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METHODOLOGY USED IN THE INTEGRATED ASSESSMENT OF PIUS-600 SAFETY*

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ABSTRACT

The revolutionary reactor design, PIUS-600 as described in the Preliminary Safety Analysis Report (PSID)[1] was subjected to analyses consisting of Failure Modes, Effects and Criticality Analysis (FMECA), Hazards and Operability (HAZOP) analysis, and conventional engineering review of the stress, neutronics, thermal hydraulics, and corrosion. These results were integrated in the PIUS Intermediate Table (PIT) from which accident initiators and mitigators were identified and categorized into seven estimated frequency intervals. Accident consequences were classified as: CC-1, minor radiological release, CC-2, clad release, CC-3, major release. The systems were analyzed using event sequence diagrams (ESDs) and event trees (ETs). The resulting accident sequences of the ET, were categorized into Event conditions (ECs) based on initiator frequency and combinations of failures. System interactions were considered in the FMECAs, ESDs, ETs and in an interaction table that also identified system safety classifications.

INTRODUCTION

Advanced reactors proposed for generating electric power in the next century are classed as: "evolutionary," meaning that they are improvements on the present generation of light water reactors (LWRs) or "revolutionary" indicating the use of principles for which there is little experience and regulatory precedence. The revolutionary PIUS (Process Inherent Ultimate Safety) reactor, conceived by K. Hannerz,[2] is the subject of this investigation. PIUS-600 is a 600 MWe pressurized water reactor with no control rods, and no active ECCS. It uses a prestressed concrete reactor vessel (PCRV) and is designed to operate in a pressure suppression containment with the primary circulation provided by "wet" motor variable-speed pumps.

PIUS OPERATING PRINCIPLES

The PIUS reactor has a primary loop consisting of a flow assembly, containing the reactor, which is connected by pipes to four steam generators cooled by four variable speed pumps (only one loop shown in Figure 1). The flow structure is immersed in a large (10^6 gal.), highly borated-water reactor pool. The reactor vessel is a pre-stressed concrete vessel (PCRV) capped by a steam dome which is removed to gain access to the core for refueling. The slightly borated primary water rises into the pressure dome to an interface with steam in the top of the dome. An external steam generator controls the reactor pressure (9.0 MPa). The nuclear reactivity is controlled by the boron concentration in the primary loop that is regulated by an external chemical volume control system.

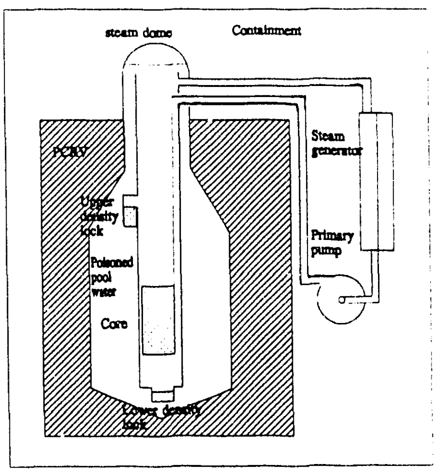

Figure 1. Sketch of the PIUS Principle

No mechanical barrier prevents entry of the highly borated pool water into the primary loop through the density locks. Such entry is prevented by balancing the natural convective flow through the core with the primary pump flow. If the convective flow and the pump flow do not balance such as

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would result from an upset condition, the pool flow is activated. This highly borated water reduces the reactivity which further imbalances the flow which increases the loop flow. This is the passive scram reactor shutdown mode. Three types of scram were identified: active, manual and passive, but both the active and manual methods cause a scram by tripping power to a dedicated pump to unbalance the flows and cause the passive scram. Once the pool loop is activated, the natural circulation loop is through the lower density lock, the core, the upper density lock, the pool, and back to the lower density lock. This loop continues to circulate and transfer the core residual heat to the pool water. The pool water is cooled by redundant active and passive cooling systems.

APPROACH

Two detailed and complementary methods, Failure Modes Effects and Criticality Analysis (FMECA)[3] and Hazards and Operability analysis (HAZOP), were chosen for the safety analysis. The former is conventional to the nuclear power industry, being recommended by IEEE-Std-352; the latter method is used primarily by the chemical industry. These systems analysis methods were supplemented by more conventional engineering methods that calculate the neutronics, thermal hydraulics, stress, and analyze corrosion and chemical effects. The three information streams merge in the PIUS Intermediate Table (PIT, see Figure 2) from which accident initiators and mitigators were identified for the event tree systems analysis.

FMECA

FMECA is a tabular investigation of the effects of failure of critical system components on the system and plant with regard to availability and safety. FMECAs are conducted by one or more individuals with a thorough knowledge of the systems, system interactions, components, and types of failures. A systematic plant taxonomy showing the tree-like structure with name and numerical designations is constructed to approach completeness. (A decimal-type numbering system that relates components to systems was effectively used.) Components believed to be critical are selected from the taxonomy and individually analyzed with regard to failure mode, failure cause, effects on their system and on the plant. They were ranked according to their judged criticality, an estimate of the frequency of failure, was provided along with mitigating effects, and analyst's remarks (Figure 3). The FMECAs are peer-reviewed for incompleteness, errors, and misunderstanding. Prioritization results, using the criticality and frequency designations, may be used by management for accident avoidance and mitigation as well as for operational improvement, including test and maintenance enhancement.

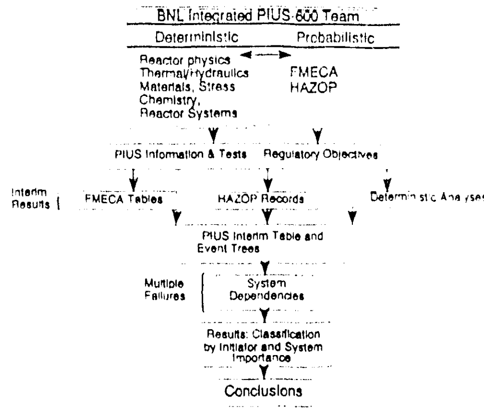

Figure 2. Plan of the Integrated Analysis of PIUS-600

HAZOP

HAZOP, primarily used by the chemical industry[4], is a formal technique for eliciting insights about system behavior from a multi-disciplinary team that, collectively, has thorough knowledge of the plant and the physical phenomena involved in the plant.

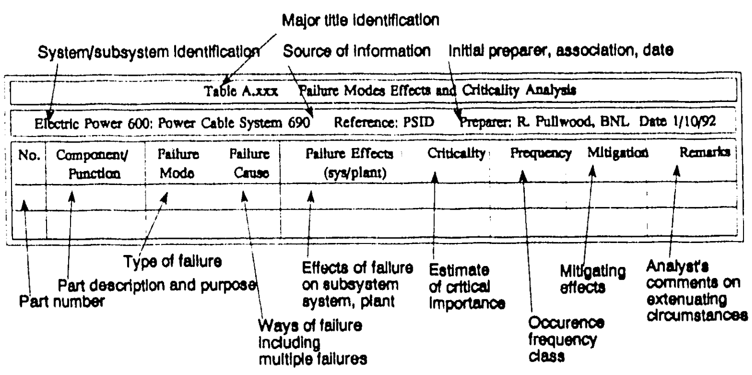

Figure 3. FMECA Form

The HAZOP team selects a system, applies guide words (a list of system stressors, e.g., over-pressure) to the selected system, and identifying causes, and consequences of the postulated event). Occasionally, an issue cannot be resolved immediately in which case a team member is required to investigate and report back to the team for final resolution. Figure 4 illustrates the HAZOP iterative process.

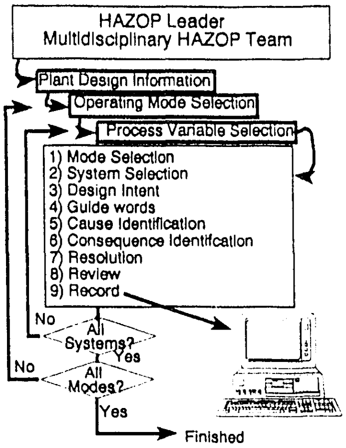

Figure 4. The HAZOP Iterative Process

COMPLETENESS AND MULTIPLE FAILURES

The taxonomy assures that FMECA is applied to all of the safety significant systems. Deterministic multiple failures are addressed directly in each FMECA item. A systems interaction matrix was prepared that shows the relationship between systems, supported systems and supporting systems with the safety classifications of each.

EVENT TREES

Initiators selected from the PIT are: Large Primary Pipe Break (LPPB), Small Primary Pipe Break (SPPB), Loss of Off-site Power (LOSP), Turbine Trip (TT), Steamline Break (SB), Feedwater Transients (FT), Computer Malfunction (CM), Severe Seismic (SS), Fuel element Drop (FED), and Flow Blockage during Refueling (FB). The mitigators (items along the top of the event tree) are: Active Scram (AS), Manual Scram (MS), Passive Scram (PS), Active Pool Cooling (APC), Passive Pool Cooling (PPC), Critical Heat Flux (CHF), Containment (C), Emergency Water Makeup (EWM - PIUS has provision for external makeup of the pool water).

Event trees were constructed for each initiator by describing the scenarios, and coding the possibilities in an event table on a word processor. The elements of these tables were converted to ASCII and imported into the BETA code that draws and evaluates the trees. In addition, event sequence diagrams were prepared and used to check the correctness of the event trees.

RESULTS EVALUATION

Each of the sequences was qualitatively analyzed to estimate the potential for core damage and for the release of radioactive materials using consequence categories (CC-1, 2 and 3). The event trees and accident sequences were then reanalyzed. Using the NRC Event Condition Methodology which was applied to the same event trees, thereby allowing the results from conventional analyses to be compared with the event condition methodology. Event condition (EC1) is termed an "Abnormal Operating Occurrence," EC2 is a "Design Basis Accident," EC3 is "Beyond Design Basis," and EC4 is "Residual Risk." Essentially, progression from EC1 to EC4 is in the direction of lower initiator frequency and more failures of mitigating equipment. In order to summarize the finding from the event tree analysis, sequences of various types were summed, importance calculations were performed, and results presented in ordered tables. The results are fully documented in Reference 7.

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