APPLICATION OF RISK ASSESSMENT TO NUCLEAR POWER PLANTS

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Summary

It is relatively simple to estimate failure likelihood and consequences for simple devices using straightforward analysis techniques. On the other hand, as the failure of a device becomes complicated by reliance on many simple, interrelated devices that require maintenance and failure repairs, the analysis is truly difficult with classic design methods. That is, it becomes impossible to state with certainty what the likelihood of failure would be for a complex design. This is especially true for high reliability designs.

Commercial nuclear power plants are complex devices designed with standards that employ redundancy and defense in depth to reduce the likelihood of an accident that would endanger the health and safety of the public to a very low probability. These design methods are clearly very good based upon the historic performance of commercial nuclear power plants designed with them. Even so, in order to make an informed

judgment about employing a particular technology for general or widespread use in society, the health and safety risk needs to be known so it can be weighed against alternatives.

In PRA, the probability of various sequences of events that have varying degrees of consequence to the health and safety of the public are calculated from knowledge of the design and the failure probabilities of various equipment that would mitigate an accident.

This is accomplished by developing sequences of events that begin with initiating events and go to a final state. Because the plant operation or maintenance may change over time, or because equipment failure probabilities are not well known when a plant is first started up, the PRA should be reviewed from time to time and the data used updated with any new information available from actual plant experience.

1. Risk

Because the potential amount of radioactive material that could be released from an operating commercial nuclear power plant could pose a serious public health threat, commercial nuclear power plants are designed using standards that require high safety equipment availability as well as defense-in-depth against adverse public health effects. These design standards could be referred to as "classical" in that they are based on deterministic methods.

The classical design method requires analysis of physically-based mechanisms related to release and transport of radioactive material from the plant in an upset condition. While it is clear from inspection of their design, commercial nuclear power plants would protect the public from radiation exposure, it is equally clear deterministic-based design standards used to build them can't tell us the extent of the protection they would afford, that is, what is the risk of operating the plants.

We become concerned with the idea of risk when we think of uncertainty in the outcome of some process. With a little imagination, one can see that uncertainty would apply to the outcome of literally any process of interest. Indeed for any process, we only become certain of the outcome following completion of the process. Risk as it is used in here is a way to pull together the uncertainty with the outcome of a process to quantify and gain understanding of the nature of the result.

This is accomplished by thinking through what basic elements or sub-processes are involved in successfully completing an overall process and then assigning a logical description to all the possible failures that would result in different outcomes (than the desired one). The probability distribution for each of the various failures is assigned and the logic solved. The result of this effort is the probability distribution for each of the outcomes we have posed as possible.

The method sketched out above is generally referred to as probabilistic risk assessment. The probabilistic approach is most powerful in the role of predicting the risk associated with complex processes and is especially valuable in the high reliability design because very little failure data at the top process level are available.

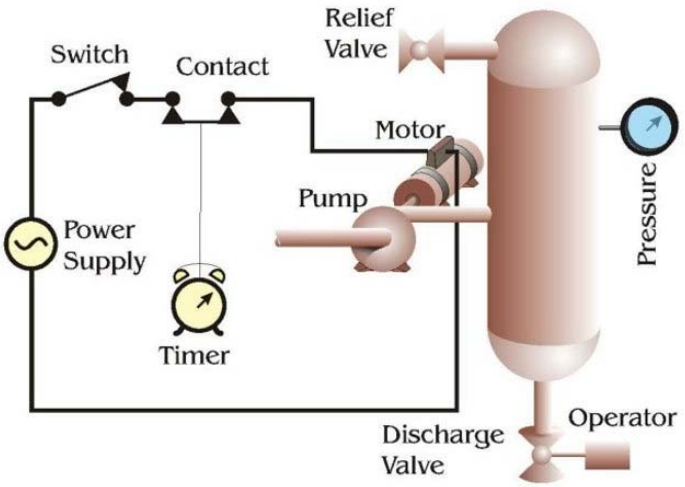

Figure 1. Schematic diagram of a system that could be the subject of PRA.

In the early 1970s, the United States Nuclear Regulatory Commission (USNRC) undertook the well-known WASI I-1400 study that would quantify health risk to the public of operating commercial nuclear power plant using probabilistic techniques. Instead of relying on classical, deterministic methods that assumed certainty in the progress of events, the probabilistic approach embraced uncertainty and randomness as basic properties of the commercial nuclear power electrical generation process. Since completion of that study, much more work has been completed both inside and outside the USNRC.

1.1. Purpose of PRA and an Example

Probabilistic risk assessment (PRA) is used to predict the (future) behavior of processes generally in terms of likelihood(s) and outcome(s). Predicting the risk associated with process operation is particularly interesting to the PRA investigator and requires the PRA to produce frequencies of outcomes.

As an example, consider the process shown in Figure 1 which could be the subject of PRA. The process is hypothesized to use a system that pumps gas from a reservoir into a tank. The tank is emptied from time to time by opening the discharge valve. The tank filling sequence is initiated when the operator manually resets the timer. After the timer runs out, power is interrupted to the pump and no more gas is pumped into the tank.

1.2. Analysis of the Tank Rupture

Tank rupture is assumed to cause personnel (operator) injury or death. To help understand this consequence, the tank can be analyzed from the point of view of energy. Say the tank is a cylinder with volume, V, defined by a height of 3 m and a diameter of 2 m. If the maximum pressure is to be 10 bar, then the stored energy in the tank after pressurization from atmospheric pressure (say 1 bar) could he calculated from thermodynamics. Assume the tank is pressurized isothermally (that is, the pump is equipped with a cooler that keeps the air at room temperature. Then:

$$V = \frac{\pi D^2}{4} L, \text{ or}$$

$$V = \frac{\pi 2^2}{4} 3, \text{ and}$$

$$V = 9.43 \text{ m}^3.$$

Take the ideal gas constant, R, to be for air:

$$R = \frac{8314.10^3 \text{Pa.m}^3}{28.97 \text{kg.K}}, \text{ and}$$

$$T = (273 + 25) \text{ K, so}$$

$$T = 298 \text{K}.$$

The mass of air stored in the tank can be approximately computed from the ideal gas equation:

$$m_1 = p_1 \frac{V}{RT}.$$

At atmospheric pressure (prior to turning on the pump) the air mass, m_1, would be:

$$m_1 = 10^5 \text{ Pa} \frac{9.43 \text{m}^3}{\left(287 \text{Pa.m}^3/\text{kg.K}\right) 298 \text{ K}}, \text{ or}$$

$$m_1 = 11 \text{kg}$$

After pumping to 10 bar (145 psia,) the new air mass, m_2 would be:

$$m_2 = 10.10^5 \text{ Pa} \frac{9.43 \text{ m}^3}{\left(287 \text{Pa.m}^3/\text{kg.K}\right) 298 \text{ K}},$$

$$m_2 = 110 \text{kg}.$$

Taking the internal energy, u, of air at low pressure and room temperature to be roughly 214.10^3 J/kg the stored energy, E, can be computed directly from the stored energy:

$$E = (m_2 - m_1) u \text{ and substituting,}$$

$$E = (110 \text{kg} - 11 \text{kg}) 214.10^3 \text{Jkg}^{-1}, \text{ or}$$

$$E = 2.1 \cdot 10^7 \text{ J}$$

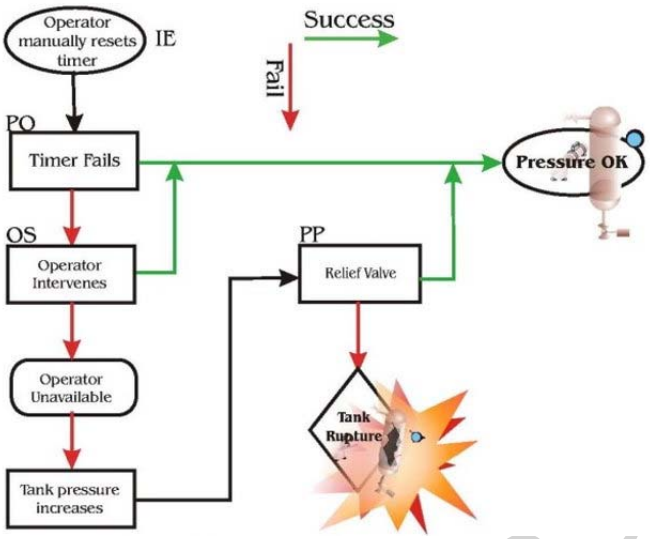

Figure 2. Event Sequence Diagram for tank rupture.

To put the tank energy potential in context, a 1361 kg (3000 lb) automobile going 194 kmh^{-1} (120 mph) would have roughly 2.10^6 J in kinetic energy. Therefore, it would appear based on this simple analysis that sufficient energy would be available to harm the operator.

An analysis that examines the total available energy or amount of hazardous material, for instance, along with possible release mechanisms can be used to form the basis for outcomes of interest to the investigator. For instance, ways that the curie content of a commercial nuclear reactor could be released to the environment would be of interest to the investigator of commercial nuclear power plant risk.

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Biographical Sketch

Ernest J. Kee is a Senior Consulting Engineer in the STPNOC Risk and Reliability Analysis Group with over 20 years experience in performing technical analyses for commercial nuclear power plants. His experience includes thermo-hydraulic analysis, nuclear fuel analysis, PRA, reliability analysis, and computer software development support for the STPEGS and other facilities. He is serving or has served in key industry positions related to nuclear power plant risk and reliability management. Mr. Kee holds a Bachelor of Science degree in Mechanical Engineering from the University of Idaho.