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SCRAM RELIABILITY UNDER SEISMIC CONDITIONS AT THE EXPERIMENTAL BREEDER REACTOR II*

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ABSTRACT

A Probabilistic Risk Assessment of the Experimental Breeder Reactor II has recently been completed. Seismic events are among the external initiating events included in the assessment. As part of the seismic PRA a detailed study has been performed of the ability to shutdown the reactor under seismic conditions. A comprehensive finite element model of the EBR-II control rod drive system has been used to analyze the control rod system response when subjected to input seismic accelerations. The results indicate the control rod drive system has a high seismic capacity. The estimated seismic fragility for the overall reactor shutdown system is dominated by the primary tank failure.

1. INTRODUCTION

The Experimental Breeder Reactor II (EBR-II) is a US Department of Energy (DOE) Category A research reactor located at Argonne National Laboratory-West in Idaho. EBR-II is a 62.5 Mw-thermal Liquid Metal Reactor (LMR) that started operation in 1964 and it has been used in a variety of research programs, recently as a testbed in the Integral Fast Reactor (IFR) Program. A Probabilistic Risk Assessment (PRA) of EBR-II was started in 1989 after the National Academy of Sciences recommended that probabilistic risk assessments be performed for DOE Category A reactors. The Level 1 PRA for internal events and most external events was completed in June 1991 [1]. Work on the seismic PRA followed the completion of the internal events PRA and is currently being finalized.

There are three important systems or functions in EBR-II that make up the 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 jeopardize both the reactivity control and the decay heat removal functions. These three aspects have been studied as part of the seismic PRA. The seismic PRA partially draws on the models developed for the internal events. However, the integrity of relevant structures or components under seismic motion had to be addressed specifically. The present paper deals in detail with the performance of the reactor shutdown system under seismic conditions.

2. REACTOR SHUTDOWN SYSTEM IN EBR-II

The reactor core is contained in a vessel. The reactor vessel and the primary circuit, containing two 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 (Fig. 1). Nine high worth control rods are driven from the top, 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. There is a separate set of two safety rods with an independent drive mechanism. The control rods fall by gravity although there is an air assist mechanism, and the safety rods fall by gravity with a spring assistance.

The reactor shutdown system in EBR-II consists of two redundant strings that contain a variety of trips to protect against internally initiated events. In addition, EBR-II is provided with a seismic trip. The seismic trip affects both shutdown strings and is the only trip signal in EBR-II that triggers the scram of both the safety and the control rods. The EBR-II seismic trip involves three seismic detectors in different locations operating in a two-out-of-three logic. Each detector has three sensors operating in orthogonal directions. A single sensor trips the detector unit. The Technical Specifications require that the seismic detectors be calibrated at no more than 0.01 g. The calibration in EBR-II is done at a more sensitive level of 0.005 g.

Three important elements were identified in the shutdown system from the seismic point of view, namely the detection system, the rod drive systems, and structural failures that could indirectly affect the reactor shutdown. The safety rod drive mechanism may be susceptible to slight misalignments during seismic motion that could render them inoperable. The highly redundant control rods (normally 1 and at most 2 rods of 9 are needed to shutdown the reactor) would be available if the seismic trip signal failed and other initiating events were induced. Therefore, it was decided to estimate the seismic scram reliability for EBR-II accounting only for the control rods. Because of the very low setpoint of the seismic detectors, a seismic trip signal failure is very unlikely and the key factor in assessing the scram reliability was to estimate the ability to drop the control rods under seismic conditions. This paper concentrates on the model and results of these calculations.

3. SEISMIC ANALYSIS OF THE EBR-II CONTROL ROD SYSTEM

The control rod system consists of a drive mechanism, a driveline, a gripper, and the control rod. The driveline is maintained in position by two roller pins inserted in respective notches. The roller pins are kept in the closed position by a magnetic clutch. During a reactor scram, the clutches are deenergized, the roller pins are pushed out of the notches, and the control rods are dropped. The control rods move inside guide thimbles in the core. In EBR-II the control rods are made of a fueled section followed by a neutron poison section. During operation the fueled section is partially in the core, so the control rod is already in its guide thimble. The only requirement for the reactor scram is for the rod to travel up to 14 inches downward.

The control rod driveline (CRDL) is located inside a guide tube whose clearances are, in some places, tight. During seismic shaking the CRDL will vibrate inside the guide tube, resulting in a number of short duration impacts that will generate friction forces that could significantly slow down the rod motion. Furthermore, the control rod driveline may suffer severe permanent nonlinear distortions that could completely prevent rod motion. These issues have been analyzed at ANL with a finite element model of the entire control rod drive system.

The finite element model, Figure 2, combines the reactor vessel and primary tank components and the CRDL and guide tube components in one model. The model contains 222 nodal points with six degrees of freedom. Horizontal earthquake motion in the x-direction is applied to the primary tank hangers and the primary tank plug seal. The impact forces generated at the contact points of the CRDL and guide tube are used with other operational forces from the control rod drop analysis. The clearances between the CRDL and the guide tube are modelled by gap springs with a conservatively assumed null damping constants. The air assist mechanism is also included in the model.

A generic design response spectrum for the EBR-II site, scaled to 1.0g was used to generate the time history for the CRDL analysis. It is a 20-sec time history with a 1.0g peak value occurring at 2.42 sec. To facilitate the nonlinear scram analysis, the first 1.8 sec of the time history are ignored. Furthermore, only 3.88 sec of acceleration histories are used in the scram analyses, which is longer than the time required to scram EBR-II, even under strong seismic motion, as has been verified during the present study.

The scram analysis calculates the control rod motion after the CRDL is released from its fully withdrawn position. The scram time is the time required for the rod to travel down 14 inches, accounting for the impact forces between driveline and guide tube generated along the CRDL nodes, and all other retardation forces on the rod during the free fall condition, such as the presence of coolant (liquid sodium) between the control rod and the guide thimble.

In the baseline case, ten calculations were performed corresponding to peak ground accelerations of 0.005g (seismic detector trip setting), 0.1g, 0.2g, 0.3g, 0.4g, 0.5g, 0.6g, 0.7g, 0.8g, and 0.9g. Additional parametric calculations were carried out to study the effect of the input acceleration history, the gap axial stiffness, the gap size, and the presence or absence of the air assistance pressure for rod movement. The sensitivity studies concentrated on cases of 0.4g, an acceleration close to the High Confidence of Low Probability of Failure (HCLPF) of the primary tank hanger failure and, at the same time, the acceleration value that corresponds to the threshold for inelastic response.

The overall results, in terms of scram times, are displayed in Table 1 for the base case and in the absence of the air assist pressure. The measured rod drop times under normal conditions are about 0.3 sec, and the Technical Specifications limit is 0.45 sec. Under seismic conditions, the scram times gradually increase to 0.41 sec for an horizontal peak ground acceleration of 0.9g. The parametric analysis show that the results are not very sensitive to the input acceleration history, the gap size or its stiffness. The unavailability of the air assist pressure has a significant effect on the drop time, increasing to 0.96 sec at a peak acceleration of 0.9g. In the absence of the air assist pressure and at the 0.4g acceleration corresponding to the threshold for inelastic response the rod drop time (0.49 sec) is still very close to the Technical Specification limit of 0.45 sec.

Based on the results of the deterministic analysis, Robert Kennedy (Structural Mechanics Consulting), assessed the seismic fragility for the control rod drive system. Although the models are not very appropriate for calculating permanent nonlinear deformations (stiff linear elastic models are used for impacts), the impacts are estimated incapable of producing significant nonlinear distortions because of their short duration. Thus the high confidence of low probability of failure (HCLPF) of the CRDL system was estimated to be in excess of 0.9g peak ground acceleration. An HCLPF equal to the threshold of inelastic response (0.4g), however, would correspond to rod drop times roughly within the Technical Specifications limits of 0.45 sec.

4. SCRAM FAILURE UNDER SEISMIC CONDITIONS

The analysis has shown that the CRDL has a high seismic capacity. For strong earthquakes, the strong high-energy content ground motion is normally carried by the seismic S-waves. Faster travelling, lower amplitude P-waves are expected to reach the site ahead of the more damaging S-waves. Given the sensitivity of the seismic detectors (0.005g), P-waves may trip the reactor under moderate ground motion and the scram be completed prior to the arrival of the strong ground motion. Therefore, the annual probability of an earthquake capable of preventing the rod drop in the allotted time will be very small.

To illustrate this point, the probability of an earthquake that would demand the control rods to scram under seismic accelerations above their HCLPF of 0.4g can be obtained as the combined probabilities of (1) an earthquake with a P-wave amplitude below 0.005g and an S-wave acceleration above 0.4g; (2) an earthquake with a P-wave acceleration above 0.4g; and (3) an earthquake with a P-wave acceleration above 0.005g and an S-wave acceleration above 0.4g, but a time delay less than the approximately 0.45 sec needed to scram the reactor without air assist under accelerations of less than 0.4g. Based on the hazard curves developed for the EBR-II site and analysis of ground motion records, R. McGuire (Risk Engineering) has estimated the combined annual probability (median value) of those three situations at approximately 5.2 10^{-7}.

An estimate of the shutdown system failure probability under seismic conditions can be obtained by including the remaining components of the scram system in the analysis. The failure of the seismic detectors must be accounted for, in the form of individual detector failures due to lack of sensitivity or miscalibration (in a 2-out-of-3 logic), common cause failure of the electronics due to seismic motion and common cause failure due to other causes. The estimate of the probability of miscalibrating the detectors is based on a median failure at 0.05g and a HCLPF of 0.1g (a decade higher than the setpoint and the Technical Specifications limit respectively).

Additional contributions to the failure to scram come from the reactor vessel cover, which could tilt and jam the control rod drives, non-seismic failures of the control rod drive system, and the failure of the primary tank. Once the control rod drive has been released from its up position, the magnetic clutch, if energized again, cannot stop its motion. Therefore, chatter of the scram relays and the magnetic clutches has not been included. Only non-seismic failures of these components are accounted for. Credit for a loss of power trip or manual scram has not been taken. The median fragility of the primary tank was estimated at 0.73g, and a preliminary estimate for the vessel cover tilting indicates a HCLPF above 1g.

It is illustrative to estimate the scram failure probability under seismic conditions with and without the contribution of the primary tank failure, since the tank is an structural component that is not part of the shutdown system and whose failure affects much more than the reactor shutdown. Table 2 summarizes the estimated fragilities of the entire shutdown system, with and without the primary tank failure, and for two CRDL HCLPF values, 0.4g and 0.9g. Table 2 also shows, in parenthesis, the estimated mean probability of failure of the shutdown system, that is, the result of the convolution of the system fragility with the EBR-II site-specific hazard curves.

The estimated probability of an unprotected seismic event is between 4 10^{-6} and 8 10^{-6} per year (mean value) when the failure of the primary tank is treated separately. The 95th percentile of the distribution ranges approximately from 2 10^{-5} to 5 10^{-5} per year. On the other hand, the annual probability of seismic-induced failure of the primary tank alone is approximately 1.0 10^{-5} (mean value).

5. CONCLUSION

Seismic analysis of the control rod drive system in EBR-II has shown that the system has a high seismic capacity, with a HCLPF of at least 0.4g. By accounting for other component failures, the system seismic median capacity of the scram system has been estimated to be at least 0.76g, in comparison with the primary tank failure fragility estimated of 0.73g. Including the primary tank as a contributor to the failure to scram, the median fragility estimate is at least 0.63g.

A direct comparison with the failure to scram estimated in the internal events PRA (mean value of 5 10^{-6} per demand) is not applicable because the seismic value includes the probability of seismic events, while the internal events estimate is independent of the frequency of the initiators. However, the estimated annual probability of an unprotected seismic event is of the order of 10^{-5}, with the primary tank structural failure dominating the value. The probability of a seismic event followed by the failure of the shutdown system is estimated at 4-8 10^{-6} per year. When compared to the estimated seismic failure probability of the primary tank, approximately 1 10^{-5}, the failure of the scram system under seismic conditions does not appear as a major risk factor in the seismic PRA of EBR-II, regardless of the value used for the HCLPF of the control rod drive system, the threshold of inelastic response or the more realistic 0.9g value.

6. REFERENCES

1. D. J. Hill, W. A. Ragland, J. Roglans, "Experimental Breeder reactor II Probabilistic Risk Assessment, Rev.2", Argonne National Laboratory, Internal Document, June 30, 1991.

Table 1. Summary of scram time results for various conditions

PGA (g)	Input History	Gap Size	Gap Axial Stiffness	Scram Time (sec) with Air Assist	Scram Time (sec) no Air Assist
0.005	Baseline	Nominal	Stiff	0.31	0.42
0.1	Baseline	Nominal	Stiff	0.31	
0.2	Baseline	Nominal	Stiff	0.32	0.47
0.3	Baseline	Nominal	Stiff	0.33	
0.4	Baseline	Nominal	Stiff	0.34	0.49
0.5	Baseline	Nominal	Stiff	0.35	
0.6	Baseline	Nominal	Stiff	0.36	
0.7	Baseline	Nominal	Stiff	0.37	0.70
0.8	Baseline	Nominal	Stiff	0.39	
0.9	Baseline	Nominal	Stiff	0.41	0.96
0.4	Alternative	Nominal	Stiff	< 0.35	
0.4	Baseline	Nominal	Soft	< 0.34	
0.4	Baseline	Large/Small	Stiff	< 0.34	
0.4	Alternative	Nominal	Soft	< 0.33	

Table 2. Summary of shutdown system fragility and probability of failure results

	Median Fragility (g) (Mean annual probability of unprotected seismic event)	
	CRDL HCLPF = 0.4g PGA	CRDL HCLPF = 0.9g PGA
Primary Tank Included	0.63 (1.3 10^{-5})	0.68 (1.1 10^{-5})
Primary Tank Excluded	0.76 (8 10^{-6})	0.9 (4 10^{-6})

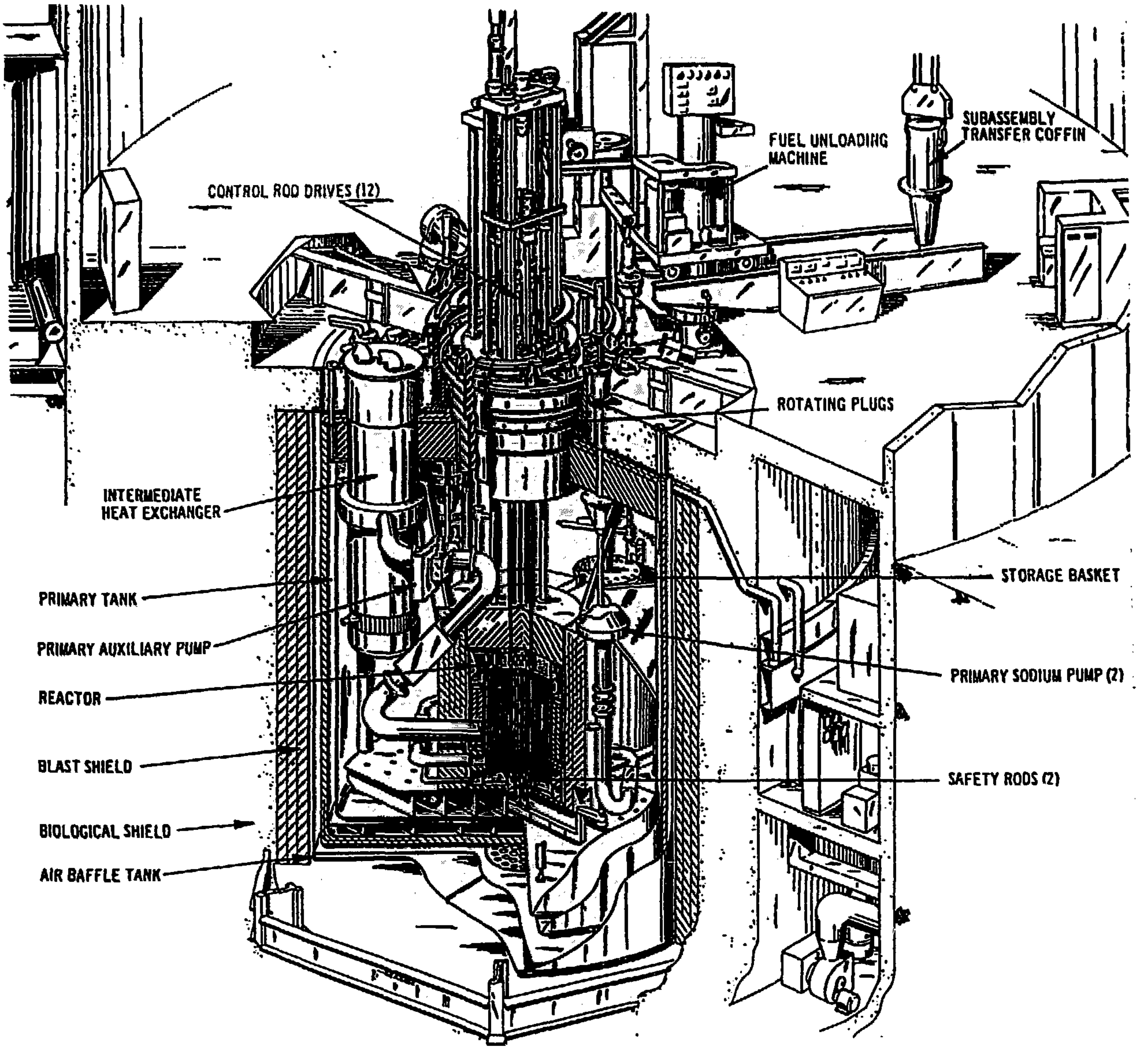

Figure 1. EBR-II Primary System Main Components.

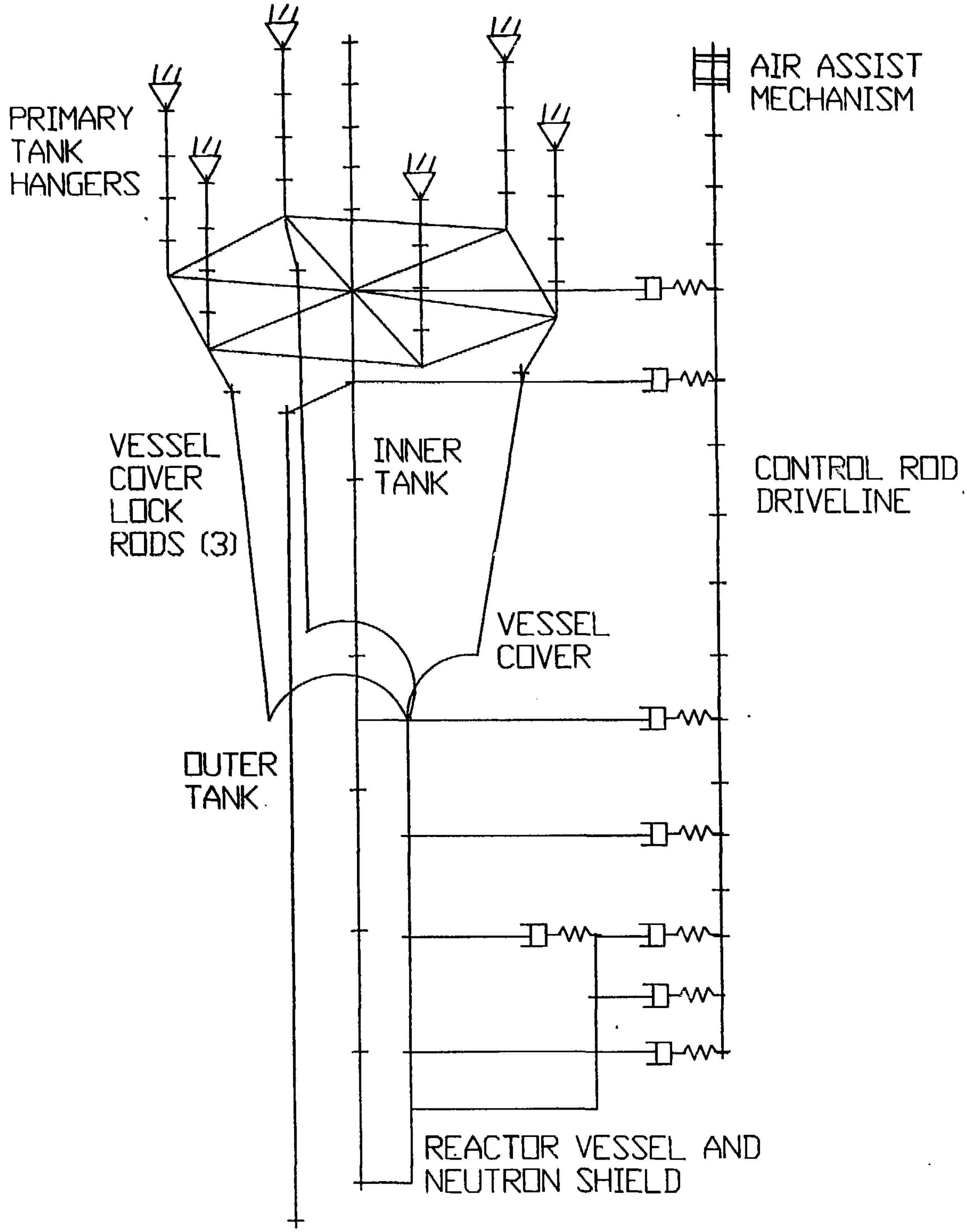

Figure 2. Finite Element Model of the Reactor Vessel and Control Rod Driveline System