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STRUCTURAL ASSESSMENTS OF POSSIBLE STEAM-EXPLOSION-INDUCED DAMAGE TO A PWR

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1 INTRODUCTION

In a severe reactor accident in a PWR melt may enter the water in the lower head. It has been postulated that if sufficient melt becomes involved in a steam explosion, vessel failure would ensue. Missiles generated by failure of the Upper Head (UH) of the Reactor Pressure Vessel (RPV) would then threaten the containment. It is generally believed that this way of breaching the containment has a low probability, even if core meltdown has occurred [1, 2]. Recently, the probability of containment failure following an in-vessel steam explosion has been evaluated for the Sizewell B PWR [3]. This paper describes the structural assessments made for that study and addresses the energy dissipated by key internal structures as well as failure of the UH. Figure 1 shows the geometry of the reactor and Table 1 shows the dimensions of relevant components.

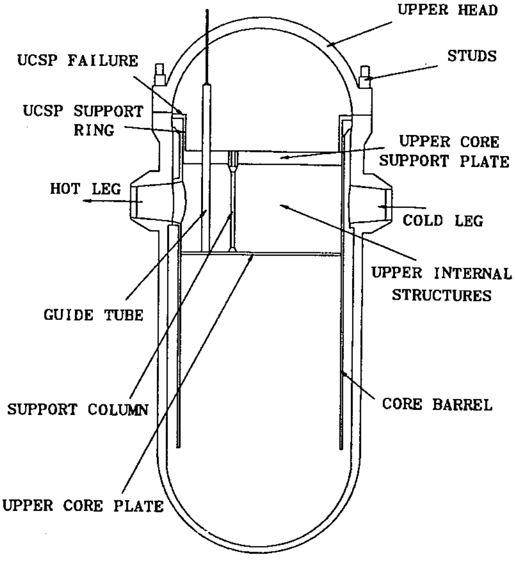

FIGURE 1. SIZEWELL B PWR GEOMETRY.

Failure of the UH is most likely if the steam explosion drives a slug of material upwards in the vessel. The slug is composed of a mixture of core debris and coolant. The interactions of this slug with the internal structures of the RPV must be considered. The starting point in these assessments is the impact of a slug of fluid on the underside of the Upper Internal Structures (UIS). Collapse of the UIS will lead to load transmission to the Upper Core Support Plate (UCSP) which may deform and fail. If such a failure occurs the combined mass will be driven upwards crushing the guide tubes between it and the UH before impacting on the head itself. Possible UH failure mechanisms are gross plastic overload of the head material and failure of the 54 studs securing the head. Failure of the UH is determined by the energy with which the head may be impacted and this is governed by the initial slug energy and the energy which is dissipated by deformation of structures within the RPV.

Table 1. Reactor Dimensions.

Component	Inner Diameter m	Thickness m	Length m	Comment
Head	4.240	0.175	-	
Studs	0.178	-	0.923[1]	1 - Effective stud length
UCSP	3.740	0.305[2]	-	2 - Flange thickness 0.127 m
Guide Tube	0.172	0.006	2.130[3]	3 - Maximum length above UCSP 3.140 m
Support Column	0.061	0.014	2.130	
UIS	3.740	-	2.510	

2 STRUCTURAL ASSESSMENTS

2.1 Material Properties

The structural assessments for the UIS and the UCSP failure follow the methodology used by Theofanous et al [2]. Based on extensive studies of the available literature, in addition to their own data, Theofanous [2] derived a set of material properties which accounted for strain rate and temperature effects. The internal structures of the RPV are made of the same material as that used in the Theofanous assessments [2], consequently, the material properties quoted in [2] have been used for structural assessments of the reactor internals. The RPV material properties have been assessed separately as the material is not exactly the same as that used by Theofanous [2]. The material properties used are shown in Table 2.

Table 2. Material Properties.

Material	Young's Modulus GPa	Yield Stress MPa	Hardening Modulus GPa	UTS MPa	Strain at UTS	Reduction of Area	Poisson's Ratio	Density kgm^{-3}
Internal Structures	180	240	2.0	641	0.51	0.7	0.3	7950
Upper Head	180	300	2.0	552	0.13	-	0.3	7950
Studs	175	707	2.8	800	0.01	-	0.3	7950

The material specifications were; type 304 stainless steel for the internal structures, and carbon steels SA508 class 3 for the RPV and type SA540 class 3 for the head studs.

2.2 UIS Collapse

Theofanous [2] performed small scale experiments to determine the load-deflection characteristics of the UIS. The results obtained were scaled up to the reactor dimensions in their study. The load-deflection behaviour for the Sizewell B UIS has been estimated by scaling the results obtained by Theofanous to account for differences in dimensions as well as the failure load of the UCSP (see Section 2.3) which forms the end point of the curve. Integration of the area under the load-displacement curve yields the energy absorbed. This was obtained as 331 MJ for the Sizewell B data.

2.3 UCSP Failure

The UCSP is supported at its flange which is clamped between the UH and the body of the RPV. Theofanous [2] assumed that the UCSP would fail by shearing of the flange as a result of the loading imposed on it by the UIS. The failure load and energy absorbed were estimated using the equations:

$$F_f = 0.6\,(2\pi r t)\sigma_u \tag{1}$$

$$E_f = 0.6\sigma_{flow}A_c t(RA) \tag{2}$$

where σ_u is the ultimate tensile stress, t is the thickness of the material to be sheared, r is the radius at which shearing occurs, σ_{flow} is the flow stress, A_c is the area to be sheared and RA is the fractional reduction in area in a tensile test. For the relevant parameters the load required to produce shearing is 574 MN and the failure energy is 35 MJ.

Theofanous assumed that when failure of the UCSP occurred the UCSP would be undamaged. However, calculations suggest that the UCSP support ring will buckle and the base plate will deform before failure of the flange. The load required to cause axial buckling of the support ring can be estimated from [4]:

$$F = 6\sigma_o t_o\,(D t_o)^{0.5} \tag{3}$$

where σ_0 is the yield stress, t_0 is the wall thickness, and D is the cylinder diameter. Using the relevant parameters for Sizewell B the axial collapse load of the support ring is obtained as 57 MN, hence this collapse would occur before shearing of the support flange. The energy dissipated in completely crushing the support ring is estimated as 51 MJ.

The collapse of the UIS would apply a distributed load over the base plate of the UCSP. The load required to cause plastic collapse of a circular plate with a fixed boundary is given by [4]:

$$F_o = 12\pi\frac{\sigma_o h_o^2}{4} \tag{4}$$

where h_0 is the plate thickness. The collapse load for the Sizewell B UCSP is calculated as 211 MN. Consequently, deflection of the base plate is likely to occur before failure of the support flange. The deflection of a circular plate under a distributed load is related to the load by [4]:

$$F = F_o\left(1 + \frac{5}{12}\left(\frac{\delta}{h_o}\right)^2\right) \tag{5}$$

where δ is the displacement at the centre of the plate. This equation has been solved for values of δ up to the failure load of the UCSP at which point the central deflection is 0.62 m. Assuming the base plate deforms into a parabola allows an assessment of the energy involved in deforming the base plate to be made. For the Sizewell B parameters this is obtained as 107 MJ.

2.4 Guide Tube Collapse

The guide tubes extend from the UIS up through the UCSP and UH to the control mechanisms above the UH. If the UCSP is deformed or failed there is the potential to crush the section of the guide tubes between the UCSP and the UH assuming that the connection between the UH and the guide tubes does not fail allowing the guide tubes to be pushed up through the UH. If the guide tubes are crushed they will be compressed to different amounts depending on their position in the UH and the deformed shape of the UCSP. An assessment has been made using equation (3) of the post collapse buckling load of the tubes and the energy dissipated in crushing them. If the UCSP base plate remains flat the energy absorbed is 33 MJ. If the tubes are crushed to their maximum extent the energy absorbed is 91 MJ. However, it is unrealistic to assume that the guide tubes could be crushed over such a distance as at some stage they would lock up and further compression would not absorb much energy.

2.5 Upper Head Failure

Assessments have been performed using finite element techniques of the impact of the slug/UCSP/UIS on the UH. Several calculations were performed to examine the effect of impact velocity, contact area, and material properties. The mesh used is shown in Figure 2. The impacting mass was taken as 160 tonnes and impact velocities of 37.75 ms^{-1} and 107 ms^{-1} corresponding to kinetic energies of 114 MJ and 917 MJ were considered. The impacting object was modelled as lumped masses and these were assigned over two areas. Firstly, three lumped masses were used over an area corresponding to contact of the UCSP support ring. This case represented impact by an undeformed UCSP. Secondly, lumped masses were spread over an area from the centre of the head to a diameter corresponding to the UCSP. In this case the UCSP was assumed to have deformed to the extent where it has the same curvature as the UH thus giving the maximum contact area.

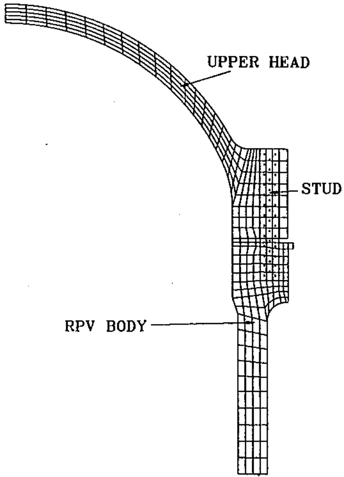

FIGURE 2. FINITE ELEMENT MESH

Axisymmetric calculations were performed with the ABAQUS code [5]. The pre-stress in the studs was also represented. The material properties were adjusted for areas where significant penetrations existed and for the studs which were represented in the model as an annular ring.

The results were interpreted by examining levels of plastic strain at stages in the calculations. Failure of the head was deemed to occur if levels of plastic strain exceeded a given level across the thickness of the head. Two failure levels were considered; 12% and 20% plastic strain. For the higher impact velocity the UH was failed in all cases within 3 ms for both failure criteria. Failure occurred between the edge of the impact area and the top of the flange of the head. For the lower energy loading failure was not produced with the concentrated loading, however, little additional energy would have been required. With the distributed loading failure of the head did occur but at the very apex of the head and this would not produce a free-flying missile. Figure 3 shows the deformation of the UH for the upper bound energy case with a concentrated load. Figure 4 shows the plastic energy dissipation as a function of time.

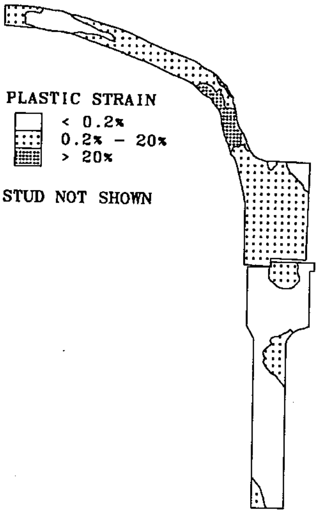

FIGURE 3. PLASTIC STRAIN CONTOURS AT 2.87 ms AFTER IMPACT.

These calculations provide estimates of the possible bounds of failure energies for the UH. The lower bound value of 120 MJ was obtained with the upper bound energy case, a concentrated impact load and a failure criterion of 12% plastic strain. The upper bound value of 291 MJ was obtained with the upper bound impact energy, a concentrated impact load, and a failure criterion of 20%. An additional case was studied where material properties based on the Theofanous work [2] were used instead of the lower values derived as part of this study. This produced an increase in the upper bound failure energy of 50 MJ. In all the calculations the stud strains remained very low.

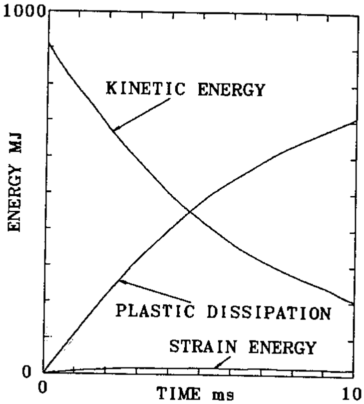

FIGURE 4. ENERGY VARIABLES AGAINST TIME.

3 DISCUSSION AND CONCLUSIONS

Assessments of the energy dissipated following impact by an explosively driven slug and some components of the upper part of the Sizewell B PWR have been made by hand calculation and finite element assessment. The energy values derived have been used in a larger probabilistic assessment for containment failure of the Sizewell B reactor [3]. In such a complex assessment it should be remembered that the energy values obtained can only be approximate because of the methods applied and the assumptions necessary in order to perform the analyses. While more complex assessments could be developed this is not necessary at this stage as the results are sufficient for use in the main assessment from which the key stages in the process can be identified. Resources can then be devoted to these areas if necessary. The structural assessments also provide a useful indication of how the reactor structures might respond to an in-vessel steam explosion. The results suggest that UIS collapse would occur simultaneously with collapse of the UCSP support ring and deformation of the UCSP base plate. Failure of the UCSP would probably occur at its support flange and impact of a large mass on the UH would occur. If UH failure was generated this would probably occur by shearing of the head material above the head flange leading to a missile with considerably less mass than the complete UH. The UH response to UCSP impact appears to be governed by the inertial restraint provided by the relatively massive UH flange and the studs play little part in the impact response. There appears to be no mechanism by which stud failure could be generated before failure of the head material as a result of UCSP impact. Failure of the UH as a result of stud failure can therefore be discounted.

4 REFERENCES

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