Paper submitted to PSAM-II, An International Conference Devoted to the Advancement of System-Based Methods for the Design and Operation of Technological Systems and Processes, March 20-24, 1994, San Diego, California.

THE EXPERIMENTAL BREEDER REACTOR II SEISMIC PROBABILISTIC RISK ASSESSMENT*

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*Work Supported by the U. S. Department of Energy, Nuclear Energy Programs, under Contract W-31-109-ENG-38.

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INTRODUCTION

The Experimental Breeder Reactor II (EBR-II) is a US Department of Energy (DOE) Category A research reactor located at Argonne National Laboratory (ANL)-West in Idaho. EBR-II is a 62.5 MW-thermal Liquid Metal Reactor (LMR) that started operation in 1964 and it is currently being used as a testbed in the Integral Fast Reactor (IFR) Program. ANL has completed a Level 1 Probabilistic Risk Assessment (PRA) for EBR-II. The Level 1 PRA for internal events and most external events was completed in June 1991 [1]. The seismic PRA for EBR-II has recently been completed.

The EBR-II reactor building contains the reactor, the primary system, and the decay heat removal systems. The reactor vessel, which contains the core, and the primary system, consisting of two primary pumps and an intermediate heat exchanger, are immersed in the sodium-filled primary tank, which is suspended by six hangers from a beam support structure. Three systems or functions in EBR-II were identified as the most significant from the standpoint of risk of seismic-induced fuel damage: (1) the reactor shutdown system, (2) the structural integrity of the passive decay heat removal systems, and (3) the integrity of major structures, like the primary tank containing the reactor that could threaten both the reactivity control and decay heat removal functions. As part of the seismic PRA, efforts were concentrated in studying these three functions or systems. The passive safety response of EBR-II reactor - both passive reactivity shutdown and passive decay heat removal, demonstrated in a series of tests in 1986 [2] - was explicitly accounted for in the seismic PRA as it had been included in the internal events assessment.

PLANT SEISMIC RESPONSE MODELING

Using the logic models developed for the internal events PRA, a seismic event tree was generated (Fig. 1). The event tree contains the relevant systems or structures that must perform their functions during a seismic event, namely, preservation of the structural integrity of the primary systems, the response of the shutdown system, and the continued availability of adequate core cooling.

Fault trees were therefore developed to model both system and structural failures. The fault trees contain both seismic and non-seismic failures of the individual components involved in the system, as well as possible human errors. The probabilities for the non-seismic failures and human errors were obtained from the internal events analysis. For the seismic-induced failures, walkdowns were conducted to identify component vulnerabilities. Based on the observations of the walkdowns and the knowledge gained from the internal events models, the components requiring detailed seismic capacity analysis were selected. Components of secondary importance were assigned screening fragility values, based on the methodology of the Seismic Margins program [3].

For the components selected for detailed analysis, a two-step process was followed, consisting of a deterministic analysis performed at ANL and a fragility estimation provided by R. Kennedy. Following the usual methodology, fragilities were expressed with three parameters: median fragility, randomness, and uncertainty, and the chosen ground motion parameter, in agreement with the hazard curves, was the peak ground acceleration (PGA).

SEISMIC ANALYSIS OF COMPONENTS AND STRUCTURES

Major Structures

The most important structure analyzed was the primary tank. The primary tank in EBR-II is suspended from a beam structure by six hangers resting on a set of rollers to allow for thermal expansion. The first failure mode analyzed was the possibility of displacing rollers from under the hangers, resulting in a drop of several inches of the primary tank. Inspection and analysis showed that sufficient clearance would not exist for the rollers to withdraw from their position. The next failure mode analyzed was the weak axis bending failure of the tank hangers. This failure was the limiting failure for the primary tank, with an estimated median fragility of 0.7g (Fig. 2).

Other structural failures studied included the fuel storage basket inside the primary tank, the reactor building, and the oscillation of the bottom core support plate. The storage basket and the reactor building were found to be rugged, and their estimated fragility well above that of the primary tank failure.

The vibration of the core support plate was analyzed for its effect on reactivity. A reactivity insertion would occur if the core moved with respect to the control rods, which are supported from the top of the primary tank. Although the reactivity insertion would be oscillatory, it was assumed that a net positive reactivity insertion would occur. Due to the EBR-II feedbacks, reactivity insertion events of less than 0.2 $ do not lead to fuel damage. The ground acceleration capable of inserting 0.2 $ was estimated at 0.4g.

Reactor Shutdown System

Protection against the effects of earthquakes has been built into the Reactor Shutdown system at EBR-II by inclusion of a set of three seismic detectors. These detectors are set at a nominal value of 0.005g, with the Technical Specification Limit of 0.01g. The failure of the detection system was included in the fault tree model, along with the mechanical failure to scram. Although the shutdown system includes two mechanically independent subsystems (control and safety rods), only the control rods were accounted for in estimating the scram reliability under seismic conditions, given the susceptibility of the safety rods to slight misalignments caused by seismic ground motions.

Nine control rods are driven from the top of the primary tank, with control rod drivelines that penetrate the primary tank and reach the core through guide tubes in the reactor vessel cover. The rod drive mechanism is located above the cover of the primary tank. A detailed structural model was developed to predict the scram times under different peak ground accelerations [4]. The control rods are driven by gravity but an air assist piston is also provided. Even when ignoring the downforce generated by the air pistons, the control rod scram times were not found to increase significantly with the ground acceleration. It was estimated that the High Confidence of Low Probability (HCLPF) to scram in approximately the Technical Specification limit of 0.45 sec was 0.4g.

Another mechanical failure that could impair the scram function is the failure of the reactor vessel cover. The reactor vessel cover is lifted during fuel transfer operations. During reactor operation, the cover is secured by three cover locks. Seismic conditions can induce the movement of the vessel cover or the failure of one of the locks. If the cover is not securely locked against the vessel, it can tilt and jam the control rod drives. The fragility estimate for the vessel cover tilting indicates a median value around 1.2g.

A key issue for the reliability of the shutdown system is the existence of the very sensitive seismic detection system and trip. Taking into consideration the delay between the seismic P-waves and the more damaging S-waves, the use of the low-setpoint seismic trip will ensure that the scram takes place under very moderate seismic conditions.

Primary Pumps System

Under seismic conditions, a loss of electrical power is expected, and therefore the EBR-II primary pumps will be deenergized. For protected (successful scram) sequences, operation of the primary pumps is not necessary to prevent fuel damage. The coastdown of the primary pumps is important to ensure a smooth transition to natural circulation. For unprotected (unsuccessful scram) sequences, a failure of the primary pump system results in a Loss of Flow (LOF) transient that leads to some degree of fuel damage, depending on the duration of the pump coastdown. The two primary pumps in EBR-II are driven by a motor-generator set coupled by a clutch.

The internal events PRA showed that unprotected double pump LOFs lead to different degrees of fuel damage depending on the nature of the pump trip. There are three possible pump coastdowns in EBR-II, depending on the type of trip, i.e., motor, clutch or generator trip. For protected sequences, none of the trips led to fuel damage. Under seismic conditions, however, the coastdowns become faster. This degradation occurs because the primary pumps have a hydrostatic bearing that is less stable when horizontal accelerations cause the shaft to impact against the journal. The shaft impacts accelerate the coastdown. The degradation of the hydrostatic bearing was modelled, and the altered coastdowns were analyzed for different ground motion levels. The results indicate that severe core damage (CD) would occur for unprotected LOF transients at all ground accelerations for clutch and generator trips, and above 0.5g for motor trips. For protected double pump LOF transients, possible experimental fuel damage (PED) would occur at accelerations above 0.8g for generator trips, while motor or clutch trips would not result in any fuel damage for ground accelerations up to 1.5g.

Although the remaining components in the primary pumps system were also modelled in the fault tree, the degradation of the hydrostatic bearing was the dominant event, since the coastdown time becomes a key parameter given that the double pump LOF is highly probable even at low accelerations because of loss of electrical power supplies.

Shutdown Cooling System

The two EBR-II shutdown coolers are passive systems. Liquid NaK naturally circulates through the shutdown cooling piping and to the shutdown cooler box located outside the reactor building. The shutdown cooler box is a natural draft air heat exchanger with chimney. When decay heat removal must be initiated, two dampers are required to open in the shutdown cooler box allowing air to be drawn over the heat exchanger and increasing the heat rejection. The dampers are fail-safe and easily opened manually and therefore readily recoverable. Total failure of the decay heat removal function leads to a gradual heat up of the primary tank that has been defined as core structural damage (CSD) in the internal events PRA [1].

The different structural components of the system were analyzed for seismic induced failures. Detailed analysis showed that only the structural failures of the cooler box or piping have any significant contribution to the unavailability of the decay heat removal system after a seismic event. The most fragile component was found to be the cooler box, with an estimated median fragility of about 1.5g.

Other Systems

Other system failures were analyzed for their relevance in the accident sequences. For example, the argon cover gas systems were studied for their potential to pressurize the primary tank. Pressurization of the tank could occur if the pressure regulation system failed and the pressure release system were blocked due to seismic induced failures.

Failure of the secondary piping was included in the models because of its potential to start liquid metal fires that could affect the decay heat removal functions. Unavailability of the secondary by itself does not contribute to the risk of fuel damage.

The steam generators are not in the reactor building, and thus steam generator failures cannot directly affect the primary systems. Unavailability of the heat sink is not a significant contribution to risk in EBR-II. Steam generator failures, however, are included in the seismic PRA for their potential impact on the primary system. A sodium-steam reaction can create a pressure wave that could propagate to the intermediate heat exchanger (IHX). If the pressure wave failed the IHX, natural circulation through the core might be impaired. The use of duplex tubes in the steam generators and the additional failures required to propagate a sufficiently large pressure wave to the IHX make this failure mechanism only a moderate contributor to the loss of the core coolable geometry.

Hazard Curves

Site-specific hazard curves were developed for EBR-II by Risk Engineering, Inc. The hazard curves were developed from USGS data for the site (anchor point), from attenuation models, and from the results obtained in an EPRI study for 57 other plants (uncertainty in the curves). The resulting hazard curves show a significant spread, in particular at high ground accelerations. The curves were extended to a PGA of 1.5g. The concept of a maximum credible earthquake that had been used in some of the early seismic PRAs was not applied in the EBR-II site hazard curves.

RESULTS AND DISCUSSION

Using the logic models developed, the plant-level fragility was estimated for each seismic accident sequence, for each bin (fuel damage class), and for the total fuel damage due to seismic events. The plant-level fragilities were then convoluted with the hazard curves developed for the EBR-II site to estimate the annual frequency of plant failure.

The overall results of the seismic PRA indicate a 90% range for the expected annual probability of fuel damage (minor or severe) between $2.5\ 10^{-7}$ and 10^{-4} yr^{-1}, with an estimated mean value of $1.7\ 10^{-5}$ yr^{-1} (median estimate of $3.9\ 10^{-6}$).

The dominant seismic failure was found to be that of the primary tank hangers.

Indeed, the primary tank failure dominates the seismic risk profile, since it can also affect the reactor shutdown and the shutdown cooling systems. Another significant contribution to the seismic risk is due to the altered primary pump coastdowns caused by the degradation of the pumps hydrostatic bearings.

The reactor shutdown system and the shutdown cooling system were found to be very rugged. For the reactor shutdown system, a very sensitive seismic detection system and a control rod driveline of high seismic capacity combine in a scram reliability that is not significantly degraded under seismic conditions.

The estimated seismic risk of fuel damage fares well when compared with that of commercial or other Class A DOE reactors, although a direct comparison is not truly appropriate because of the different site seismicity. Comparing the EBR-II seismic risk with that due to internal events [1], the seismic risk is an order of magnitude higher than the internal events contribution and a factor of 5 higher than the risk due to fires.

This comparatively high damage frequency is largely driven by the uncertainty in the hazard curves. With the EBR-II hazard curves, it would require a plant with an overall median fragility of 1.3g to make the estimated damage frequency comparable with the internal events. Examining the results in terms of plant-level fragility rather than annual failure frequency, provides a better insight into the seismic capacity and response of EBR-II, showing a seismically rugged plant. The overall plant-level fragility (Fig. 3) shows a median capacity approximately at a PGA of 0.55g, with a HCLPF of about 0.3g, which is around the current seismic design criteria for modern facilities.

Most of the fuel damage that results from the seismic sequences is of the extensive core damage type (CD), which is the type of damage expected after the failure of the primary tank hangers. The contribution of the tank failure to the total fragility can be seen by comparing Figures 2 and 3. This contrasts with the type of predominant damage in the internal events, which tended to be less extensive.

No structural or procedural improvements at EBR-II have been identified that could significantly reduce the seismic risk. Modest gains can be made by improving anchorage and support systems.

The results of the EBR-II seismic PRA indicate that a LMR reactor based on the EBR-II design can be built with a high seismic capacity and be structurally simple. Key factors in achieving a design with a high degree of protection against fuel damage are the reactivity feedback characteristics, the reliability of the shutdown system, and the passive decay heat removal systems. Lack of dependence on human actions and power supplies enhances the reliability of the safety systems.

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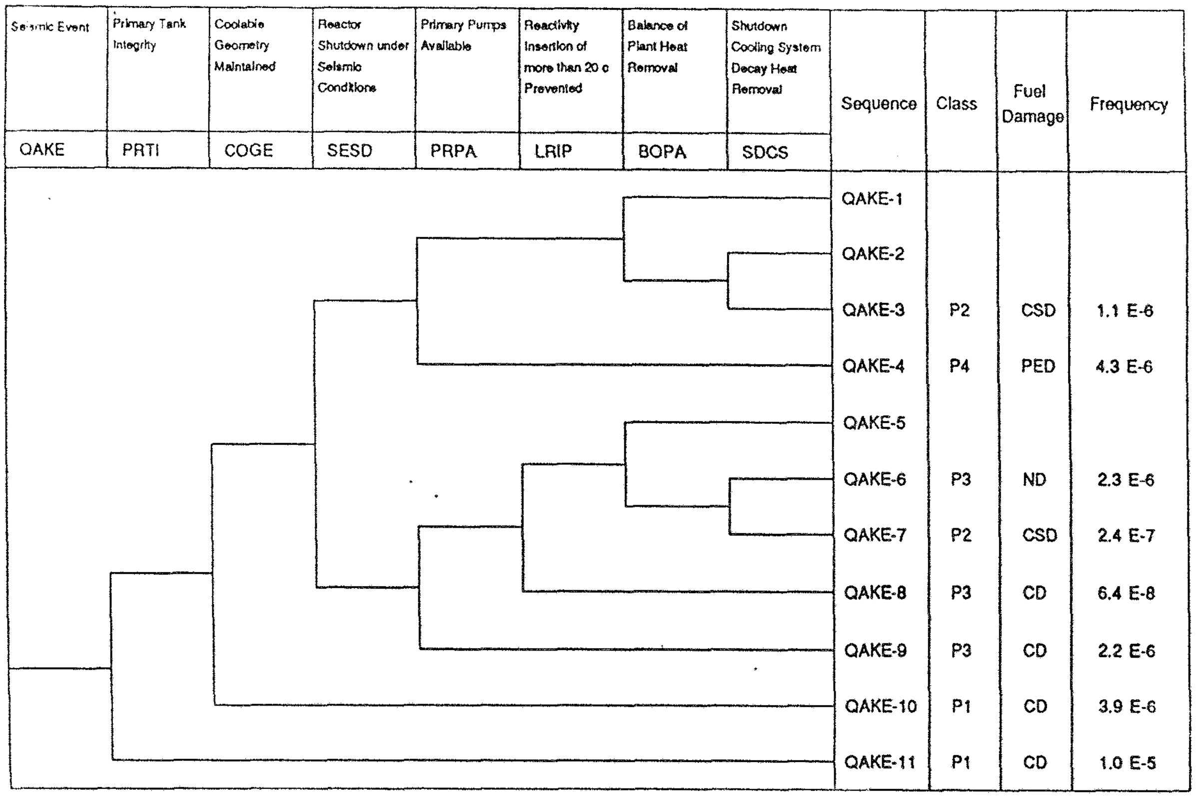

Figure 1. Seismic Event Tree

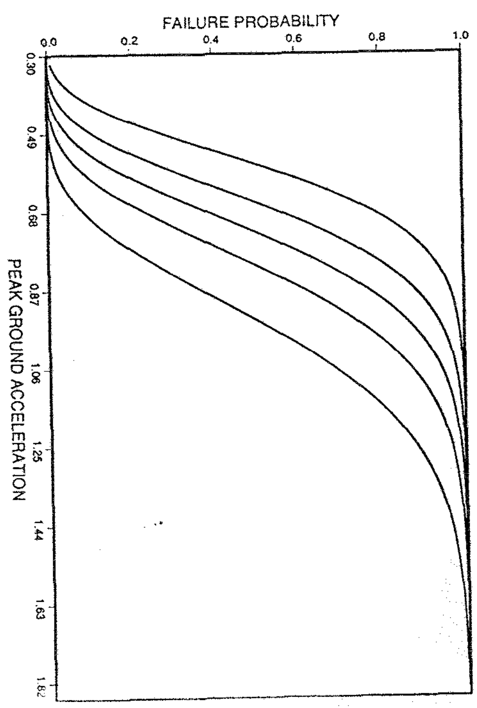

Figure 2. Primary Tank Hanger Failure Fragility Curves

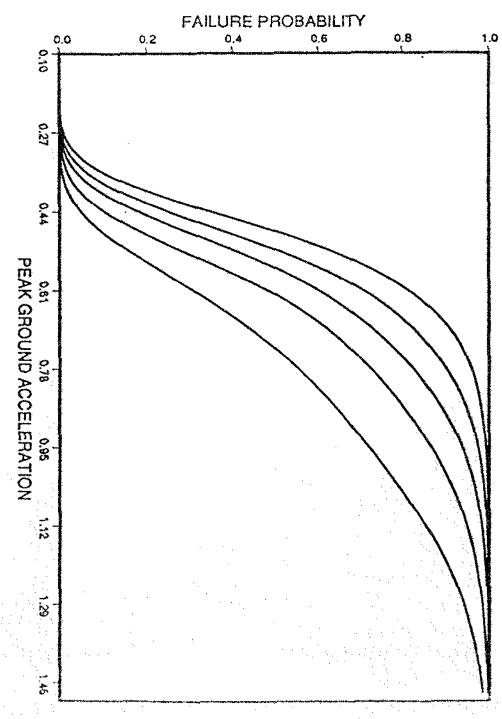

Figure 3. Plant-Level Fragility Curves for Fuel Damage