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ACHIEVING SAFETY/RISK GOALS FOR LESS ATR BACKUP POWER UPGRADES

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ABSTRACT

The Advanced Test Reactor probabilistic risk assessment for internal fire and flood events defined a relatively high risk for a total loss of electric power possibly leading to core damage. Backup power sources were disabled due to fire and flooding in the diesel generator area with propagation of the flooding to a common switchgear room. The ATR risk assessment was employed to define options for relocation of backup power system components to achieve needed risk reduction while minimizing costs. The risk evaluations were performed using sensitivity studies and importance measures. The risk-based evaluations of relocation options for backup power systems saved over $ 3 million from what might have been otherwise considered "necessary" for safety/risk improvement. The ATR experience shows that the advantages of a good risk assessment are to define risk significance, risk specifics, and risk solutions which enable risk goals to be achieved at the lowest cost.

INTRODUCTION

The Advanced Test Reactor (ATR) is a Department of Energy reactor materials irradiation testing and isotope generation facility located at the Idaho National Engineering Laboratory in Idaho. It is still, 27 years after initial operation, the most powerful and advanced materials irradiation reactor in the world. Some fuel and system heat removal characteristics of the ATR are listed in Table 1. The ATR has a unique core design (seen in Figure 1) which produces high neutron fluxes in nine in-core flux traps using only 40 fuel assemblies arranged in a serpentine ribbon around the flux traps.

The core fuel design of the ATR, with thin plates, high thermal conductivity, and small heat capacity, results in a rapid decrease in thermal power and heat removal needs by a rapid shutdown (reactor scram) in response to heat removal upsets. Water cooling is still required for a long period of time, however, to remove the significant decay power. Large primary pumps powered from the off-site power loop provide forced circulation during reactor operation. Forced circulation for decay power removal is usually by one of the two low flow capacity emergency flow pumps. One emergency flow pump is powered from a swing bus normally supplied from a running diesel generator but which will automatically transfer to off-site power on a loss of the diesel generator power. The other emergency flow pump is powered by a dc motor supplied from a battery backed uninterruptible power system. The design of the heat removal loop, or primary coolant system, does not support natural circulation through the loop and heat exchangers. However, if forced circulation is not continued, the core fuel has been shown to be capable of being successfully cooled by natural circulation within the large reactor vessel with up flow through the fuel channels and down flow through core flow bypass paths. This mode of decay heat removal has been demonstrated by pre-startup in-core thermal hydraulic tests for the ATR. Without eventual restoration of forced

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until coolant inventory is discharged out the vessel relief valves. Sufficient coolant loss to lead to a core uncovery, fuel failure, and release of radionuclides can eventually occur if forced circulation is not restored or low pressure emergency coolant makeup added, within 10 to 72 hours depending on the operating conditions and the specifics of the event scenario.

The ATR electric power support systems are listed in Table 2. Backup power is primarily provided at ATR by a running diesel generator powering those loads considered important for plant and experiment operations and for plant recovery following a loss of off-site power. The running diesel generator is backed by a fast-auto start diesel generator. Safety and reactor instrument and control systems, including the dc emergency flow pump, are powered from two separate battery backed power systems. However, emergency coolant makeup can be provided, if a total loss of power and forced circulation occurs, without any electrical power by gravity flow from an overhead tank and then by one of two diesel engine-driven fire pumps. The reactor vessel would need to be depressurized to allow injection of the low pressure emergency coolant makeup; but the redundant vessel vent or depressurization valves are powered from two of the four Plant Protection System (PPS) battery backed power systems.

ATR POWER SYSTEMS COMMON CAUSE FAILURE VULNERABILITY

A comprehensive probabilistic risk assessment (PRA) has been performed for the ATR including external hazards and internal fire and flooding events (Atkinson et al., 1993). A recent addition to the PRA was completed for shutdown operation. The PRA was a key element of a major seven year ATR safety upgrade program completed in September, 1994. Two of the significant goals of the ATR PRA program are:

- To incorporate an aggressive and comprehensive risk reduction effort for identified, significant vulnerabilities or weaknesses, and
- To provide comprehensive risk management application of the PRA for improved facility operations and safety.

A potential common cause failure vulnerability for a complete loss of most power sources was recognized early in the studies for the ATR safety upgrades due to the location of all the power source switchgear and panels, except for the newer PPS system, in a common switchgear room. Main piping for auxiliary and fire water systems also passed through this room possibly providing a major flooding source.

In response to the perceived vulnerability, a conceptual design effort was started to define project scope and costs for complete separation of three major power subsystems, off-site power, diesel generator power, and the Utility Battery Backed Power System (UBBPS). The conceptual design proposal was to relocate the diesel generator power switchgear and panels and the UBBPS to separate buildings adjacent to the ATR. Projected costs of this proposal were $ 2.5 million for the diesel generator power switchgear and panels relocation and $ 1.5 million for the UBBPS relocation. The difference in estimated costs for the two relocation projects was largely due to extensive labor costs to re-route the many diesel generator power system conduits and cables.

ATR INTERNAL FIRE AND FLOODING RISK ASSESSMENT

A rigorous and comprehensive internal fire and flooding risk assessment was performed for the ATR PRA (Thatcher and Eide, 1991). All areas of the plant were evaluated for fire and flood potential with an initial screening analysis (Thatcher et al., 1994) using a location transformation or vital area analysis methodology (Stack and Hill, 1984) to define the most vulnerable areas for their possible affect on the risk for core fuel damage. The screening analysis assumed all components in a room were failed by the fire or flood event and applied screening probabilities for fire or flood initiating event frequency, propagation probabilities (to other areas through barriers or flood propagation paths), and human errors. The components and piping and conduits in each location were identified. The system fault tree models were modified to include location-dependent common-cause fire or flooding failure modes for the components. When a component could be failed by failure of a cable or conduit in another area, then that location was included in the location-dependent failures for the component. Location-specific human errors or operator recovery errors were also defined based on ability to enter an area and carry out the recovery action. A human error probability of one was used for the screening analysis in fire or flood affected areas. The marginally trained local emergency brigade was not credited for being able to mitigate a fire, so arrival of the site fire department would be required if the fire suppression system failed to limit the fire.

Those areas that were risk-significant following the screening analysis were then evaluated in more detail. The risk-significant areas were broken down into specific locations or zones over which a local fire or flood event would be expected to affect all components within the zone. Fire risk analyses considered whether transient

TABLE 1. SOME CHARACTERISTICS OF THE ADVANCED TEST REACTOR

Reactor

- Light water moderated and cooled thermal fission reactor

Reactor Fuel

- 40 thin plate type fuel assemblies
- High enriched fuel, high flux density
- Uranium-aluminum fuel core matrix
- Aluminum cladding and structural elements

Coolant heat removal system

- Moderately pressurized (< 2.7 MPa)
- Highly subcooled (> 125 K)
- High flow forced circulation through core and heat exchangers
- Decay heat removal by 1 of 2 redundant low flow capacity emergency flow pumps on two separate backup power systems (one is battery backed)
- No natural circulation capability through the primary heat transfer loop
- Core fuel decay heat adequately removed by natural circulation within the reactor vessel and with low pressure feed and bleed (system depressurization required)

TABLE 2. ADVANCED TEST REACTOR ELECTRICAL POWER SYSTEMS

- **Commercial or Off-Site power for normal operations support**

- **Diesel generator power system**

  Provides power to loads important to reactor and experiment operation, especially for operation during and recovery from a loss of off-site power. The system consists of:

  Two primary (slow speed, high reliability) diesel generators
  - One operating and supplying the loaded system
  - One normally on standby

  One Auto-quick start backup diesel generator

- **Utility Battery Backed Power System**

  Provides safety related loads with uninterruptible power including the safety/risk significant dc motor driven emergency flow pump

- **Instrument Battery Backed Power System**

  Provides uninterruptible power to reactor instruments and control systems

- **Plant Protection System Battery Backed Power System**

  Provides separate uninterruptible power to the redundant plant protection systems and safety functions such as the Vessel Vent System.

combustibles were present and the effect of fire suppression system actuation by including parameters in the fault trees for fire severity (large fire probability) and suppression effectiveness (by a non-suppression probability). The beneficial effect of fire suppression system actuation was limited to restraining the area of the fire; failure of all components within the local zone was assumed (a non-suppression probability of one). Failure of other components in a larger area due to actuation of fire sprinklers was also considered. Flood propagation and smoke propagation was considered through doors, stairwells, ventilation systems and other specific identified paths. Operator recovery errors were evaluated based on the specific scenarios considering ability to enter the area, to perform the recovery action, and stress.

The internal fire and flooding risk assessment identified the common-cause location-dependent failures and the resulting minimum cut sets including the additional unrelated or independent failures needed for the sequence to result in fuel damage (usually a failure to depressurize the vessel for injection of low pressure emergency coolant makeup). This comprehensive analysis provided the means for a realistic assessment of the vulnerability of the reactor to internal fire and flooding events. The analysis also defined the significance of the events in relation to the overall risk, identified the specific scenarios, event sequences, and failures of concern, and provided the information and tools needed to define the most effective and cost-beneficial solutions to any defined risk problem.

The results of the internal fire and flood risk assessment validated the concern over potential common cause failure of important power sources in the common switchgear room; fuel damage event sequences were identified which had a relatively large frequency estimate for a complete loss of ac and UBBPS power, a long term complete loss of forced circulation, and an eventual core uncovery when emergency response to this type of event by feed and bleed heat removal and coolant inventory makeup failed to be implemented or effective. (The mean frequency, 7×10^{-4}/yr, did not suggest an immediate hazard but one large enough to make the ATR risk for fuel damage a high outlier for nuclear reactors and to indicate that the risk for a severe accident was not acceptable over the long term.)

The risk assessment also revealed some surprises concerning the specifics of the risk. The flooding hazard from the piping in the switchgear room was inconsequential because of the presence of a large ventilation floor grate leading directly into a basement area below and because of the small probability for low pressure piping ruptures. The fire risks were primarily local because of the fire suppression system and the cleanliness commonly practiced at ATR (transient combustibles are seldom found to be present).

The significant risk was not due to an event originating in the switchgear room but in the diesel generator area above the switchgear room (see Figure 2). The dominating event sequence was initiated by a large diesel engine fire, which has a significant probability, associated with one of the two primary diesel generators (the auto-quick start backup diesel generator is in a separate building). The diesel fire frequency, as were all fire frequencies used in the analysis, was based on a commercial nuclear data base (Bohn and Lambright, 1989). The large diesel fire event could be expected to activate all of the overhead fire sprinklers in this large area as hot gases spread along the ceiling resulting in a significant release of water to the area. This water from the sprinklers would quickly flood the pit in which the diesel generators sit. The conduits from the generators pass straight through the floor to the diesel generator power switchgear in the switchgear room below. Previous small diesel pit flooding events had shown that water could propagate via the generator conduit to the diesel generator power switchgear causing some wetting of the switchgear (but no switchgear failure was experienced). Therefore, if the water propagation were severe enough, all diesel generator power could be lost making the backup diesel generator ineffective.

The UBBPS also was located below the diesel pit and oil had been known to leak through floor cracks on top of the UBBPS panels. Although the floor cracks had been sealed by application of a coating on the diesel pit floor, the effectiveness of the sealant during a fire was unknown. Another possible water propagation path to the UBBPS panels was identified from cable and conduit penetrations in the diesel pit to cable trays to the UBBPS panels. Only one of the two emergency flow pumps is powered by the UBBPS; the other is normally provided power from the running diesel generator with an automatic transfer to off-site power. But, because of some other system dependencies, both emergency flow pumps are assumed lost for this scenario.

The internal fire analysis therefore determined that the one initiating event, a large diesel engine fire, could fail, with some significant probability, the important backup power systems for decay power removal and the redundant systems for depressurizing the primary coolant system to enable emergency coolant makeup and feed and bleed cooling. Subsequent failure of off-site power, or primary pump failure or shutdown in response to the pressure decay that will occur in the ATR with loss of diesel generator power to the pressurizing system pumps, or primary pump motor failures due to a partial loss of forced air cooling or due to humidity or smoke propagation or other causes will result in a complete loss of forced circulation. Because of the multiple failure possibilities for the primary pumps, primary pump shutdown was assumed to occur. Operators, if unable to restore primary pump operation, will be required to depressurize to allow injection of low pressure emergency coolant makeup. Failure to accomplish this emergency makeup and feed and bleed cooling could eventually (over many hours) result in core uncovery.

Other sequences were also defined, but the diesel pit fire and flood sequences completely dominated the results of the risk assessment for core fuel damage frequency.

APPLICATION OF THE RISK ASSESSMENT FOR RISK MANAGEMENT

The ATR PRA not only identified the significance of the risk and the specific dominant event scenarios with their associated cut sets and significant contributing component failures and human errors, but it also provided the information and tools needed to define the most effective and cost-beneficial solutions to the identified risks. The significance of the dominant diesel pit fire and flooding sequences were immediately recognized. Therefore, sensitivity analyses were performed using the PRA models for different assumed fixes and upgrades involving different combinations of components and subsystems. But, the sensitivity analyses also evaluated the affect of a failure or a parameter being worse than assumed (more likely to fail). The sensitivity analyses were performed by setting the fixed components or other parameters to an unfailed state (an unavailability of zero) and to a failed state (unavailability of one). This included water propagation probabilities and fire severity factors that had been included in the fault trees and human errors. Component and failure importance measures were also useful for evaluating a single component or failure, but sensitivity analyses were necessary to evaluate the effect of combinations of fixes or of a difference in assumptions. The sensitivity cases analyzed were:

(1) Increased and decreased human error probabilities (recovery errors) by a factor of ten for the important errors.

(2) Assumed no water propagation from the diesel pit (conduit and cable seals fixed, floor cracks fixed or UBBPS relocated).

(3) The battery backed power for the vessel vent (depressurization) system will not fail due to fire, smoke, or water propagation sequences.

(4) Cases 2 and 3 combined.

(5) Non-suppression probability reduced from the failed state (1.0) used in the base analysis to 0.9 (allowing a probability of 0.1 for local suppression before failure).

(6) A small diesel pit fire (less severe but higher probability) fails all three diesel generators but without diesel pit flooding or water propagation to the switchgear room.

(7) Same as case 6 except the quick-auto start diesel generator (in a separate building) is not failed.

Cases 5, 6 and 7 help determine the risk benefit of improved fire suppression and containment in the diesel pit.

The following conclusions were obtained from the evaluation for facility fixes and options for backup power system upgrades using the PRA sensitivity analyses and component importances:

(1) Immediate significant risk reduction could be obtained at very little cost by simply upgrading the cable and conduit seals in the diesel pit and opening up the small diesel pit drains. (The diesel pit drains had been closed to prevent oil contaminated water from being discharged to the waste water system which did not have a capability for cleaning up the diesel oil contamination.) This action included redirecting the drains to a tank (or several smaller tanks for an interim but immediate fix) for collecting the waste water for later treatment. This upgrade eliminated the risk for the small to moderate diesel pit flooding events. However, for large floods or fire with diesel pit flooding, the integrity of the seals could not be assured, and the drains would not be adequate.

(2) Since the existing diesel pit drains could not handle a large diesel pit flood event or a large fire with flood event, an upgrade to add a large capacity drain to an existing exterior concrete vault was proposed.

(3) The largest, most effective risk reduction would be achieved by relocating the UBBPS. Since risk-significant upgrades were also identified as needed for the UBBPS for seismic events and the system needed replacement of some obsolete components, then several safety, risk, and operational improvement objectives could be satisfied by the relocation. The evaluation also determined that if the UBBPS were relocated, then relocating the diesel generator switchgear would have no additional risk benefit. Therefore, the proposed $ 2.5 million diesel generator power switchgear and panels relocation could be eliminated.

(4) Upgrade of the fire suppression system in the diesel pit area by itself or in conjunction with other upgrades was not risk-significant. Relocation of the UBBPS would still be needed; but with UBBPS relocation the high potential cost of a fire suppression upgrade in the diesel pit would not be justifiable on only a risk basis. (This evaluation does not address operational concerns or property loss risk, but only the risk to workers and the public due to a radiological release from the reactor fuel.)

The critical risk-reduction need was therefore defined to be the relocation of the UBBPS. the risk reduction benefit of this action along with the upgrade of the diesel pit seals and the opening of the drains was very significant. It was the single most effective risk reduction upgrade action for the ATR risk assessment, reducing the mean estimated fuel damage frequency by 70 percent (see Figure 3.)

The PRA results and models were again used for the UBBPS relocation design effort to define the needed extent of the UBBPS relocation. The conceptual proposal was for relocation of the entire system to a new building adjacent to the ATR. Although this would provide maximum separation, it then subjected the UBBPS to potential new hazards associated with earthquakes, high winds, and other external events and would be the most expensive option. The questions regarding possible options for the relocation that were evaluated for the UBBPS were:

- Whether partial relocation would be acceptable, especially concerning the battery bank and battery room. The evaluation determined that the batteries in the adequately closed and sealed battery room in the switchgear area did not have to be relocated. This was potentially a large cost item.
- Which locations for the relocation within the ATR would be acceptable or preferred, and does the relocation have to be out of the switchgear room, which is spacious, or just away from the diesel pit? The evaluation determined that relocation within the switchgear room but away from the diesel pit or other power switchgear would be equally acceptable to other locations in the ATR. Also, relocation within ATR was equally acceptable to relocation outside ATR. Since the ATR provides a firm seismic foundation and protection from external hazards for the UBBPS, relocation within ATR could be preferred considering that a risk assessment including external hazards was not performed for the exterior building option.

Once a preferred location for the relocated UBBPS was established, based on obtaining complete separation from other power systems and upon operational preferences, the fire and flooding sequences were again evaluated for fuel damage risk before final design. The preferred location was determined to be acceptable although it did have some small additional flooding risk above a relocation elsewhere within the switchgear area (because of the effectiveness of the large switchgear room floor ventilation grate for preventing immersion type flooding). The PRA was also used to provide some input for the final design for:

- Pedestal height for protection from the more-probable flood sources.
- Power cable routing for the risk-significant dc emergency flow pump motor to eliminate some significant risk sequences for internal fires at locations where the power cables for both emergency flow pumps were in close proximity.
- The risk acceptability or significance for a new transfer switch proposed by operations to enable use of the UBBPS as a backup power source for control rods.
- To provide some risk bases for determining if the relocated UBBPS had to be upgraded to IEEE-1E components or if current components or components replaced-in-kind with standard industrial components could be shown to provide sufficient reliability based on the risk assessment, data sources, and experience.

The need for the proposed large capacity diesel pit drain was also evaluated for risk significance with the completion of the other upgrades for the diesel pit fire and flood events. the evaluation determined that adding the large capacity drain resulted in an insignificant incremental reduction in fuel damage frequency. Therefore, the proposed large capacity diesel pit drain could be eliminated from a risk-benefit perspective.

The final UBBPS relocation project, now complete including seismic upgrades and component upgrades and the new transfer switch, cost $ 650,000 as compared to the $ 1.5 million (or more) estimate for the conceptual proposal based only on perceived needs without any risk basis. This total backup power systems upgrade savings, over $ 3.3 million in proposed upgrades, was achieved while still obtaining a low estimated risk for severe fuel damage accidents.

The ATR PRA continues to be utilized for evaluation of backup power systems for evaluation of the risk significance of occurrences, operational changes (such as backup power options during an extended outage of a primary diesel generator for overhaul) and operational upgrades. The most recent evaluation is for a change in the diesel generator power system to provide uninterruptible power to the most important loads by use of one or more uninterruptible (battery backed) power systems until a standby diesel generator comes on line following a loss of off-site power. This change would eliminate the current uncommon practice of continually running a diesel generator. This latest upgrade can result in significant savings, paying for itself in three to four years. The PRA diesel generator power system fault trees had to be modified for this evaluation because of the significant changes being proposed in both system design and components. The PRA evaluation defined the risk significance of the proposed upgrade and also identified any needed enhancements to the proposal to maintain the current low risk for severe fuel damage accidents at ATR.

CONCLUSIONS AND INSIGHTS

The experience at ATR in the development and application of a comprehensive probabilistic risk assessment shows that a good probabilistic risk assessment is very beneficial for reasonable and cost-beneficial risk management. The advantages of a good risk assessment for risk management are to define risk significance, the important risk specifics, and the most effective risk solutions for identified risk vulnerabilities or weaknesses or in response to occurrences, failures, or operational changes, and for proposed system upgrades. More specifically, the risk assessment is best applied to define:

(1) Risk Significance: To define the truly significant risk vulnerabilities instead of those perceived risks that are based on gut-feel speculation or worse-case what-if scenarios.

(2) Risk Specifics: Define the specific initiating events, event scenarios and sequences, cut sets, systems, components, and other failures or parameters that are the cause of the significant, dominant risks. Then, these specifics of the risk can the focus of additional evaluation and to determine if further action is warranted.

(3) Risk Solutions: Knowing the risk significance and the risk specifics, then the most effective, applicable, and cost-beneficial solutions for the risks of concern can be evaluated and defined, or the risk can be defended as acceptable on a cost-benefit basis.

ATR experience has also shown when utilizing a PRA for risk management, especially to evaluate and develop solutions or upgrade options to reduce risk to acceptable levels, or to maintain a desired risk level, that it is important to:

(1) Be sure that the risk assessment, its event and fault tree modeling and results, provide the capability for sensitivity analyses and use of importance measures by being sure that common cause failure modes are included, even if they are believed to have a low probability.

(2) Define the quick and easy fixes first; those that can have a significant risk affect at little cost. These are usually things that make inherent safety design sense, like adequate floor mounting of power panels to prevent tipping during an earthquake.

(3) Explore the options using sensitivity analyses to include changes or upgrades to several components or parameters simultaneously. Ask if upgrades really need to be all or nothing. Look for the fixes and upgrades that make the most impact, those that provide the most bang for the buck. Look to see if other proposed changes or upgrades are eliminated if the most effective change is made. Also consider if some changes or upgrades are able to accomplish several risk reduction actions or accomplish other desirable objectives (such as a future replacement of an aging component).

(4) Don't do more than is necessary. If an upgrade has no risk importance, then eliminate it from the recommendations for risk-based changes or upgrades. Also, do not make the risk assessment more detailed than necessary for the identification and evaluation of the risk important sequences, cut sets, systems, components, and other parameters (such as human errors and event progression parameters).

(5) Take advantage of the risk assessment to establish risk-bases for design solutions to sell the most effective and cost beneficial solutions to those who may perceive them as being less than required.

(6) Be able to address the effect of uncertainties in the analysis by including in the sensitivity analyses evaluation of the affect of worse failure probabilities, event progression, human errors, etc. Then the sensitivity analyses can identify any significant sensitivities to a worse-than-expected failure probability or facility condition which should be addressed for risk management.

The ATR probabilistic risk assessment and its applications for evaluating upgrades and design options has saved over $ 3.3 million in possible backup power system upgrades that would not have been risk significant.

This savings is approximately equal to the cost of the ATR Level 1 (for fuel damage sequences) PRA with external events analyses (including internal fire and flood events). But, more importantly, the utilization of the risk assessment has enabled the ATR to achieve a low relative risk exposure for severe accidents, with very great potential political and social consequences, and then provided the capability to manage this risk with respect to system problems, changes, and proposed upgrades for the benefit of the continuing mission of the facility, the Department of Energy, and the citizens of the United States.

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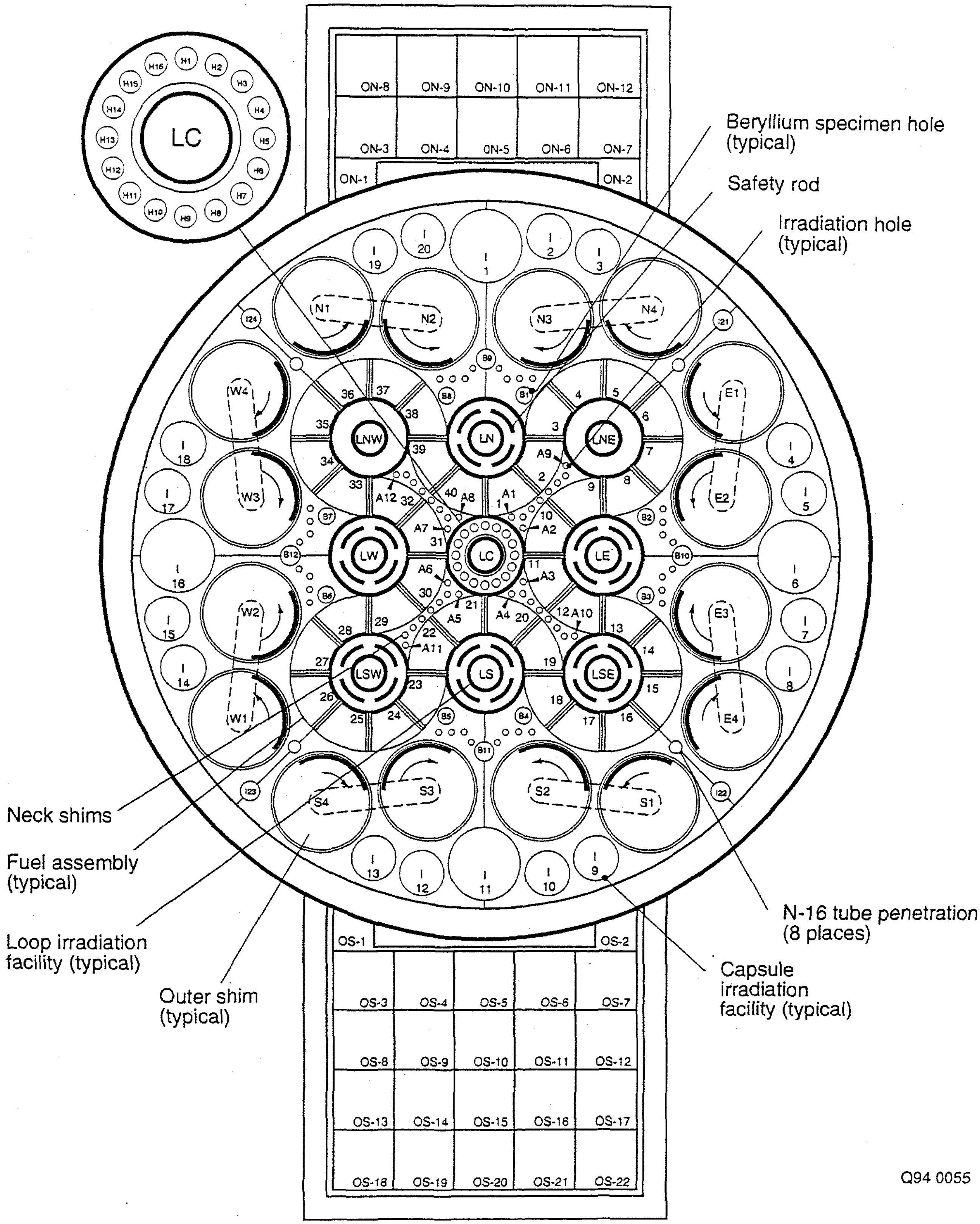

FIGURE 1. HORIZONTAL CROSS SECTION OF ATR CORE

Diesel Pit Flood Propagation Paths

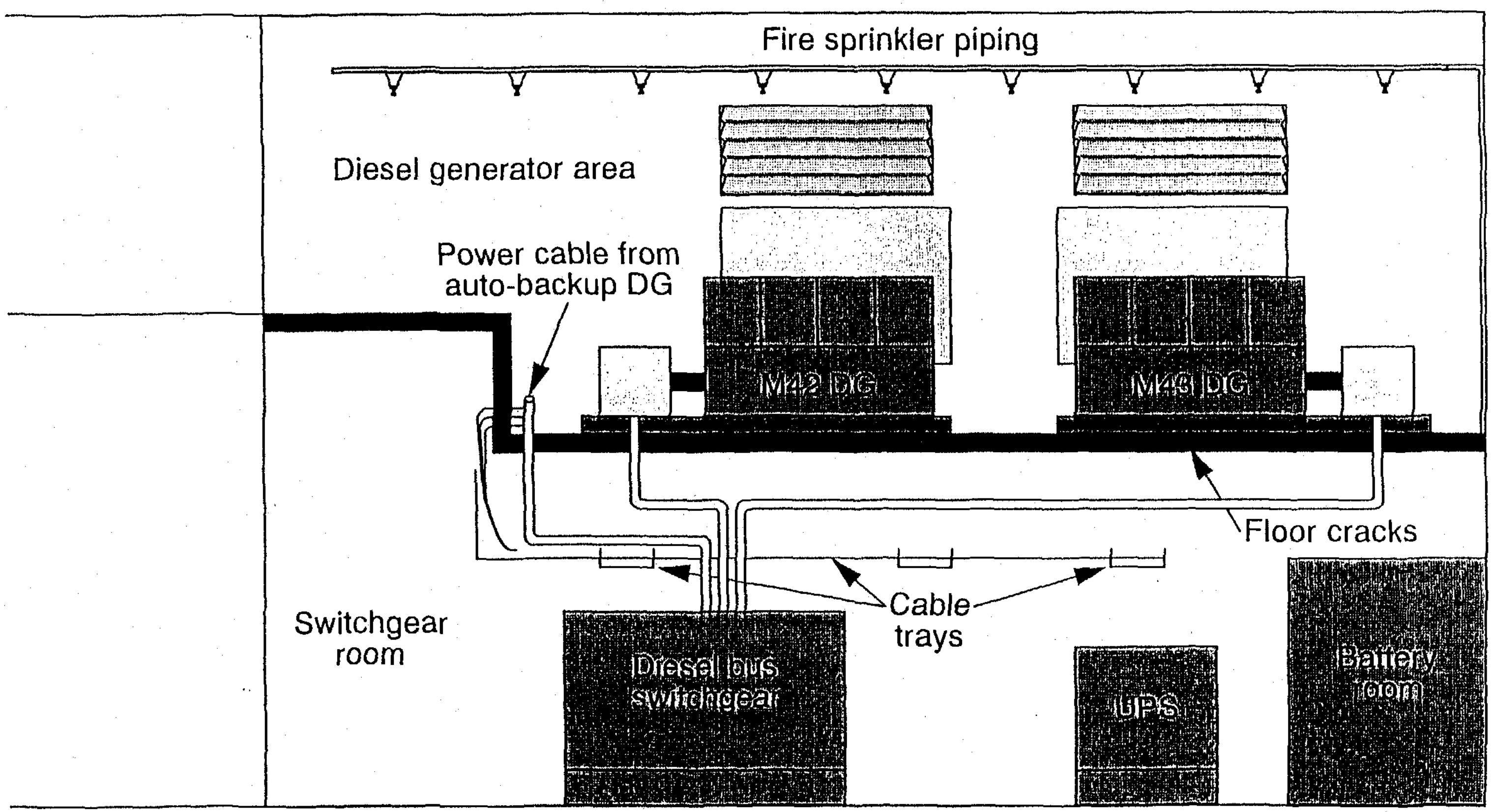

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FIGURE 2. DIESEL PIT FLOOD PROPAGATION PATHS

ATR Risk-Significant Upgrades

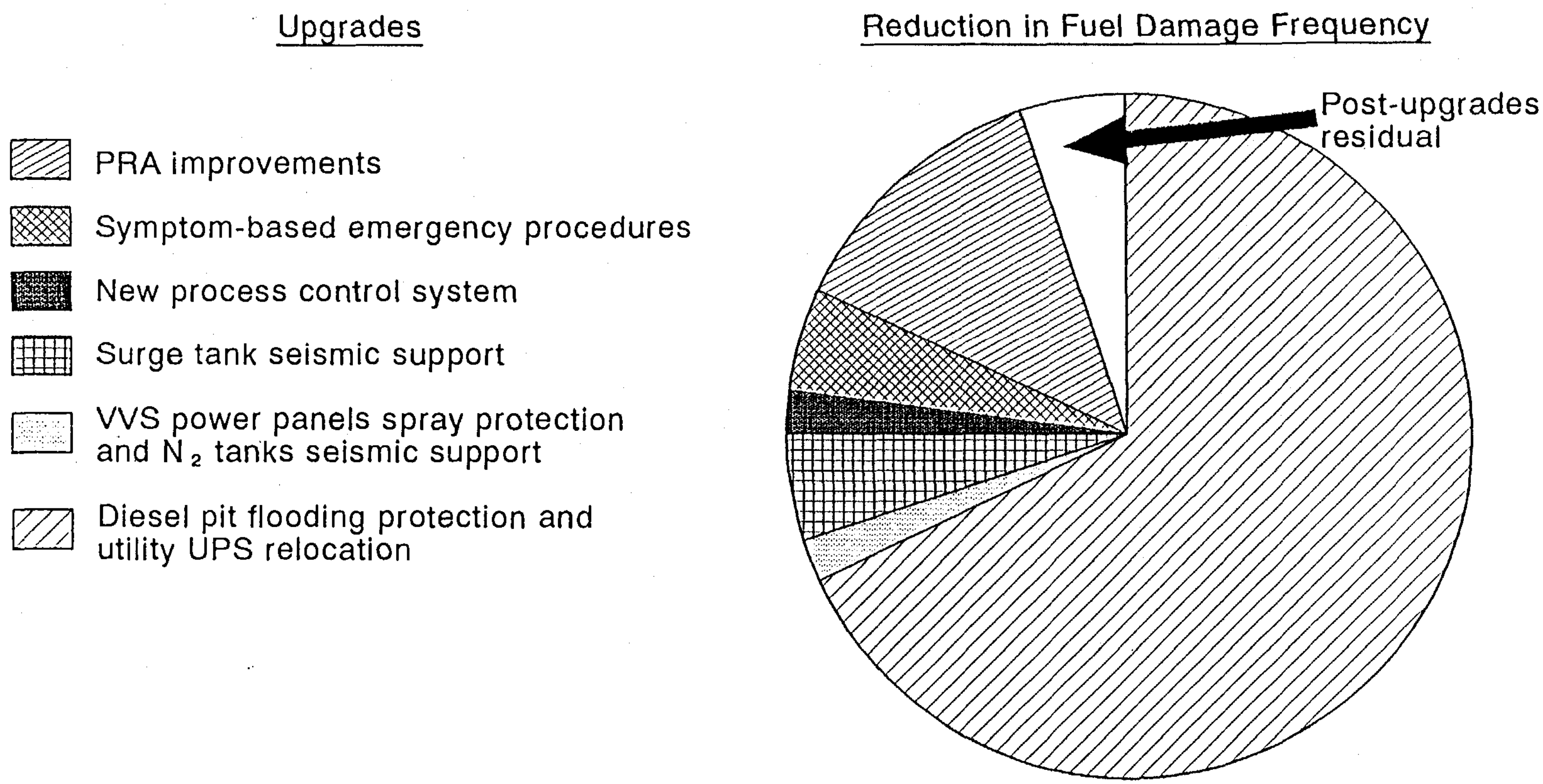

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FIGURE 3. SIGNIFICANCE OF ATR RISK REDUCTION UPGRADES