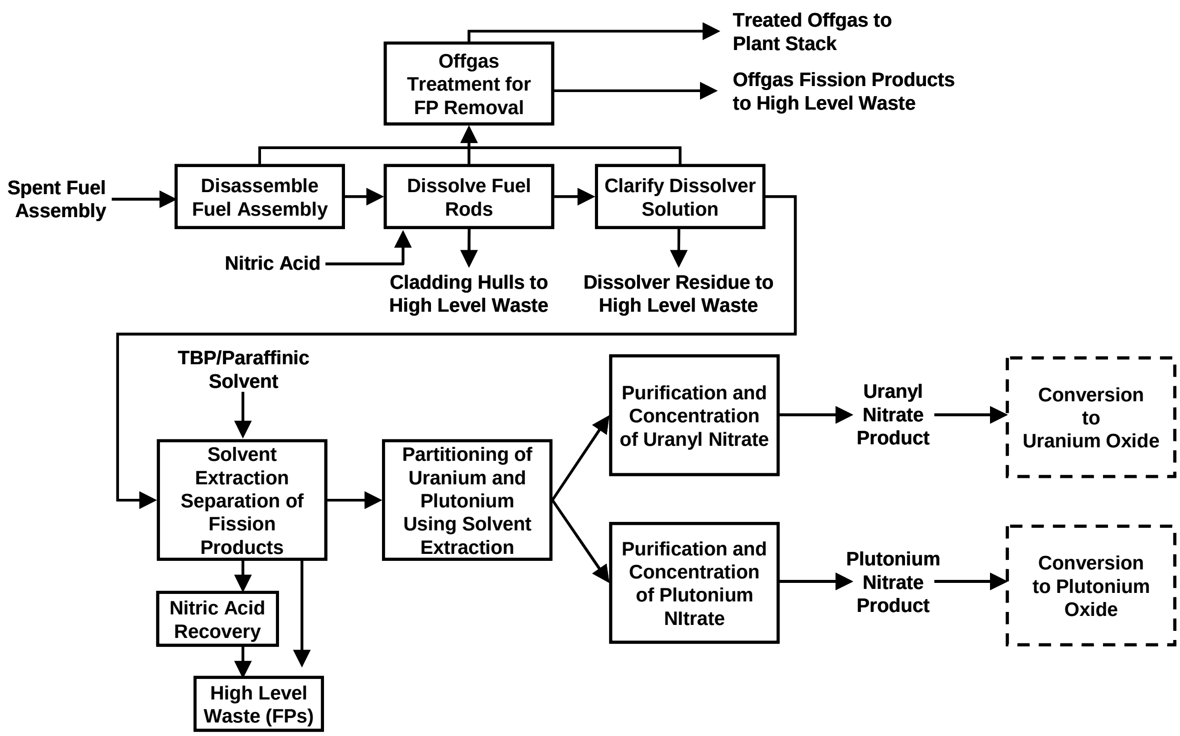

Figure 6. Simplified PUREX Process Flow Chart

For any given plant it may be different depending on the operating objectives of that plant; e.g., whether that plant will supply both plutonium and uranium products for use in fuel fabrication and the form of the products required by the fuel fabrication operation. A brief description of the generic PUREX process follows.

Spent fuel from nuclear reactors used in power plants is shipped to the PUREX facility in spent fuel casks. The fuel casks are placed in a spent fuel pool which provides shielding from radiation associated with the spent fuel. The casks are then opened and the spent fuel assemblies are placed in criticality safe racks. When scheduled for processing the spent fuel assemblies are removed from the rack and transferred to a shielded head end processing unit where the inlet nozzle is cut off the fuel assembly. The head end facility and downstream processes are remotely operated in shielded cells until the fission products have been separated from the spent fuel.

After removal of the inlet nozzle from the fuel assembly the fuel rods, consisting of cylindrical oxide pellets inside a long stainless steel or zircalloy tube, are pushed out of the assembly from the bottom end into a fuel chopping system. In the chopping system the tubes or cladding containing the spent fuel pellets are chopped into short lengths and collected in criticality safe baskets. Fission product gases released during chopping are sent to the offgas treatment system for removal of radioiodine and subsequent monitoring and dilution for release to the facility stack. While this is current practice, future plants in the U.S. will be required to remove additional radioactive fission product gases such as ^{85}Kr and tritium.

The baskets are then transferred into a dissolver vessel where they are placed in rack positions in the dissolver. Nitric acid is added to the dissolver at a controlled rate to dissolve the fuel pellets and the temperature is increased to 90°C at a rate that keeps offgas generation within the operating range of the offgas treatment system. Temperature control is provided for the dissolver by return of cool offgas condensate and by steam to the dissolver steam jacket. Fission product gases in the fuel pellet matrix are released from the matrix as the pellets dissolve. The offgases are directed from the top of the dissolver to the offgas treatment system for removal of radioiodine and subsequent release to the stack. The dissolver offgas stream is the primary source of radioactive offgases in the process. After the dissolution of spent fuel pellets is complete, the nitric acid solution is drained from the dissolver to an accountability and feed adjustment tank where the solution is analyzed and the concentration of dissolved elements and acidity of the solution is adjusted. The adjusted mixture is then pumped to a feed tank for the partitioning process step. The baskets containing undissolved tube fragments or cladding hulls are transferred to an unloading facility where the hulls are collected and prepared for disposal. The empty baskets are returned to the head end facility for reuse.

This feed solution for the partitioning cycle contains dissolved fission products and nitrates of uranium, plutonium and other transuranic elements. The separation of fission products from the U and Pu is accomplished by feeding the solution to a solvent extraction system, typically a pulse column, where the aqueous feed stream flows countercurrent to an organic mixture of about 30% tributyl phosphate (TBP) and kerosene. As the aqueous and organic solutions mix, the nitrates of uranium and plutonium are selectively extracted into the organic solution and flow out of the extraction system with the TBP-kerosene solution. The aqueous solution containing over 99.9% of the fission products flows into a feed tank for the nitric acid recovery system to reduce liquid waste volume and minimize the need for additional acid.

The aqueous phase/organic phase extraction technology is at the heart of the PUREX process. The aqueous phase is an acidic solution and the organic phase is a TBP-kerosene mixture. Chemicals are added to the aqueous phase to selectively reduce or oxidize the plutonium and allow its transfer between the aqueous and organic phases. The PUREX process has been used since the 1940's and the chemistry is well known. Proper control of the chemistry and the solution temperatures and extraction system operation in the extraction steps is key to achieving very high separation efficiencies and guaranteeing that contaminants do not accumulate in unplanned locations or amounts in the various process steps.

After removing the fission products, the U-Pu nitrate mixture is sent to the Pu separation unit feed tank and mixer where the Pu chemistry is adjusted to cause the Pu nitrate to selectively enter the aqueous phase in a solvent extraction system. The U nitrates remain in the organic phase. The Pu chemistry is again adjusted to selectively transfer the Pu nitrate into the organic phase. The U and Pu nitrates are then sent to respective second stage product purification units that also use solvent extraction for removal of essentially all of the remaining fission products.

From the second stage cleanup cycle the separate U and Pu nitrate streams are then sent to respective evaporation units to concentrate the nitrate solutions. The concentrated solutions are then passed through ion exchangers to remove trace amounts of zirconium and niobium fission products. The product nitrate solutions are then transferred to a fuel fabrication process where the solutions are fed to a calciner or denitrator where the nitrate cation is decomposed causing release of NO_x gases and the uranium and plutonium is converted to a dry oxide powder for use in fuel fabrication.

There are numerous support systems associated with the above operating steps. Examples are (1) offgas treatment systems, (2) waste treatment systems, (3) acid and solvent recovery, cleanup and recycle systems, and (4) essential process/instrument air, water, steam and electrical power systems. For purposes of illustrating the QRA process only the main process steps are considered. In particular, based on the process flow chart, a top level success diagram for the process takes the form of Figure 7. It is assumed that the evaporation and purification is the last step of the process and denitration or calcining the uranium and plutonium to an oxide is part of the fuel fabrication process which may or may not be at the same site.

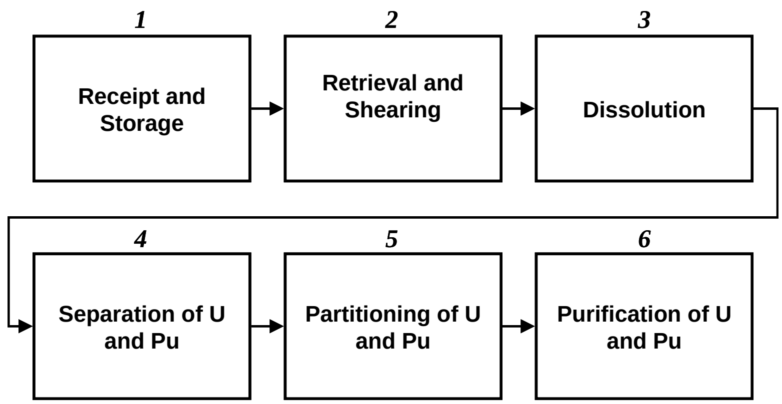

Figure 7. Top Level Success Diagram for a PUREX-Type Fuel Reprocessing Plant (Definition of the Success Scenario)

To keep the illustration simple and interesting, only one block of the diagram in Figure 7 will be considered. In particular, Block 6 is assessed in terms of a possible red oil explosion (DNFSB, 2003). In a fuel reprocessing plant opportunities for red oil generation and potential red oil incidents exist in the evaporators provided for concentrating nitrates of uranium and plutonium and in the acid recovery unit where recovered nitric acid is purified. The uranium and plutonium evaporators are of particular interest. The nitric acid concentrators or evaporators are located in a non-radioactive process area and are not part of Block 6. Thus, the success diagram for Block 6 becomes the basis for our example.

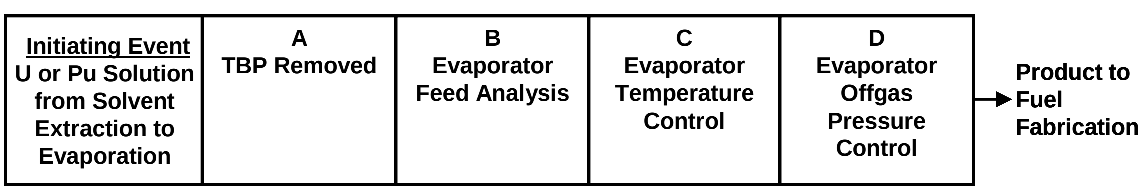

Figure 8. Success Diagram for Product Evaporation

Step 2. Identify and characterize the hazards

The overarching hazard of concern is ionizing radiation. Of course, other hazardous materials are involved and the same methodology could be applied to address them. For our example, we go only so far as a precursor event that could possibly lead to the spread of alpha contamination, namely the risk of a red oil explosion.

Step 3. Develop "what can go wrong" scenarios to establish levels of damage

As indicated earlier, the process of developing initiating events and the subsequent event sequences is the creative part of the risk model. This part of the risk assessment must involve experts on the process, the plant design, and operations. Once the initiating events are developed, the course of the subsequent events is best characterized in the form of an event tree of the type of Figure 2 shown earlier. Given a specific threat or initiating event, it is a matter of determining how the scenario is affected by the functions, A, B, C, and D of the success diagram, Figure 8. An event tree, Figure 9, identifies all possible combinations of success and failure for the process steps.

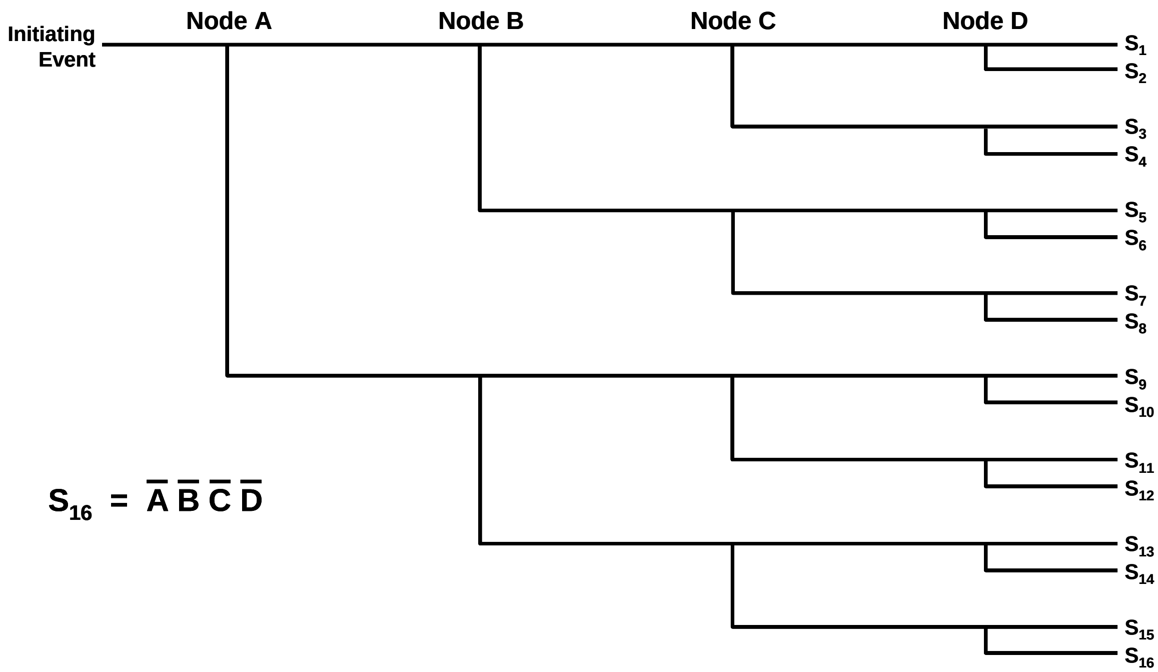

Figure 9. Event Tree for Red Oil Explosion Risk

Each path through the event tree is a scenario or event sequence and can be represented by a Boolean equation. For example, the expression for scenario 16 (S_{16}) is

$$S_{16} = \overline{A}\ \overline{B}\ \overline{C}\ \overline{D}$$

Table 1 is a summary of the 16 scenarios characterized by the event tree of Figure 9. Each scenario in the table is characterized by the success or failure of each step or node identified in the top level diagram for Block 6. Failures to properly complete each step are called the split fraction for that step. The combinations of successes and failures in the process steps are then used to define the consequence for each scenario.

Table 1. Summary of Scenarios and Consequences

Scenario	Description	Consequence or Outcome
S_1	Evaporator systems operate as designed.	Product conforming to specification.
S_2	All systems work except offgas system pressure fails high or low.	Off spec product.
S_3	Evaporator temperature control fails high increasing heat input to evaporator; pressure control compensates for increased heat input.	Off spec product.
S_4	Temperature control fails high; pressure control does not compensate.	Off spec product; possible nitrate precipitation in evaporate and shut down for repair.
S_5	Evaporator feed analysis fails. All other systems function.	Possible off spec product.
S_6	Evaporator feed analysis fails; evaporator pressure control fails.	Off spec product.
S_7	Evaporator feed analysis fails; temperature control fails high; pressure control works.	Off spec product.
S_8	Evaporator feed analysis fails; evaporator temperature control fails high; evaporator pressure control fails.	Off spec product; possible nitrate precipitation in evaporate and shut down for repair.
S_9	Excess TBP in feed tank; feed analysis detects TBP.	Rework of evaporator feed required.
S_{10}	Excess TBP in feed tank: feed analysis detects TBP; temperature control works; pressure control fails high or low.	Rework of evaporator feed required.
S_{11}	Excess TBP in feed tank: feed analysis detects TBP; temperature control fails high; pressure control works.	Rework of evaporator feed required.
S_{12}	Excess TBP in feed tank: feed analysis detects TBP; temperature control works; pressure control fails high or low.	Rework of evaporator feed required.
S_{13}	Excess TBP in feed tank: feed analysis fails to detect TBP; temperature control works; pressure control works.	Off spec product; possible fire in fuel fabrication denitrator from TBP in product.
S_{14}	Excess TBP in feed tank: feed analysis fails to detect TBP; temperature control works; pressure control fails high or low.	Off spec product; possible fire in fuel fabrication denitrator from TBP in product.
S_{15}	Excess TBP in feed tank: feed analysis fails to detect TBP; temperature control fails; pressure control works.	Off spec product; possible fire in fuel fabrication denitrator from TBP in product.
S_{16}	Excess TBP in feed tank: feed analysis fails to detect TBP; temperature control fails; pressure control fails high.	Red oil formation and possible overpressure or red oil explosion.

Step 4. Quantify the likelihoods of the different scenarios and damage states

This step requires quantification of the various split fractions of the event tree, the development of their probability density functions and convoluting them in the manner of Figure 3. For this example the steps are treated as independent and the split fractions are not conditional upon prior failures or successes. The development of the probability distributions for the split fractions start with the examination of the details of all of the red oil events that have occurred and a detailed assessment of the specific plant systems involved. Accounting for the uncertainties allows the use of all supporting evidence. The reliability data base developed by the Center for Process Safety of the American Institute of Chemical Engineers (AIChE, 1989) provides a good starting point for data. It can be augmented by data generated in additional studies such as the SRS H-Canyon fault tree analysis performed by Christensen and Vail (Christensen and Vail, 1995).

For each split fraction, the likelihood of failure is quantified from data that is judged applicable to the equipment failure(s) being considered. In some cases quantification may require development of fault trees with the split fraction failure as the top event and the tree development carried to a point at which basic data can be determined for input to the identified failure events. Examples of fault trees that might be associated with the feed analysis failure and evaporator overtemperature are given in Figures 10 and 11.

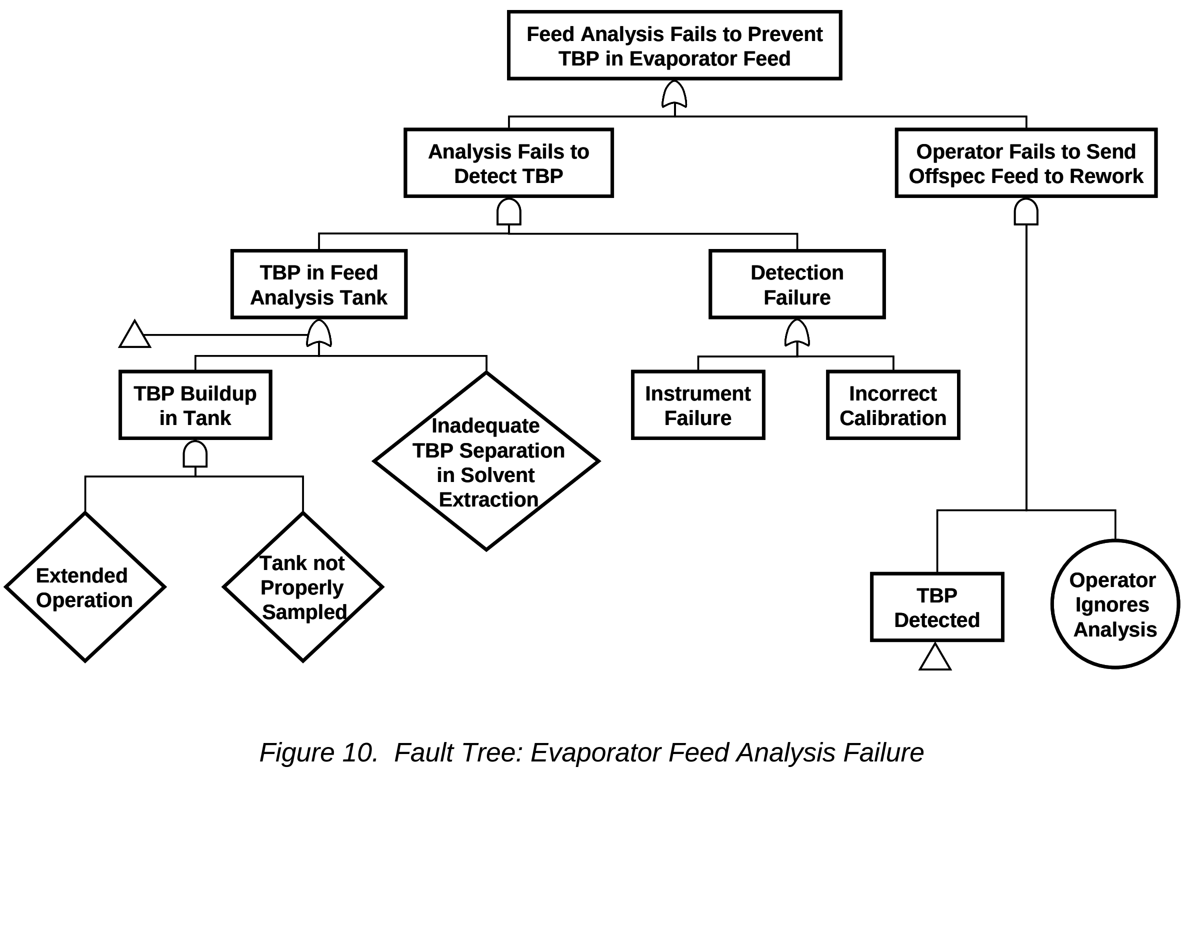

Figure 10. Fault Tree: Evaporator Feed Analysis Failure

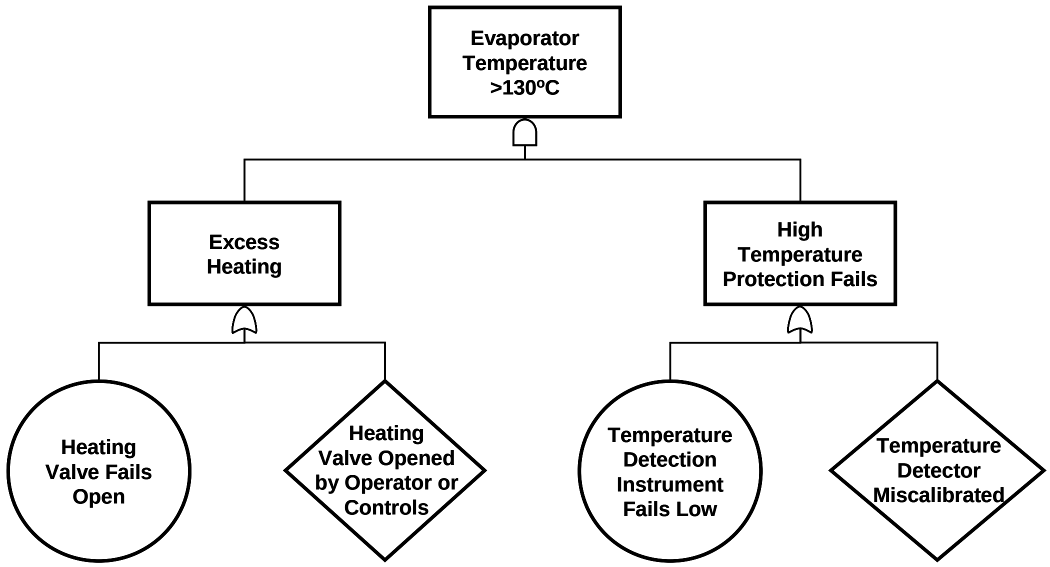

Figure 11. Fault Tree: Evaporator Temperature Control Failure

This is as far as the example is taken in terms of implementing the six QRA steps. The above steps are believed sufficient to have confidence that such analyses are feasible not only for recycling plants but any kind of natural or engineered system.

Steps 5 and 6. Assemble and interpret the results

As noted, our example was taken only far enough to illustrate some of the most creative aspects of a QRA. For example, we have illustrated for a subsystem of a nuclear fuel recycling plant the concept of the success diagram, the manner in which threats to successful operation are treated, the structuring of scenarios that could lead to different damage states, and some features of the quantification of the scenarios. What remains is the actual numerical quantification of the scenarios and the assembly of the scenario results into total risk curves of the form of Figure 5. These are all straightforward applications of probability arithmetic, which are highlighted in Figures 1 to 3 and the associated discussions.

On the matter of interpreting the results to support the risk management of a chemical operation, one very good example of where this was actually done is the U.S. Army's risk assessment work to support their program to destroy chemical weapons (National Research Council, 2002). QRAs were developed in parallel with the design of chemical agent disposal systems to provide feedback on design specifications and planned operating procedures to assure that the level of risk was being appropriately managed. As noted in the National Research Council report, "The QRAs, and an understanding of their results, provide a framework for managing the risk …" These and other applications of QRA provide considerable evidence of the value of such comprehensive assessments.

Conclusion

The advances that have been made in the theory and practice of quantitative risk assessment set the stage for a new era of safety analysis of nuclear fuel recycling plants. The principles of QRA that have been developed and applied to other segments of the nuclear industry such as nuclear power plants and nuclear waste repositories equally apply to other segments of the nuclear fuel cycle. The result is not only a much more complete representation of the risk of such plants, but a detailed blueprint for managing that risk.

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