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Seismic Qualification of the BR2 Test Reactor

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ABSTRACT: The Belgian Authorities required a seismic analysis of the BR2 high flux material test reactor for restart after a major refurbishment. A deterministic reference earthquake with an intensity of VII (MSK-scale) was defined, taking into account the data from the historically most significant earthquakes. The analysis was limited to the safety related barriers, which are all structural components since BR2 needs no forced cooling after scram of the reactor. Various calculation methods were used: finite element models with synthetic time histories including soil structure interaction, the response spectrum method or simplified methods. The results indicate that the major part of BR2 can resist the reference earthquake. Some minor modification were required. Two components, namely the primary circuit and a ventilation duct needed more significant construction work.

INTRODUCTION

The Belgian Reactor 2 (BR2) is a Material Test Reactor with a maximum thermal power of 125 MW. Operation of the reactor started in 1963. From June 1995 to April 1997 the reactor was shut-down for a major refurbishment project. The most important issues were the replacement of the beryllium core and the inspection of the reactor vessel. To restart the reactor a new safety analysis had to be submitted. In the conditions for restarting the reactor, the licensing authorities asked for a seismic analysis.

Description Of The BR2

The core of BR2 is composed of a beryllium reflector, with cylindrical holes. These holes can contain uranium-aluminium fuel elements, control rods, experimental devices or a beryllium plug. The reactor is cooled with water under pressure of 12 bar. Outlet temperature is approximately 50 °C. The reactor vessel is located under water in a pool. The reactor and its experiments are situated in a Containment Building, which can be isolated under accident conditions. Components of the primary circuit (pumps, heat exchangers, pressuriser) are located outside the containment building. Besides these components, the Process Equipment building contains the storage pool for spent fuel elements and the hot-cell. Auxiliary buildings include the Ventilation Building which is connected to the Containment Building with a pipe bridge, an office building, experiment hall, diesel generator building, cooling towers and the water treatment plant.

An important feature of BR2 is that after scram the reactor can be cooled by natural convection, where the reactor pool serves as heat sink. As long as the control rods can drop and the structures remain intact during an earthquake, no active components are required to maintain cooling of the core.

SEISMIC CHARACTERISTICS OF THE ENVIRONMENT

General Description Of The Seismic Activity In The Region (1).

BR2 is located in the north-east part of Belgium, a sandy region called Campine (Kempen). The eastern border of the Campine is formed by the valley of the Maas. On the southern border the massif of Brabant is located. Both borders play an important role with respect to the seismology of the SCK•CEN site, as will be explained further.

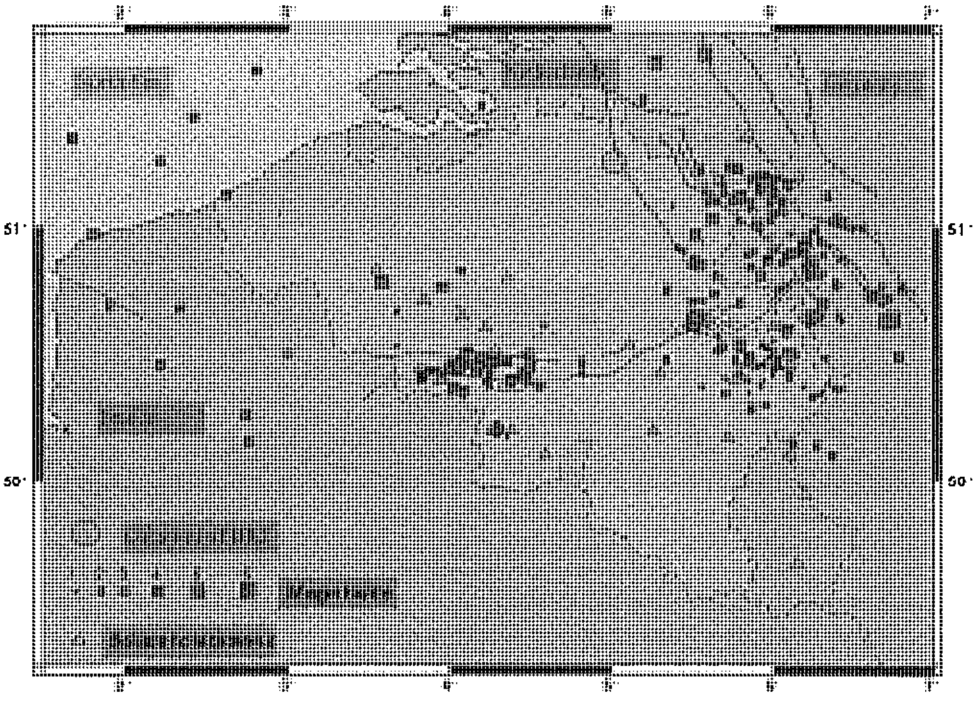

Figure 1: Seismicity of Belgium

The sub-soil of the region is composed of varying sand layers to a depth of 160 m. The top layer (Sand of Mol) is nearly pure SiO_2 and is used in the glass industry. The sand is saturated with the water table approximately one meter under the surface. Below the sand layers a layer of clay with a thickness of about 100 m (Clay of Boom) is located. Below the Clay of Boom there are alternate layers of sand and clay. A limestone bedrock is found at a depth of 570 m. This was formed during the varistic mountain-building period. The varistic mountain building was located south and east of the Kempen. Below the limestone layer the cambro-silure is located, dating from the Caledonian mountain-building and belonging to the massif of Brabant. The depth is about 1300 m.

Figure 1 presents a map of the recorded earthquakes in Belgium. Two active regions can be recognised (2). In the southern part of the country the seismic activity is generated by the southern border of the massif of Brabant, which has a fault system in the east-west direction. The other fault system is located mainly in Germany and the Netherlands and is known as the Roer Valley Graben. It is connected to the Rhine Graben structure.

The Historically Most Significant Earthquakes

Two earthquakes in recent history were considered to be the most significant events. The first occurred in 1938, (3) with the epicentre located in the massif of Brabant, about 50 km from the location of BR2. The magnitude was 5.9 and the observed local intensity was MSK VII. The hypocentral depth was estimated to be 20 km. In the region of BR2 the observed intensity was IV.

The other significant earthquake occurred in the Roer Valley Graben on April 13, 1992. The epicentre was located in Roermond (Netherlands). The magnitude was 5.8 and the focal depth 17.4 km. The local observed intensity was VII (4). In the region of BR2 the intensity was IV-V. A simplified representation of the fault system in the Roer Valley is given in figure 2 (after L. Ahorner (5)).

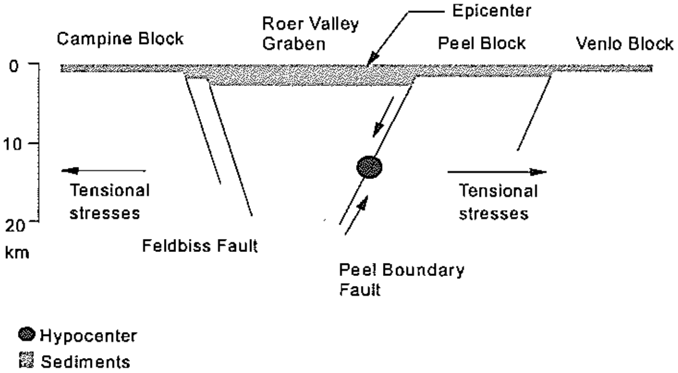

Figure 2: The fault system of the Roer Valley Graben

The observed intensity of VII in the epicentre is low for an earthquake with a magnitude of 5.8. The reason is the thick layer (1500 m) of unconsolidated Cainozoic sediments present in the graben. This layer allows absorption of seismic energy, resulting in a lower intensity at the surface. It is considered that an earthquake with an intensity of VIII is credible in the region. The minimum distance between the Roer Valley rift and Mol is about 50 km (border of the Feldbiss fault). The Rauw fault belongs to the Roer Valley rift and is located 8 km east of the SCK•CEN site. To the west no further faults of the Roer Valley rift are known.

The Probability For Occurrence Of An Earthquake.

Knowledge of the historical seismicity was used to define the magnitude of the reference earthquake. However, it is also useful to have information about the probability for occurrence of an earthquake. It is important to be sure that the reference earthquake has a very low probability. The probability of occurrence can also be used to assess the risk from components which, according to the calculations, are not capable of withstanding the reference earthquake.

The probability of occurrence for the BR2 site was calculated using the method of Rosenhauer and Ahorner (6). The results are shown in figure 3. It can be seen that the occurrence of an earthquake with an intensity of VIII is a very unlikely event (less than 10^{-7} per year).

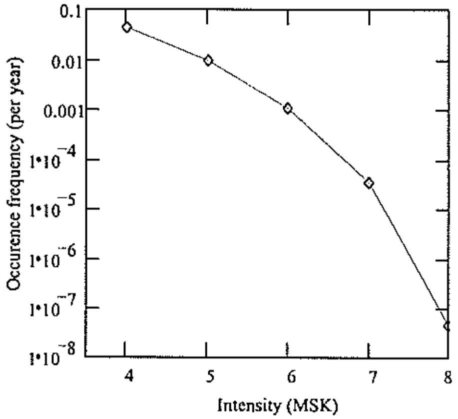

Figure 4: Occcurance frequency

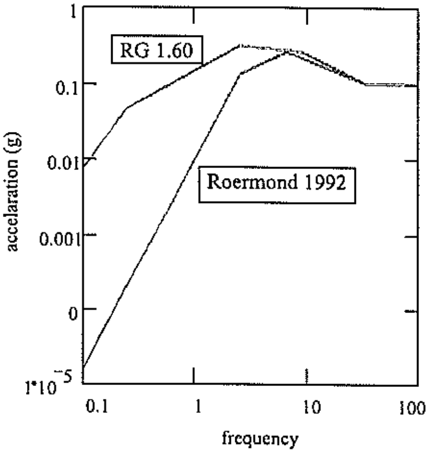

Figure 3: Frequency content

DEFINITION OF THE REFERENCE EARTHQUAKE

For the reference earthquake a response spectrum had to be defined. From the previous discussion it is clear that the probability of an intensity greater than VII is sufficiently low. This corresponds with a zero period peak ground acceleration of 0.1g (7).

The frequency content of the reference earthquake was defined according to the USNRC Regulatory Guide 1.60 (8). This spectrum is considered conservative for the re-evaluation of existing facilities. Comparison with a spectrum measured during the 1992 earthquake in Roermond, it has much more low frequency energy. The Roermond earthquake spectrum was measured 54 km from the epicentre (4). Measurements on shorter distances are not available due to saturation of seismographs.

DEFINITION OF THE STRUCTURES OF BR2 TO BE ANALYSED.

The reference earthquake was considered as a "Safe Shutdown Earthquake". Only those components and structure which are important for safety after shutdown of the reactor were considered. Since the reactor can be cooled by natural circulation after a shutdown only passive components were considered. The concept of "Operating Base Earthquake" was not used since it is not possible to qualify all components necessary for operation, and also because it was not required by the licensing authorities. However, the reactor continued operation without disturbance during the earthquake of 13 April 1992, which was felt in the region with an intensity of IV-V.

Structures Important For Safety

The following structures and components are part of the defence in depth system against release of radioactive material and were included in the seismic assessment:

The fuel elements: During an incident the fuel elements have to remain intact. Therefore it is necessary that the scram operates correctly (the rods are fully dropped) and that enough cooling is available (the reactor pool remains intact) to prevent damage to the fuel elements.

The reactor vessel: The vessel itself has no safety function because it is not considered as a barrier against fission product release. Rupture of the vessel would not cause a loss of coolant accident since the vessel is located in the reactor pool. However, the vessel was included in the analysis because an inelastic deformation could prevent control rod movement.

The reactor pool: The reactor pool contains the water for the emergency cooling after a reactor scram and isolation of the building. It is essential that the reactor pool remains intact during the reference earthquake.

The reactor building: In case of damage to the reactor core, the reactor building is the ultimate barrier for the fission products. Clearly, the weakest points are the isolation valves of the main ventilation line.

Two additional structures which do not directly belong to the reactor safety systems were included in the assessment because their failure could potentially have serious consequences:

The storage pool for spent fuel elements: The storage pool for spent fuel elements is located outside the containment building, in the machine hall. A large break in the wall of the pond would lead to a loss of shielding for the stored fuel.

The primary circuit outside the reactor pool: The hydraulic calculations made for an earlier Probabilistic Safety Assessment indicated that a large break in the primary circuit outside the containment building could lead to core pond draindown and hence loss of decay heat removal. For this reason, an assessment of the major piping (diameter greater than 12") of the primary loop is included.

Structures Which Can Cause Secondary Damage

A number of components or structures which do not have a safety function can damage safety related components when they collapse during an earthquake. These components were identified during a walk-down. Typical examples are: polar crane, shielding walls and adjacent buildings.

METHODOLOGY OF THE SEISMIC ANALYSIS

The selection of the methodology for the seismic analysis of the structures necessary to ensure reactor safety was initially undertaken by SCK•CEN staff who have a detailed knowledge of the key features of the likely safety case which could be developed for the reactor. Having selected those facilities which required seismic qualification a partnership was then developed between SCK•CEN and AEA Technology to ensure that the seismic qualification methods provided the necessary confidence to the safety regulators whilst ensuring a cost effective strategy. The key benefit of this approach was that AEA Technology was encouraged to develop both innovative and cost effective solutions and to select methods which would generate the required confidence with the least risk of re-work should the method either not be sufficiently refined to calculate the required result or should it be too complex and result in wasted effort. The direct result of this approach was that the methods chosen were in general simple ones which reflected both the relatively simple structural forms and the low seismic demand at the Mol site.

The seismic analysis of the structures important for safety and for those which have the potential to cause secondary damage took a number of different forms varying in complexity and conservatism. The most complex methods were adopted for the main elements of the reactor building. The complex methods used finite element models analysed by linear elastic time history analyses using time histories generated to match the design response spectrum.

More simplistic response spectrum calculations and hand calculations were adopted for those elements which were required to be shown not to collapse or which could readily be justified using simplistic and more conservative methods.

The above approach was found to represent a cost-effective methodology to the initial analysis of the buildings and systems. Whilst adopting this methodology, the authors recognised the potential to identify fallacious failures of structures and equipment by the systematic introduction of excessive conservatism. In all cases where the analysis led to results which indicated that the original structure was inadequate to resist the applied seismic loading, the predicted loads were reviewed to ensure that the reason behind the postulated failure was a genuine lack of structural capacity and not an excessive demand calculation.

Model Of The Reactor Building Including Soil Structure Interaction

A detailed model of the reactor building including all of the main load resisting elements in both horizontal and vertical directions was developed. This model also included an explicit representation of the reinforced concrete containment shell. No model of the steel containment shell was developed because its seismic response is controlled by the internal concrete shell and by compatibility of displacements. This model also included a representation of the reactor vessel and the pool.

The Mol site is underlain by extensive depths of mainly sandy soils. The sands are fine with a relatively uniform grading, particularly close to the surface, and have a typical shear wave velocity of the order of 100m/s. The basemat of the reactor building is a continuous reinforced concrete circular foundation and as such can be reasonably represented as a uniform raft. This form of construction and the sub-soil was readily represented by a soil spring and dashpot model and this was adopted for the finite element model. The stiffness and damping characteristics were calculated using the closed form solutions presented in (8) and were varied by +100%, -50% to give reasonable bounds to the actual response of the site.

The time history analyses of the main building and soil spring model were run using the three time histories generated to match the site response spectrum. These time histories were rotated in accordance with (8).

Analysis By The Response Spectrum Method

Simple finite element representations were developed for a number of the ancillary structures and equipment items. These models were subsequently analysed either by applying equivalent lateral accelerations or by response spectrum methods using suitable modal and spatial combinations (8).

The structures which had finite element response spectrum analysis were the ventilation stack and the primary circuit pipework. The remaining civil engineering structures were analysed using equivalent methods as these were sufficiently accurate given the structural form and the relatively low input motions calculated for the Mol site.

Structures Analysed By Simplified Methods

A number of structures were analysed using yet more simplistic methods. These included the Process Equipment building (PEB) including the Storage Canal and the Hot Cell. The structural form of the PEB below +7.1m level is an essentially box like structure which will have a single shear mode of deformation with the dominant primary horizontal modes at or close to the peak of the response spectrum. The structure was therefore analysed by applying a lateral coefficient of 0.284, which represented the peak of the response spectrum multiplied by a multi-mode factor of 1.5.

A similar level of lateral input was also applied to the PEB structures above +7.1m level. Whilst recognising the potential for this input to be non-conservative, it allowed an initial estimate to be made of the seismic demand of this part of the structure which by inspection had a limited seismic capacity.

The reactor building ventilation system was also analysed using simplified methods and the results were subsequently back checked by considering the likely wind forces for which they would have been designed. This comparison showed that the seismic loads were approximately a factor of 3.9 greater than the wind loads. This confirmed that the structure would be highly likely to collapse during a seismic event.

A significant amount of equipment contained both within the PEB and the reactor building has the potential to cause secondary damage to primary safety systems. In most cases. this equipment was analysed using simple hand calculation methods. The input motions adopted were the peak of the secondary response spectra applicable to the level of the supports to the equipment, multiplied by a multi-mode factor of 1.5. The analysis generally calculated reaction forces at the supports to allow the connections to be assessed, together with some simplified stress calculations to show that the equipment was structurally competent and would not collapse independent of its supports.

RESULTS OF THE ANALYSIS

The Reactor Building, Reactor Pool And Vessel

The reactor building structures are in essence two separate structural systems. The outer containment building with both the steel outer shell and the concrete inner cylinder was relatively lightly stressed by the seismic event and calculated factors of safety were in the range 2 to 5. Similarly the displacement compatibility between the concrete and steel structure generated very low stresses within the steel shell which thus had larger factors of safety than the concrete cylinder. The concrete cylinder also provides support via corbels to the concrete floors of the reactor building experimental floors. With a tolerance of 25mm prior to impact of the slabs to the shell, the relative movement of the shell compared to the inner pool support structures was also a further significant parameter. The calculated relative displacements of no more than 3mm indicated that large margins were available against impacts with substantially greater margins against loss of support to the floors,

The reactor pool structure which is a heavy concrete box mounted on six large sub-pile columns together with the concrete box structure of the rear shielding room also supports the inside of the experimental floors. Thus the sub pile columns and the box structure carry both significant vertical loads under gravity loading and were subject to significant horizontal loads, even from the relatively low seismic loading calculated. The structural form is also one which introduces plan torsion with the centre of stiffness and the centre of mass significantly offset. This torsional form of response was suitably accounted for by the relatively detailed model of the reactor pool area.

The assessment of the reactor pool walls showed that the walls were not subject to significant out of plane loads and the minimum factors of safety calculated were of the order of 3 for out of plane loads, reducing to 1.5 when in plane shear effects were included. The floor of the pool was not shown to have such large margins with a calculated factor of safety of just 1.0 based on the high yield reinforcement. The calculations also determined the degree of sloshing which would result from the seismic event to determine the degree of potential for loss of water. These calculations resulted in a slosh height of 88mm, a figure well within the available margin at the top of the pool.

A sub pile column was shown to have a minimum factor of safety of 1.1 for the 0.1g seismic loading with this minimum on only one of the six columns, all of the others having larger margins.

The most highly loaded area of the support structure to the reactor pool was the box structure of the rear shielding room. A significant opening in one of the walls resulted in a significant degradation in the integrity of the structure in one local zone. The wall adjacent to this opening was shown to have a factor of safety less than unity for the 0.1g seismic loading with a calculated maximum withstand of 0.086g. Given the margins in the sub-pile columns and the low probability of the design basis earthquake, this was deemed acceptable by SCK•CEN.

The floor slabs within the reactor building and the columns which support them as they span between the reactor pool walls and the outer concrete shell were all calculated to have factors of safety in excess of unity, This was primarily because of the high live loadings for which these floors were designed and to which they have been subjected during the life of the facility. Currently however, the experimental rigs present within BR2 are relatively light and utilise only a fraction of the available capacity, leaving a large margin to resist seismic loading.

The aluminium reactor vessel itself was shown to be lightly stressed by the seismic event and by the attached piping loads. This was mainly due to the presence of both anchor bolts to the base of the vessel and horizontal guides to the top of the vessel anchored to the reactor pool walls. The factor of safety calculated for the aluminium vessel was in excess of 7. The relative displacement of the vessel from top to bottom was also calculated to ensure that the reactor control rods would not bind during insertion. The relative displacement of the top of the vessel to the bottom was 2mm, indicating that the control rods would readily fall into the core as this is less than the available tolerances.

The Primary Circuit

The seismic capacity of the piping was assessed based on the Level D design code rules of ANSI/ASME B31.1 for a safe shutdown earthquake. The seismic analysis took due account of the high stress levels in the aluminium piping and used spectra which were developed at 2% damping with a higher damping level of 5% at lower frequencies as shown within the code case (9).

The analysis of the primary circuit was completed using three separate models of the piping, an example plot of the loop 2 piping is shown in Figure 5. The three models were developed based on the various fixed supports to the piping available from the reactor vessel, the main and auxiliary pumps and the heat exchangers. In all three models of the piping the initial analysis indicated that factors of safety were less than unity. Thus in all three cases, modifications were required to the piping to enhance its seismic capacity. These are discussed later.

Once all of the modifications were incorporated into the three models of the primary circuit piping, the resulting minimum factors of safety for each loop were: 1.04, 1.12 and 1.37. Thus the modifications were shown to significantly improve the seismic capacity of the piping, the static and thermal analyses also undertaken indicated that the use of resilient buffers which allow thermal growth of the piping resulted in no significant increase in piping stresses for normal operation load cases.

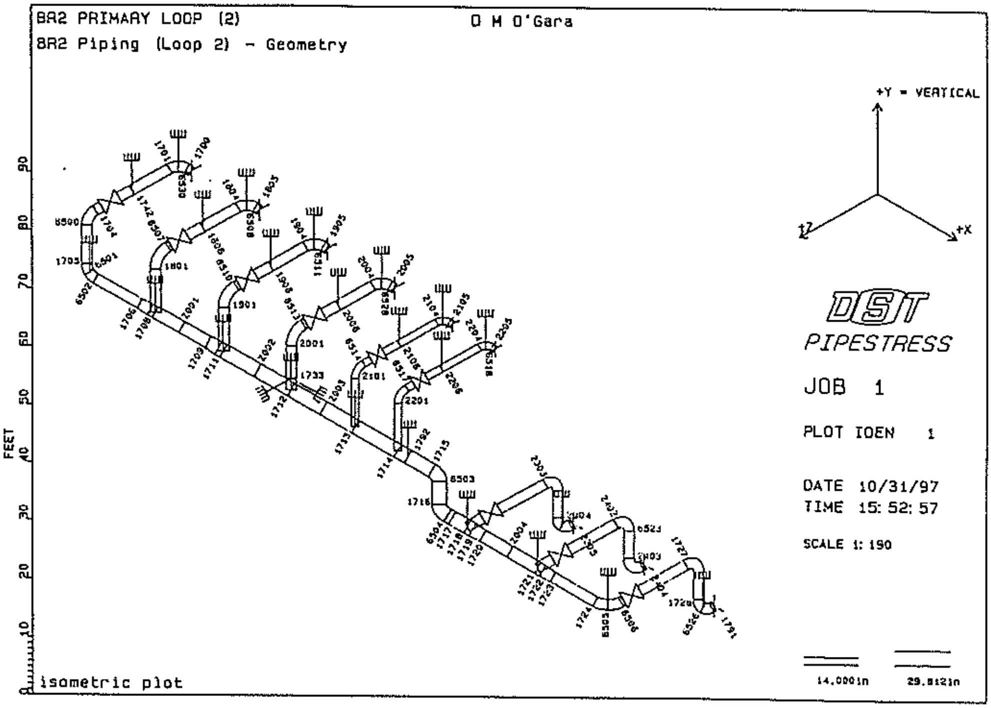

Figure 5: Model for calculation of loop 2 of the primary piping

The Storage Pool For Spent Fuel

The storage pool structure is a long concrete pool founded directly on the Mol sands. The structural form is such that in the longitudinal direction the walls act as shear beams and in the transverse direction they act as cantilevers from the base of the pool. The high yield reinforcement of the walls is sufficient to calculate factors of safety of 1.4 for the walls under the 0.1g seismic loading.

The pool is contained within the Process Equipment Building. This building also houses the primary circuit piping, pumps and heat exchangers. Below 7.1m level, which corresponds to the top of the pool concrete, the PEB is formed by heavy shield walls around the pumps, heat exchangers, piping and the storage canal with a heavy shielded floor slab above. These shield walls act as shear walls under seismic loading and were calculated to have significant margins of the order of 1.5 under 0.1g seismic loading. The upper section of the PEB consists of concrete portal frames with a heavy concrete roof. Under wind loading the lateral load resistance of this structure is developed by the masonry infill panels between the concrete portal frames. The large size of these masonry infills is such that no account of their strength was taken for the seismic event as they would be extremely unlikely to survive even low levels of seismic shaking. The concrete columns of the portal frames are weakest as they pass close to the storage canal walls and tie beam elements are present to add stability to the columns. The minimum factor of safety calculated for the tie beam elements was 0.27 for 0.1g input. Following tie beam failure the columns were calculated to have factors of safety of 0.89. In the longitudinal direction, the building does not have the benefit of portal action and the cantilever nature of the columns makes them extremely weak following failure of the masonry infill panels. The maximum seismic input which could be shown to have a suitable factor of safety from deterministic calculations was 0.02g. Whilst it was recognised that this figure is pessimistic, it was considered that there was no confidence in being able to increase this factor of safety by more sophisticated analysis. The heavy floor at 7.1m level over the piping, heat exchangers and pumps was judged adequate to resist the impact of the higher elements of the PEB structure. Failure of the over building onto the fuel in the racks within the pond was considered to be acceptable because the racks are equipped with cadmium shields to prevent criticality, similarly the low decay heat levels in the fuel elements also allows them to remain air cooled for considerable periods of time. Thus the only significant difficulty would be high dose rates over the top of the pond.

Another structure adjacent to the storage canal is the Hot Cell. This is a concrete cell structure of a similar height to the top of the PEB and separated from it by a structural gap to produce two independent structures. The Hot Cell supports both its own self mass and the floors which span from the cell walls to a perimeter of columns. The Hot Cell was modelled using a simple beam finite element representation and the results indicated that factors of safety of 1.0 could be calculated for the walls under horizontal seismic loading. Thus the heavy shielding walls from provided sufficient stiffness and strength to allow this structure to be seismically qualified.

Secondary Damage

A large number of items were considered for their potential to cause secondary damage. These included both major structures adjacent to the reactor building and smaller equipment items which have the potential to collapse onto the primary circuit or ventilation systems.

The majority of these structures and plant items were shown to have large factors of safety against collapse under seismic loading. Examples include a FOS of approximately 3 for the ventilation stack, 1.9 for an access gantry over the reactor pool and 2.2 for the personnel airlocks. A number of other items and structures had significantly lower factors of safety and have required either more sophisticated analysis and assessment or structural modifications. The vehicle airlock is an example of a structure where more sophisticated assessment is ongoing. Examples of equipment and structures which have been modified include lead brick shield walls and regions of the ventilation ductwork adjacent to the reactor pool.

Other structures such as the Experimental Hall were shown to be very poor. Although the masonry walls could be strengthened, they are not full height and a significant line of weakness exists at the top of the walls where the columns act in minor axis bending and have limited reinforcement. The minimum FOS calculated was 0.16. Thus even though the masonry panels could be strengthened, the building was still extremely poor. Possible damage to the Containment Building due to collapse of the Experiment Hall is rather limited.

ENGINEERED MODIFICATIONS

The major structures of BR2, such as the reactor building and the reactor pool, can withstand the reference earthquake without modifications. Two important modifications were required, namely on the primary piping and the ventilation duct.

Primary Circuit

As noted previously, modifications to the piping were introduced to restrain the piping against horizontal movement transverse to the main axis of the piping, whilst still permitting thermal growth of the piping in the longitudinal direction. A sketch of a typical horizontal guide to the piping in included as figure 6. The sketch indicates how the guide utilises resilient rubber buffers to allow the load from the piping to be gradually taken up by the restraint, thus avoiding impact type loading regimes. On the primary loop 4 restraints were required. The heat exchangers required connections between the individual support frames to restrict horizontal movement and collapse. A further horizontal restraint was necessary on the secondary piping to limit the load on the heat exchangers during an earthquake.

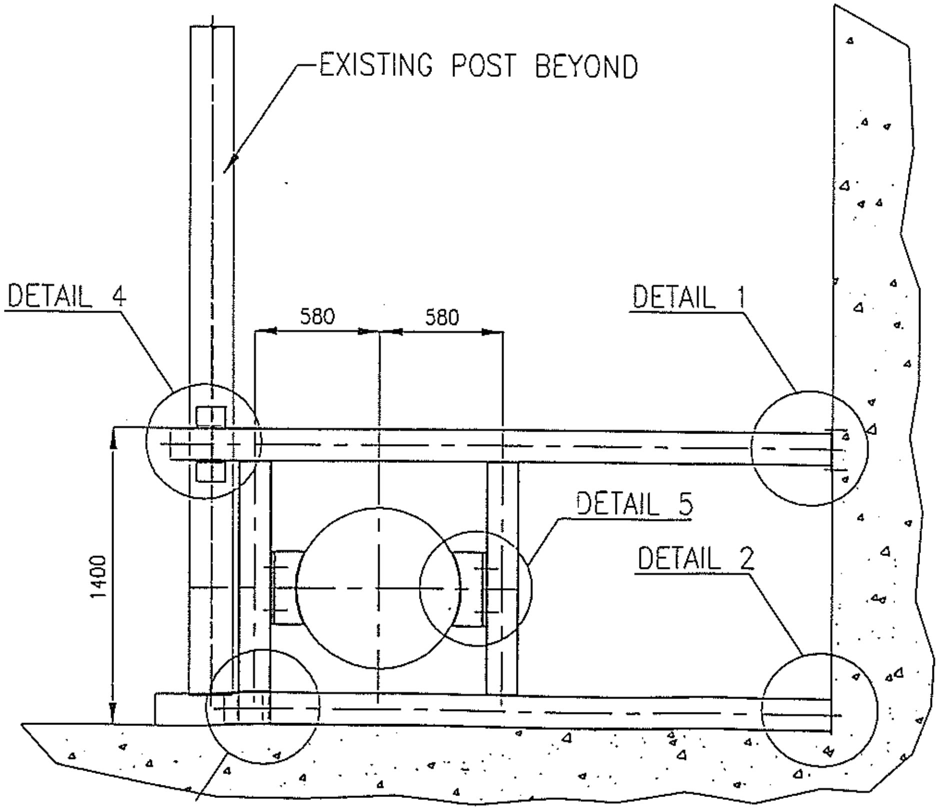

Figure 6: Additional restraint on the primary piping

Ventilation Duct

Collapse of the ventilation duct could damage the containment isolation valves. To prevent such an event, two solutions were possible: full qualification of the ventilation duct or separation between the heavy steel structure and the isolation valves, such that should the ventilation duct collapse no damage would be done to the isolation valves.

The second solution namely separation was adopted. The remaining structure connected to the isolation valves is light. With additional support it can readily made resistant to the reference earthquake. On the other side of the valves a new supporting system for the ventilation duct was necessary. This is a major task and detail design is ongoing.

Minor Modifications

For a number of items which could cause secondary damage, modifications were necessary to prevent damage to safety related components. These modifications were straightforward and easy to implement. Typical examples were replacement of standard bolts by high strength bolts or additional supports to shielding walls.

CONCLUSIONS

The major structures of BR2 (reactor building, reactor pool, storage pond) can resist the reference earthquake. Modifications were necessary for the primary piping and the ventilation duct. The upper part of the process equipment building could not be qualified without extensive reconstruction work. However, it could be shown that the consequences of a collapse of this building can be accepted.

On completion of this project confidence exists that BR2 presents no hazard to the environment in the event of an earthquake of intensity VII (MSK) occurring nearby which is a very unlikely event. It cannot be guaranteed that the installation would remain operational after such an event. This conclusion is due to the fact that after scram only passive cooling of the reactor is necessary, combined with the low seismic demand.

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