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INTRODUCTION

Boiling water reactors (BWRs) incorporate many unique structural features that make their expected response under severe accident conditions very different from that predicted in the case of pressurized water reactor accident sequences [1]. The effect of the BWR procedural and structural differences upon the progression of a severe accident sequence during the period preceding movement of core debris into the reactor vessel lower plenum has been discussed previously [2]. It is the purpose of this paper to briefly address the events occurring after debris relocation past the core plate and to describe the subsequent expected modes of bottom head pressure boundary failure. As an example, the calculated timing of events for the unmitigated short-term station blackout severe accident sequence at the Peach Bottom Atomic Power Station is also presented.

BWR LOWER PLENUM STRUCTURES

The internal structure of the BWR reactor vessel is illustrated in the cutaway drawing of Figure 1. For a large 1050 MW(e) BWR such as Peach Bottom, the distance from the low point (vessel zero) of the bottom head to the bottom of the core plate is 5.207 m. Depending on the water temperature, the mass of water in the bottom head varies between 72,000 and 90,000 kg, which is more than enough to quench an entire mass of molten core and associated structural material.

Forced circulation flow during power operation is downward through the jet pumps into the water volume surrounding the control rod guide tubes in the lower plenum, then through orifices in the upper portion of the guide tubes and upward into the fuel bundles of the core. The structure of a single control rod guide tube is shown in Figure 2, where the control blade is shown withdrawn, as in normal power operation. The guide tubes are 3.912 m in length, have an outer diameter of 27.94 cm, and are located on a 30.48 cm pitch. It follows that two-thirds of the lower plenum volume immediately beneath the core is blocked by the control rod guide tube cluster. Since the free cross-sectional area between

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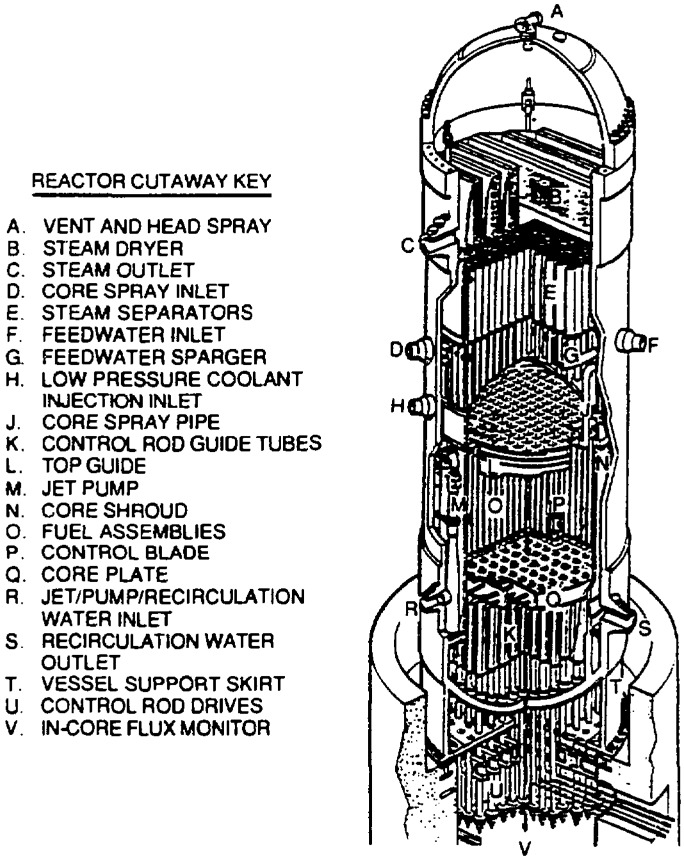

FIGURE 1. Internal structural assembly of the BWR reactor vessel. The control rod guide tubes are located immediately beneath the core.

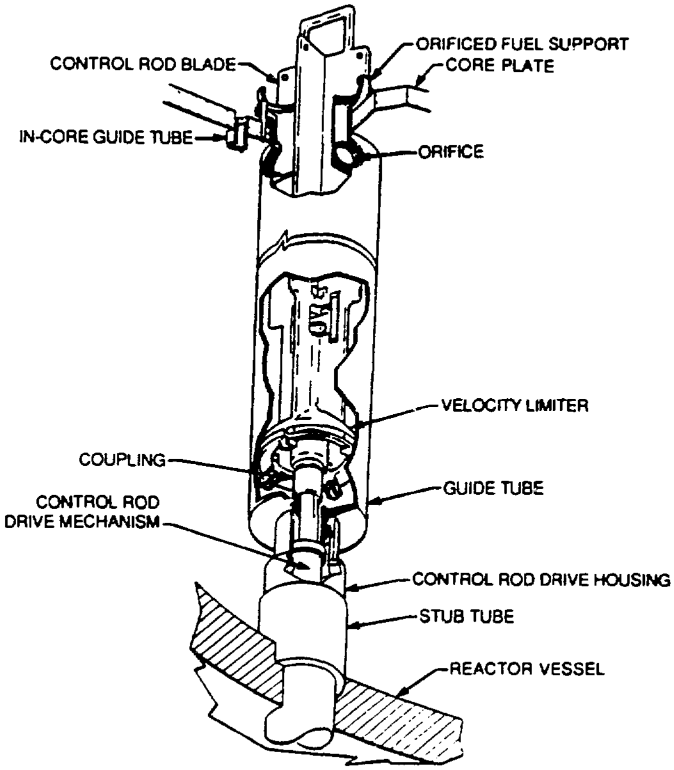

FIGURE 2. The control rod guide tubes hold the control blades when they are withdrawn from the core into the lower plenum.

any four control rod guide tubes is only 0.0316 m^2, it is obvious that the underwater forest of guide tubes in the BWR lower plenum would limit the size of downward moving debris masses and thereby promote quenching of the relocating material.

DEBRIS BED FORMATION IN THE BWR LOWER PLENUM

After structural deformation and downward relocation of molten control blade, channel box, and candling clad material (in that order) onto the dry core plate [2], local creep rupture failures of the core plate would introduce relocating material into the lower plenum water and begin the accumulation of quenched debris in the reactor vessel bottom head [3,4]. Relocation of the metal structure of the core is expected to leave the fuel pellet stacks standing until weakening, by overtemperature, of the ZrO_2 sheaths surrounding the fuel pellets and similar loss of strength by the previously molten material that tends to weld the fuel pellets together. It should be noted, given the progressive relocation methodology outlined above, that the majority of the debris entering the lower plenum is expected to be in the solid state when it enters the water.

As the relocated core material accumulates in the BWR reactor vessel bottom head, it is expected that the composition of the quenched debris bed would vary with height. Lowermost in the bed would be the mostly metallic debris (control blades, canisters, candled clad and dissolved fuel) that had either accumulated on the core plate before local core plate failure or had subsequently relocated downward above the core plate failure locations before fuel pellet stack collapse. Higher, within the middle region of the bed, would be the collapsed fuel and ZrO_2 from the central region of the core. The initial local core plate structural failures would cause temporary bursts of steaming as the relocated metallic debris was quenched; however, with the collapse of the central core fuel pellet stacks, a constant heat source (the decay heat associated with the pellets) would be introduced to the lower plenum reservoir, initiating a rapid continuous boiloff of the lower plenum water.

After bottom head dryout, the debris bed temperature would increase, causing thermal attack and failure of the control rod guide tube structure in the lower plenum, which the debris would completely surround to a depth of two or three meters. Since the control rod drive mechanism assemblies and the control rod guide tubes support the core, the remaining standing outer regions of the core would be expected to collapse into the vessel lower plenum when these support columns fail. Thus, the uppermost portion of the completed bottom head debris bed should be composed of the collapsed metallic and fuel material from the relatively undamaged outer regions of the core. The stainless steel of the control rod guide tubes and mechanism assemblies would be subsumed into the surrounding debris as it becomes molten.

BWR BOTTOM HEAD PENETRATIONS

There are more than 200 reactor vessel bottom head penetrations in a BWR reactor vessel of the size employed at Peach Bottom, where there are 185 control rod drive mechanism assembly penetrations, 55 instrument guide tube penetrations, and a 5.08 cm drain line penetration near the low point in the bottom head. The general arrangement of the in-core instrument housings and the stub tubes for the control rod drive mechanism assemblies is indicated in Figure 3. It seems certain that the initial pressure boundary failure after bottom head debris bed dryout would occur through the vessel penetrations and not by melt-through of the 21.43 cm-thick bottom head itself. This point will be discussed in the next two sections.

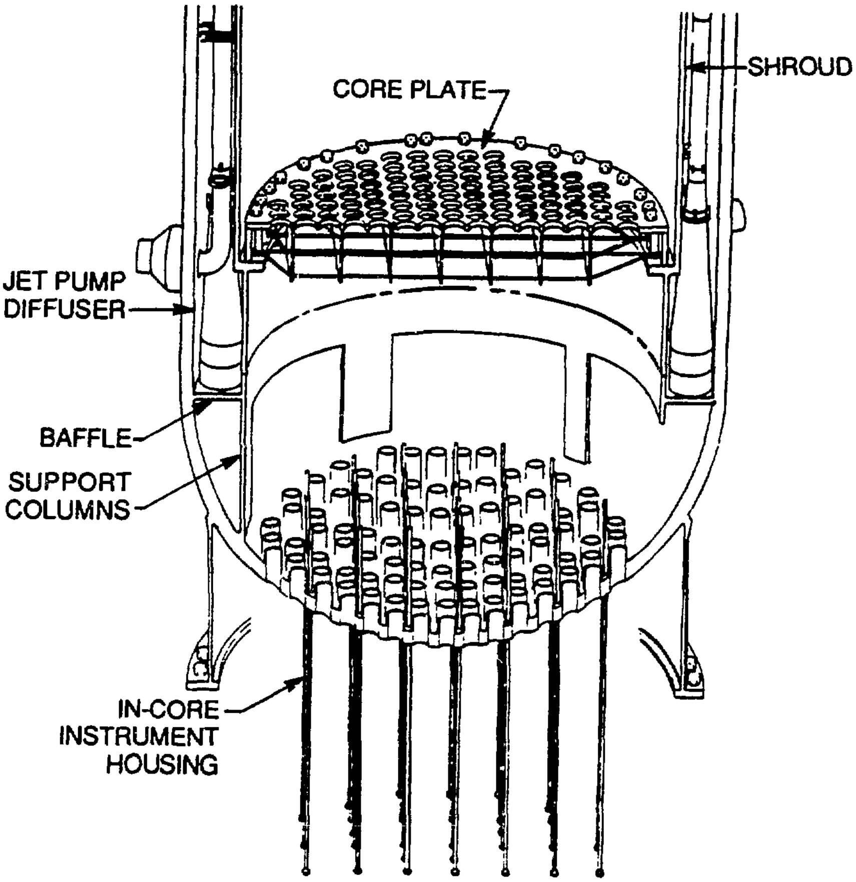

FIGURE 3. The BWR reactor vessel bottom head accommodates 241 penetrations and therefore is thicker than the remainder of the reactor vessel pressure boundary.

The bottom head of a BWR reactor vessel is clad with Inconel (thickness 0.3175 cm) while the control rod drive mechanism assembly and instrument guide tube penetrations are stainless steel. Cross sections of the control rod drive mechanism assembly and instrument tube penetrations and their weldments are illustrated in Figure 4. It should be noted that each in-core instrument tube is held in place by an Inconel-stainless steel weld located at the inner surface of the bottom head wall, whereas the control rod drive mechanism assemblies are held in place by similar welds at the upper ends of the Inconel stub tubes. These latter welds would be located about 10 cm within the bottom head debris bed expected to be formed during an unmitigated BWR severe accident.

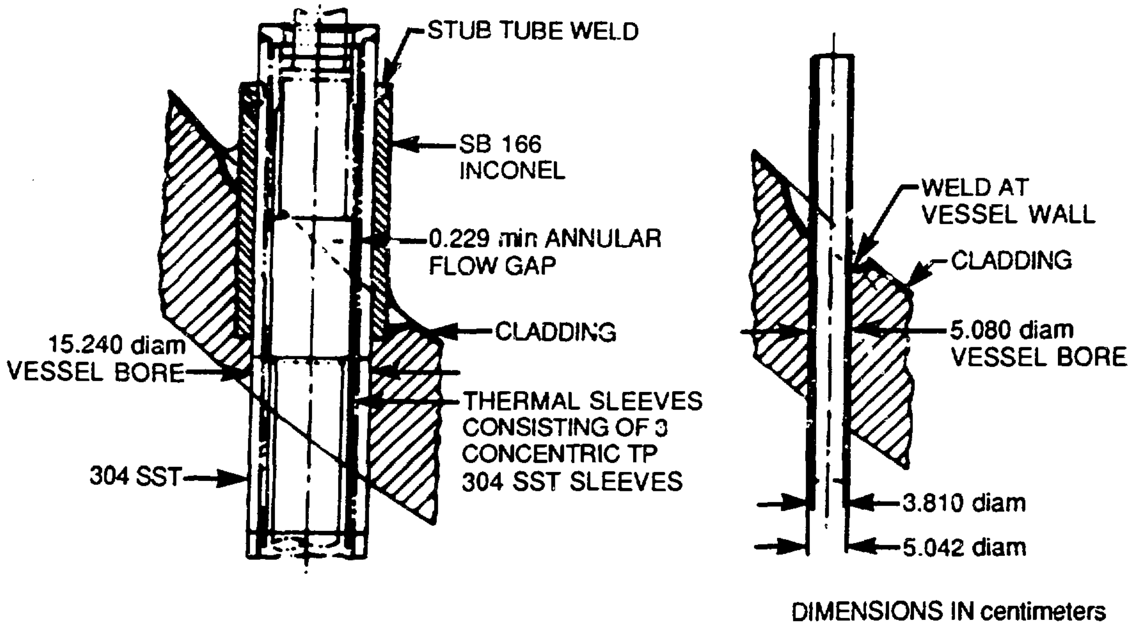

FIGURE 4. The BWR control rod drive mechanism assemblies are held in place by stainless steel-to-Inconel welds at the upper ends of the stub tubes whereas the in-core instrument tubes are supported by stainless steel-to-Inconel welds at the vessel wall.

FAILURE AT THE BOTTOM HEAD PENETRATIONS

Since the lower portion of the debris bed would be composed almost entirely of metallic materials while the UO_2 fuel pellets would constitute more than half of the central portion of the bed, the central portion would heat up much more rapidly after bottom head dryout than would the lower portion, and heat transfer within the debris bed would be toward the wall. As the temperature of the bed increased, materials in the central portion would begin to melt, migrate within the bed, freeze, and subsequently melt again. Eventually, temperatures near the walls would be sufficient to induce penetration failure and thereby open a path for gas blowdown and passage of molten material from the vessel. (In general, it is expected that most of the bottom head debris bed would still be solid at the time of penetration failure and initial vessel blowdown, so that relatively little of the debris would be expelled during the initial vessel blowdown.)

Since the stainless steel-to-Inconel welds supporting the control rod drive mechanism assemblies are located above the vessel wall, at the top of the stub tubes and within the adjacent portion of the debris bed, it is expected that these welds would reach failure temperatures first. The failure mechanism would be creep-rupture and would occur at lower temperatures if the reactor vessel remained pressurized at the time of failure. J. T. Han provides guidance on the time required at various temperatures and pressures for this failure mechanism for Inconel-to-stainless steel welds [5].

Although reactor vessel bottom head pressure boundary failure should occur first at the upper stub tube welds, this failure is less important to debris relocation from the vessel than the subsequent instrument tube failures. This is because BWRs are required to have a structure beneath the vessel bottom head that would limit the downward movement of any control rod mechanism assembly to about 3 cm in the event of failure of its stub tube weld. (The concern is to guard against the expulsion of a control blade from the core during power operation.) Since the vessel bottom head is 21.43 cm thick, this limited downward movement could not open a wide path through the vessel wall even if the control rod drive mechanism assembly were melted within the debris bed. This is not true for the instrument tubes, for which there is no provision to limit their downward movement.

Temperatures at the inner surface of the reactor vessel wall would eventually become sufficiently high to cause failure of the welds that hold the instrument tubes in place. However, it is probable that a different mode of failure for the instrument tubes would occur first. This predicted initial failure of the in-core instrument housing guide tubes for the source, intermediate, and power range detectors (55 penetrations in all) involves melting of the portions of these guide tubes within the central portion of the bottom head derbis bed; then, when the downward relocation and freezing of molten metals has progressed to the point that molten metals are standing in the central portion of the bed, these metals could spill into the failed instrument tubes and pour through the vessel wall.

Would movement of molten metals through an instrument tube result in tube failure outside the vessel wall? Although it is known that small amounts of metallic debris did exit the vessel by this means at Three Mile Island (TMI), tube failure did not occur in this accident. This feature of the accident sequence has been extensively analyzed [6–9]. With regard to consideration of the applicability of the TMI results to the case of a BWR undergoing a severe accident, it should be recognized that the BWR instrument tube internal diameter is more than twice as large (3.810 vs 1.560 cm) while the BWR tube wall thickness is only slightly larger (0.61' vs 0.554 cm). In addition, the TMI reactor vessel bottom head was always filled with water, whereas for the BWR, instrument tube penetration failure is only predicted to occur after bottom head dryout, when the portion of the instrument tubes immediately beneath the vessel would be dry as well.

L. J. Ott at Oak Ridge National Laboratory has recently applied the approach of A. W. Cronenberg for TMI [6] to the BWR severe accident situation, substituting the appropriate BWR structural dimensions for the TMI values. This work provides the following observations:

1. The penetration distance for refreezing of molten debris within the BWR instrument guide tube walls is at least twice that of TMI; that is, the melt would be expected to travel more than twice as far ex-vessel as did the TMI melt.

2. The estimated peak temperature of the BWR instrument tube wall ex-vessel is significantly higher than for the TMI case. This establishes the need for a more precise calculation of the BWR instrument tube response than can be provided by Cronenberg's steady-state constant heat source approach.

In recognition of the need, L. J. Ott has developed a detailed transient model of the melt, vessel wall, instrument tube wall, and structures interacting (radiation heat transfer) with the instrument tubes beneath the reactor vessel. A metallic pour with no superheat and no heat generation at a pour rate estimated by the BWRSAR code [4] was used to drive this BWR instrument guide tube failure analysis model. The metallic pour is estimated to freeze and thereby plug the instrument tube at a distance from the reactor vessel about twice that sustained at TMI. Although the tube wall is not predicted to melt, the BWR instrument tube is predicted to sustain temperatures above 1478 K for a period of minutes in the simulation. Creep-rupture considerations ensure that the tube wall could not mechanically survive these temperatures for long. With an estimated weight of 90 kg for ex-vessel guide tube, internals, and debris plug, stress in the wall area for a depressurized reactor vessel would be slightly more than 1×10^6 N/m^2 which for 304 stainless steel at temperatures above 1478 K would produce rupture on the order of tens of seconds. Thus, instrument tube failure after bottom head dryout for an unmitigated BWR severe accident seems assured.

Downward relocation of molten material from the central portion of the bottom head debris bed through the instrument tube locations is expected to cause ablation of the lower portion of the debris bed as well as ablation of the vessel wall itself. This ablation is modeled in the BWRSAR code [4] based upon experimental observations at Sandia National Laboratories [10,11]. See also the work with regard to bottom head penetration failure in Ref. 12.

CREEP-RUPTURE FAILURE OF THE BOTTOM HEAD ITSELF

After bottom head dryout, heat transfer from the central portion of the bottom head debris bed would increase the temperature of the reactor vessel bottom head wall, eventually to the point of failure by creep-rupture. However, about 95% of the wall stress under normal operating conditions is due to the internal vessel pressure and the BWR Owners Group Emergency Procedures Guidelines [13] direct the control room operators to manually depressurize the reactor vessel during a severe accident sequence long before the onset of debris relocation into the lower plenum. The wall stress after bottom head dryout with the reactor vessel depressurized and taking into account the weight of debris resting on the bottom head and the weight of the bottom head itself is approximately 1×10^6 N/m^2. At this low stress level, creep rupture failure would occur only at temperatures approaching the melting temperature of the ASME SA-508 Class 2 carbon steel wall, and the vessel instrument tube penetrations are predicted to fail long before this. Thus, most of the metallic debris would have left the vessel by means of the penetration failures before failure of the bottom head itself.

It should be recalled that one of the dominant BWR severe accident sequences is Long-Term Station Blackout, for which the reactor vessel could not be depressurized [2]. For this accident sequence, the tensile stress in the bottom head wall would be approximately 26×10^6 N/m^2 so that creep-rupture failure would be expected to occur about four hours after the wall temperature reached 1225 K. Nevertheless, BWRSAR code calculations again predict that penetration failure would occur within a few minutes after bottom head dryout when the maximum wall temperature is about 800 K. Therefore, it is expected that most of the metallic debris would have left the reactor vessel by means of the instrument tube penetration failures for this case as well.

SHORT-TERM STATION BLACKOUT

The recent ASEP results assign 30% of the total risk of Peach Bottom core melt to the short-term station blackout accident sequence [14]. The estimated timing of events for this relatively fast-moving accident sequence as recently calculated with the BWRSAR code at Oak Ridge National Laboratory [3] is provided in Table 1. Events prior to central fuel column collapse have been discussed in a previous paper [2].

TABLE 1. Timing of events for Peach Bottom short-term station blackout

Event	Time after scram, s
Swollen level below top of core	2 412
ADS system actuation	4 800
Core plate dryout	4 854
Debris relocation begins	7 944
First local core plate failure	7 962
Central fuel column collapse	13 368
Lower plenum dryout	15 294
Bottom head penetration failure	15 300
Failure of the reactor vessel bottom head wall	28 020

As indicated, the BWRSAR code predicts a delay of about 3½ hours between the time of initial bottom head penetration failure and the time that the bottom head (beneath the vessel skirt) is melted through. The calculation takes into account the effect of ablation of the vessel wall as molten materials pour through the instrument tube penetrations.

SUMMARY

This paper has briefly described the approach taken by the BWRSAT Program at Oak Ridge National Laboratory towards understanding the probable sequence of events for an unmitigated BWR severe accident. There are many associated uncertainties, and experimental verification of the approach is certainly desirable.

For an unmitigated BWR severe accident involving the progressive relocation of material from the core region into the lower plenum of the reactor vessel, the control rod guide tube structure and the large amount of water in the lower plenum would be expected to provide for distribution and quenching of the relocating debris. Since the earliest relocation of materials from the core region would consist of metals from the control blades, channel boxes, and cladding, the lower portion of the bottom head debris bed should be metals-rich. The subsequent collapse of fuel pellet stacks into the lower plenum would provide an underwater decay heat source and provide for continuous boiloff of the surrounding water. After bottom head dryout, the debris bed temperature would begin to increase.

The cluster of control rod guide tubes in the lower plenum would be heated by the surrounding debris bed and would be weakened at high temperatures to the point of failure. Loss of control rod guide tube strength would cause collapse of the remaining standing outer regions of the core that are supported by the guide tubes. This collapse would form the upper portion of the bottom head debris bed while the stainless steel mass of the control rod guide tubes would be subsumed into the surrounding debris bed as they melt. Thus, there is expected to be a large amount of stainless steel included in BWR bottom head debris.

As the bottom head debris reaches high temperature, failure of the bottom head pressure boundary would occur at some point. Penetration failures can occur by weakening of the stub tube welds supporting the control rod drive mechanism assemblies or by failure of the instrument tube welds at the reactor vessel wall. However, failure of a stub tube weld would only cause a small downward motion of the associated control rod drive mechanism assembly, and therefore, although gas blowdown would be initiated by such a failure, gross release of debris from the vessel would not.

For the instrument tube, although there is nothing to prevent its complete detachment from the vessel given weld failure at the vessel wall, it seems probable that an earlier failure would be by opening of the tube in the middle (hottest) point of the bottom head debris bed with subsequent spillover of molten material into the tube with passage through the vessel wall, causing heatup and creep-rupture of the tube just outside the wall. Instrument tube failures in this manner would provide pathways for release of molten debris from the vessel.

The individual components of the debris bed would be expected to leave the vessel in the order in which they reach their melting points and transform to the liquid state. Solid metallic material surrounding the lower portion of the original instrument guide tube locations would be ablated into the molten material flowing from the reactor vessel via these pathways.

Gross failure of the portion of the reactor vessel bottom head underneath the vessel support skirt would be expected to occur long after the penetration failures discussed above. The reactor vessel bottom head wall is thick, and there is relatively little wall stress after the vessel is depressurized. BWR severe accident sequence calculations with the BWRSAR code predict failure of the bottom head wall only after the majority of the metallic debris has left the vessel.

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