# FAILURE MODES OF THE BWR REACTOR VESSEL BOTTOM HEAD

S. A. Hodge      L. J. Ott

Boiling Water Reactor Severe Accident Technology Program
Oak Ridge National Laboratory
Oak Ridge, Tennessee

Letter Report

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CONTENTS

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## 1. INTRODUCTION

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 2-inch (5.08 cm) drain line penetration near the low point of 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 Fig. 1.

The BWR bottom head is clad with Inconel [thickness 0.125 inch (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 Fig. 2. It should be noted that each in-core instrument tube is held in place by an Inconel-to-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 four inches (ten cm) within the bottom head debris bed expected to be formed during an unmitigated BWR severe accident.

Given the perforated status of the BWR bottom head, it is reasonable to expect 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 8 7/16 inch (21.43 cm) thick bottom head itself. Available information and results of analyses to demonstrate this point are the subject of this letter report.
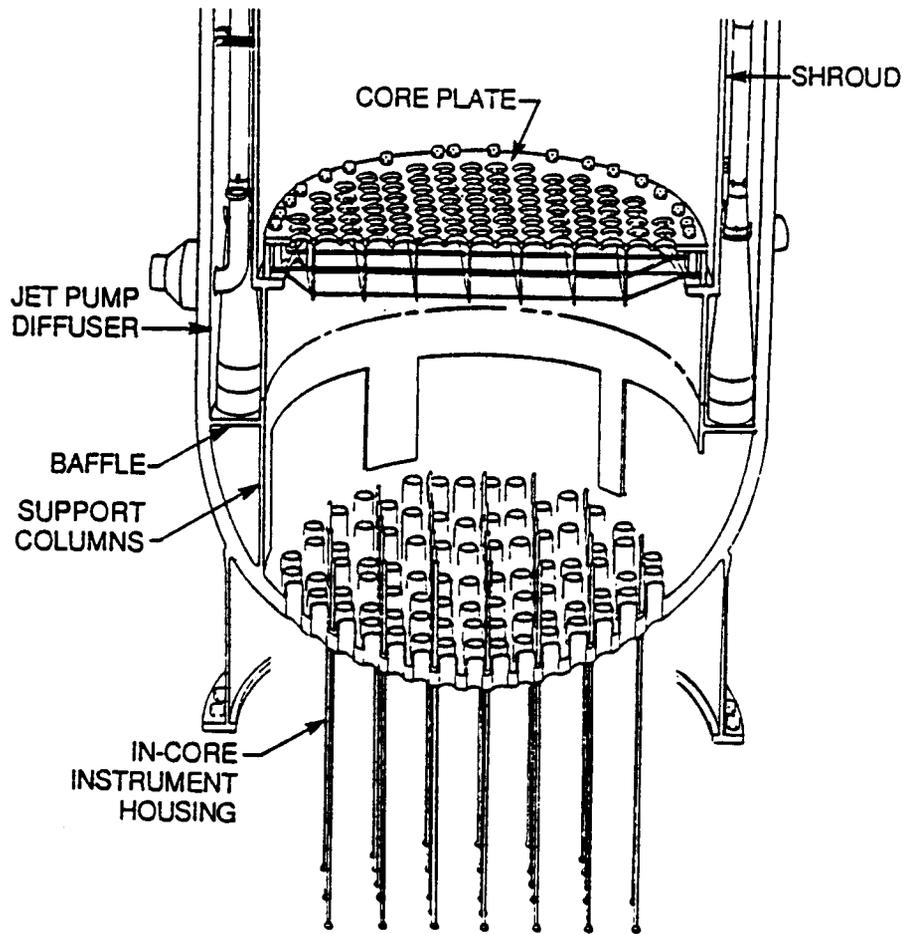
Fig. 1. The BWR reactor vessel bottom head accommodates 2·11 penetrations and therefore is thicker than the remainder of the reactor vessel pressure boundary.



DIMENSIONS IN centimeters
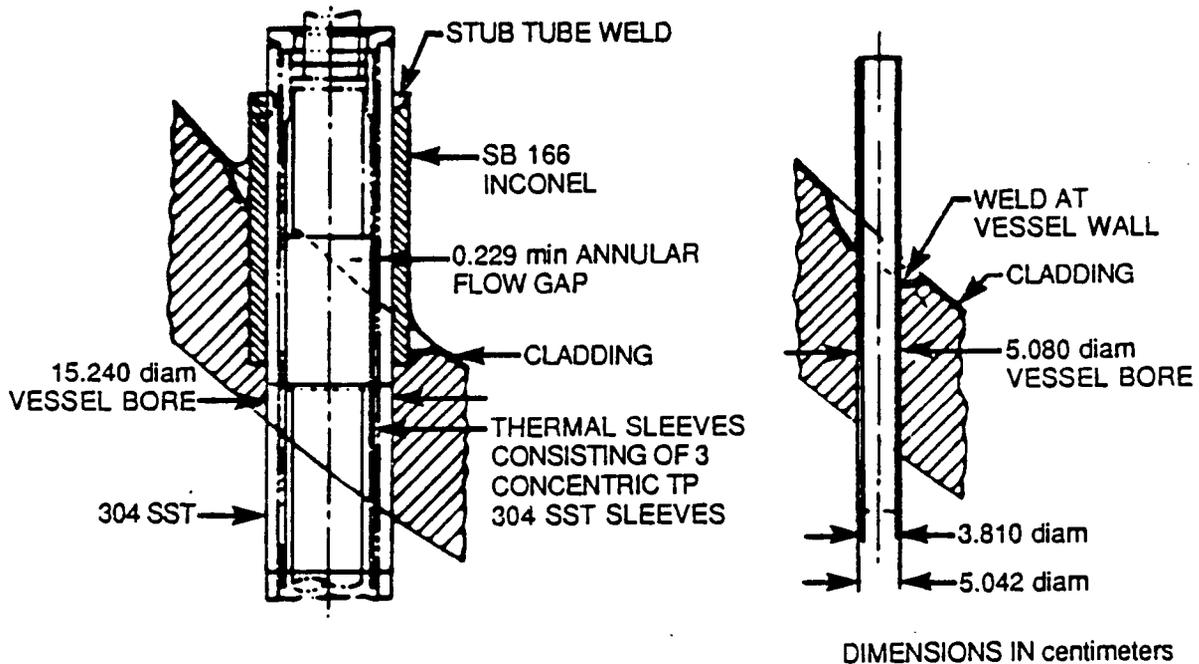
Fig. 2. The BWR control rod drive mechanism assemblies are held in place by stainless steel-to-Inconel welds at the upper ends of the stub tubes, whereas the incore instrument tubes are supported by stainless steel-to-Inconel welds at the vessel wall.

## 2. BOTTOM HEAD PENETRATION EXPERIENCE AT THREE MILE ISLAND

The Three Mile Island (TMI) Unit 2 reactor vessel bottom head penetrations accommodate the PWR instrument guide tubes as indicated in Fig. 3. The portion of the penetration nozzle passing through the vessel wall is schedule 160 pipe with internal diameter 0.614 inch (1.56 cm) and wall thickness 0.218 inch (0.554 cm). The tube wall thickness within the reactor vessel adjacent to the wall is 0.693 inch (1.76 cm). There are 52 such penetrations in the vessel bottom head.

Post-accident wire probing of 17 of the TMI-2 bottom-entry instrument penetration tubes revealed 16 of these to be blocked at points outside the reactor vessel.[1] Entry of debris into the penetration tubes must have been by ablation of the in-vessel portion of the penetration nozzle, as indicated in Fig. 4.

5/8 in. diam

1-3/4 in. diam

INCONEL

2 in. diam

12 in.

3/16 in SS-LINER

REACTOR VESSEL
BOTTOM HEAD

5-3/8 in.
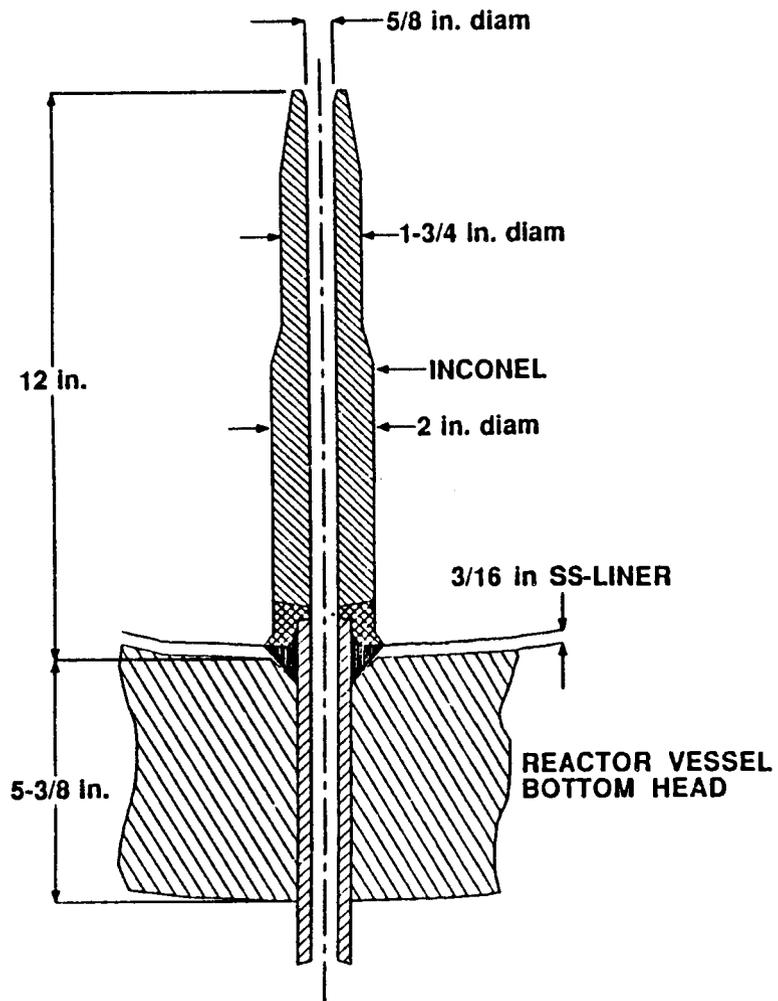
Fig. 3. The Three Mile Island (PWR) reactor
vessel bottom head penetrations are smaller than
those found in a BWR reactor vessel.
(From EGG-TMI-7222)



2B INLET

1A INLET

UPPER GRID
DAMAGE

CAVITY

COATING OF PREVIOUSLY-
MOLTEN MATERIAL ON BYPASS
REGION INTERIOR SURFACES

LOOSE CORE
DEBRIS

CRUST

HOLE IN
BAFFLE PLATE

PREVIOUSLY
MOLTEN MATERIAL

ABLATED INCORE
INSTRUMENT GUIDE

LOWER PLENUM
DEBRIS

POSSIBLE REGION
DEPLETED IN URANIUM

Fig. 4. The post-accident state of the
Three Mile Island (PWR) reactor vessel includes
an ablated incore instrument guide tube and core
debris within the exvessel portion of the tube.

# 3. BOTTOM HEAD FAILURE MODELS IN THE BWRSAR CODE

The Boiling Water Reactor Severe Accident Response (BWRSAR) Code[2] has been developed at Oak Ridge National Laboratory to provide BWR-specific models for application in analyses of the effects of hypothetical severe accidents. It is the purpose of this chapter to discuss the rationale and basic operation of the code models for debris bed formation in the BWR bottom head and for failure of the bottom head pressure boundary.

## 3.1 The Expected Sequence of Events

As there have been very few severe accident experiments performed in BWR geometry and there have been no actual plant BWR accidents causing uncovering of the fuel, it is necessary for any analyst requested to predict the sequence of events for an unmitigated BWR severe accident to consider carefully the geometry differences from a PWR and to evaluate the effect of these differences when formulating the expected general progression of events. This approach has been followed in the development of the BWRSAR code, and the conclusions reached are discussed in the remainder of this Section.

### 3.1.1 Debris bed formation in the BWR bottom head

After structural deformation and downward relocation of molten control blade, channel box, and candling clad material (in that order) onto the dry BWR core plate,[3] local creep rupture failures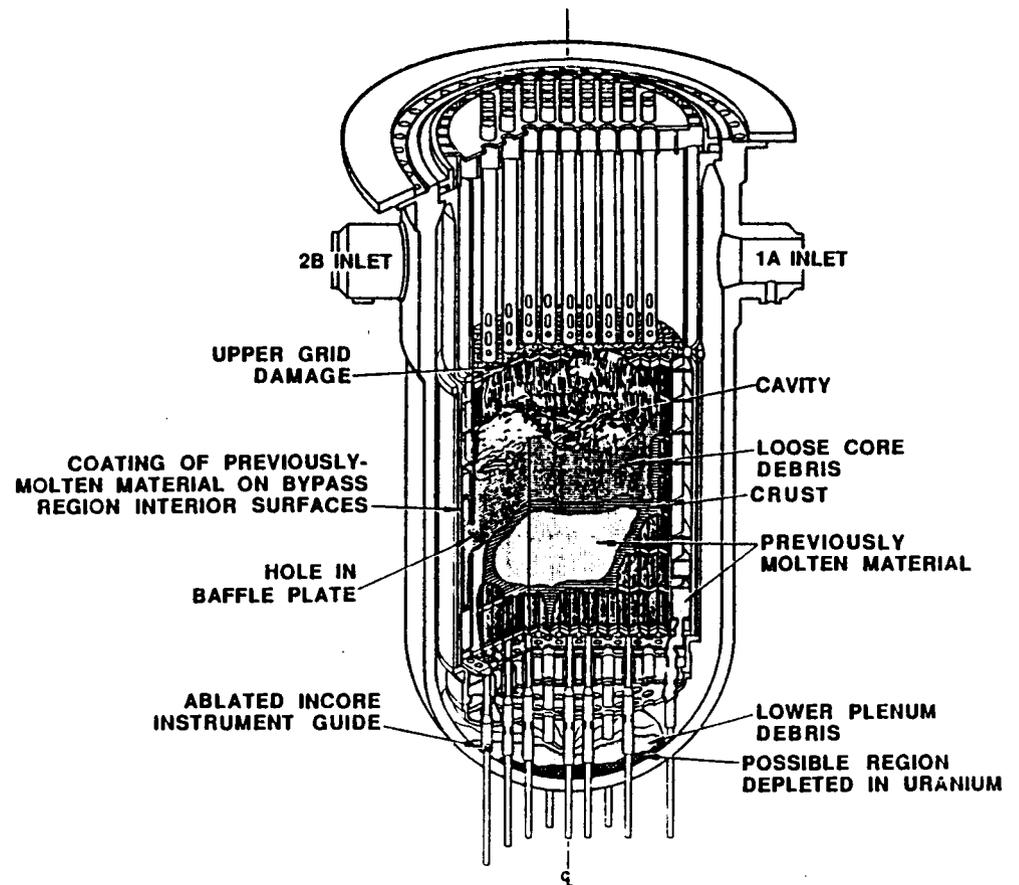 of the core plate would introduce relocating material into the lower plenum water and begin the accumulation of quenched debris in the reactor vessel bottom head.[2,4] Relocation of the metal structure of the core is expected to leave the fuel pellet stacks standing until weakening, by overtemperature, 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 about 10 feet (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.

## 3.1.2  Failure of 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 wall 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 1 inch (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 8 7/16 inch (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 debris 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.[6-8] 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 [1.50 vs 0.614 inch (3.810 vs 1.560 cm)] while the BWR tube wall thickness exvessel is only slightly larger [0.243 vs 0.218 inch (0.616 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[1] 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 exvessel as did the TMI melt.

2. The estimated peak temperature of the BWR instrument tube wall exvessel 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 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 in the exvessel region above 2200°F (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 200 lbs (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 145 psi (1 MPa) which for 304 stainless steel at temperatures above 2200°F (1478 K) would produce rupture on the order of tens of seconds. Thus, exvessel instrument tube failure after bottom head dryout for an unmitigated BWR severe accident is indicated by this analysis.

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. Information pertaining to this ablation is available from experimental observations at Sandia National Laboratories.[9,10] See also the work with regard to bottom head penetration failure in Ref. 11.

### 3.1.3 Creep-rupture failure of the bottom head

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[12] 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 145 psi (1 MPa). 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. For this accident sequence, the tensile stress in the bottom head wall would be approximately 3770 psi (26 MPa) so that creep-rupture failure would be expected to occur about four hours after the wall temperature reached 1750°F (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 725°F (660 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.

### 3.2 BWRSAR Models for Debris Bed Formation in the BWR Bottom Head

In this Section, the operation of the BWRSAR code models to represent the sequence of events for a BWR severe accident are described. After regional failures of the core plate structure occur, the code provides that relocating debris including the failed portions of the core plate itself accumulates in the reactor vessel bottom head. The standing portions of the fuel pellet stacks are modeled to fall into the bottom head by radial column. Each of the radial columns collapses if and when its axially-averaged clad temperature reaches a user-input value [currently 4400°F (2700K)], at which very little of the fuel mass in the column has become molten. The envisioned failure mechanism is weakening, by overtemperature, of the $ZrO_2$ sheaths surrounding the fuel pellets and the previously molten material that tends to weld the fuel pellet stack together. The falling masses are quenched by the water in the bottom head until the time of bottom head dryout.

The argument that the falling heated masses of core debris would be quenched in the reactor vessel bottom head is buttressed by the geometry of the structures and the large water mass present in the BWR lower head. For example, at the Peach Bottom nuclear plant there are 185 control rod guide tubes [11 inch (0.2794-m) outer diameter on a 12 inch (0.3048-m) pitch] in the vessel lower head; thus, within a unit cell the debris must pass through a 0.340 $ft^2$ (0.032-$m^2$) opening (see Fig. 5) that is 12 ft (3.7 m) in length. This, plus the fact that there is sufficient water in the bottom head [160,000-210,000 lbs (72,000-95,000 kg) depending on the temperature] to completely quench more than one molten core, leads to the assumption employed in BWRSAR that the relocated debris is quenched. It should be noted, given the progressive relocation methodology outlined above, that the majority of the debris (failed core plate regions or collapsed fuel columns) entering the lower plenum would be solid when it enters the water. The rate of quench of the relocated debris is determined by state-of-the-art debris bed models (normally Lipinski's).

Displacement of water in the lower plenum by the accumulated debris is modeled by BWRSAR. Depending on the accident sequence, this

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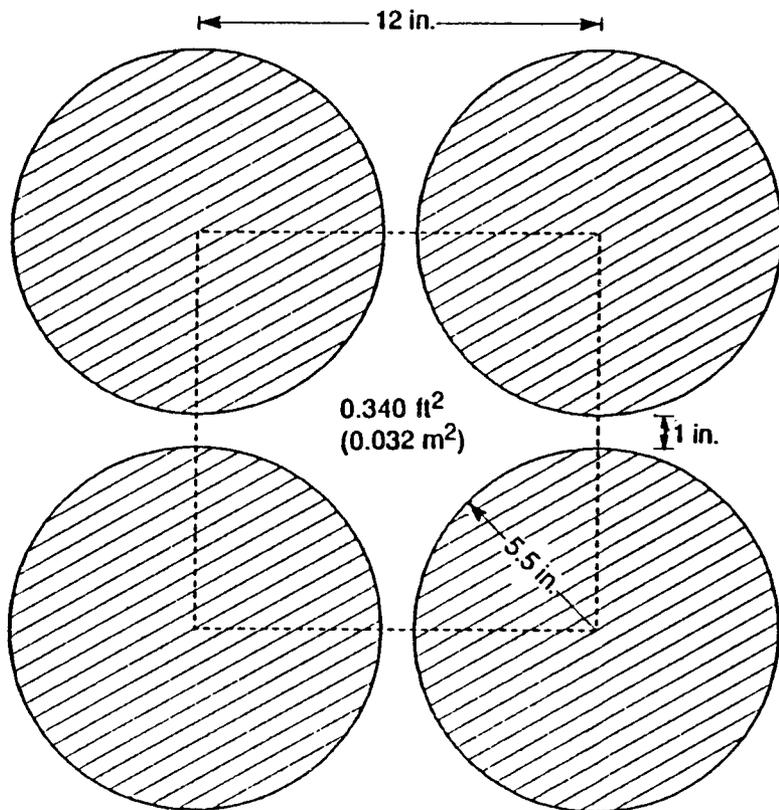
Fig. 5. Control rod guide tube spacing and available open flow area in the BWR reactor vessel bottom head.

- DEBRIS BED DISCRETIZED INTO RADIAL AND AXIAL NODES
- LOWER HEAD MODELED AT EACH DEBRIS NODE IN CONTACT WITH WALL
- HEAT GENERATION ASSOCIATED WITH PRESENCE OF FUEL
- ALL HEAT TRANSFER MODES CONSIDERED
- MASS BALANCES TRACK SPECIES AS THEY MELT, MIGRATE, REFREEZE, EGRESS FROM VESSEL
- CHEMICAL REACTION OF STEAM AND DEBRIS



Fig. 6. Description of models and illustration of noding employed for the BWR reactor vessel bottom head debris bed.

displacement can result in water being forced from the lower plenum back up into the core region after core plate dryout has occurred; the core plate is cooled whenever this happens, however, given the state of the core, the water displaced above the core plate is rapidly boiled off.

As the relocated core material accumulates in the BWR reactor vessel bottom head, the BWRSAR models recognize three layers of debris. The bottom layer is comprised of the mostly metallic debris (control blades, canisters, candled clad and dissolved fuel) that either had originally accumulated o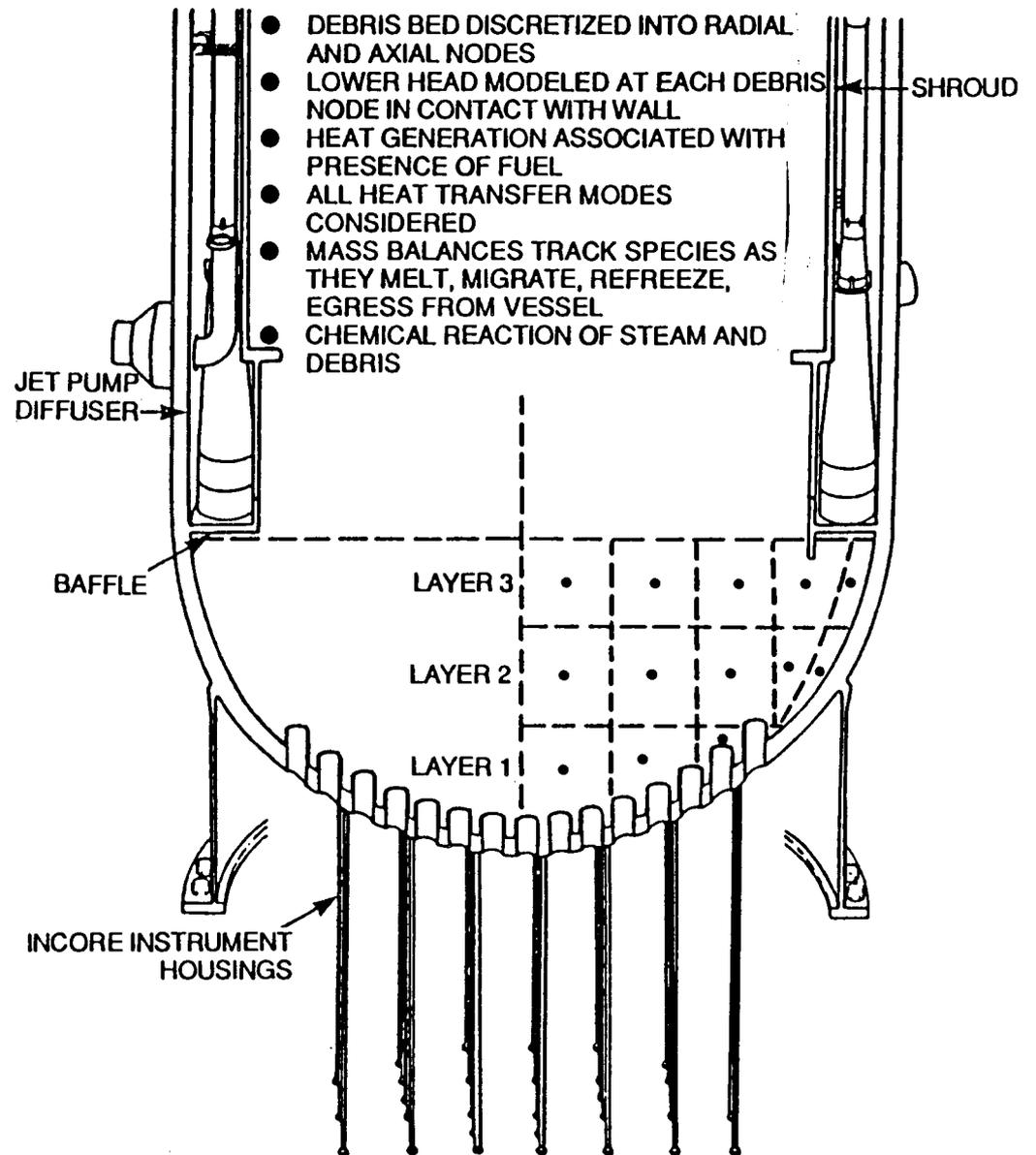n the core plate before local core plate failure, or had subsequently relocated from above the locations of local core plate failure before fuel pellet stack collapse. The middle layer is initiated by the first collapse of the fuel pellet stacks in a radial fuel column. Subsequent relocated materials, including failed core plate regions or additional collapsed fuel columns, are then added to the middle layer. The initial failure of the core plate and the formation of the bottom debris layer causes temporary bursts of steaming as the relocating debris is quenched; however, with the initiation of the middle layer, a constant heat source (the decay heat from the collapsed fuel columns) is introduced to the lower plenum reservoir which results in a rapid continuous boiloff of the lower plenum water.

After bottom head dryout, the debris in the bottom and middle debris layers begins to heat up, and it is assumed that the debris thermally attacks and fails (at a user input debris temperature) the control rod guide tubes, which the debris completely surrounds to a depth of 8 to 10 ft (2-3 m). Since the control rod drive mechanism assemblies and the control rod guide tubes support the core, the remaining standing regions of the core collapse into the bottom head when these support columns fail. Thus, the top layer of the debris bed is formed when the control rod guide tubes fail. The material (stainless steel) of the control rod guide tubes is assumed to be subsumed into the surrounding debris of the bottom, middle, and upper layers, as appropriate.

The upper debris layer consists of the collapsed outer portion of the core, any unfailed core plate regions and accumulated debris remaining at the time of control rod guide tube failure, the top guide (which is normally calculated to melt during core heatup, but is not added to the debris until control rod guide tube failure), and the portion of the control rod guide tubes that is not subsumed into the bottom and middle debris layers. The vessel structural masses as they exist at the initiation of the simulation (i.e., prior to oxidation) that are normally included in the formation of the bottom head debris bed for Browns Ferry and Peach Bottom calculations are outlined in Table 3.1.

With control rod guide tube failure and collapse of the outer regions of the core, the formation of the debris bed is complete. As described, it is discretized on formation into three vertical layers; additionally, each vertical layer is discretized into radial nodes resulting in the debris bed nodalization illustrated in Fig. 6. The

lower head of the vessel is modeled at each debris node in contact with the wall; each wall segment is also discretized radially into nodes with the outside nodes having the capability of transferring heat to the drywell atmosphere. Heat generation within the debris bed is associated with the decay heat of the fuel and with the chemical reaction of steam, passing from the vessel atmosphere through the bed, with the zirconium metal of the debris.

In the heat balances for each debris node, normal heat transfer mechanisms are employed for node-to-node and node-to-wall energy transfer. Additionally, radiation and convection from the surface nodes to the vessel gaseous contents and to intact structures above the debris bed are considered. Radiation to the shroud and axial conduction along the vessel wall causes boiloff of water remaining in the downcomer jet pump region. Also included in the nodal heat balances are the change-of-phase heat of fusion of species (or eutectics) as they melt or refreeze within the bed. Mass balances track species as they melt, migrate, refreeze, and eventually egress from the vessel.

### 3.3  BWRSAR Models for Reactor Vessel
### Bottom Head Penetration Failure

As the temperature of the debris bed increases, the BWRSAR code calculates the melting, migration, freezing, and remelting of the materials composing the bed. The eutectic mixtures formed and the associated melting temperatures assigned by default within the BWRSAR code are listed in Table 3.2. (Other combinations of mixtures can be specified by user input.) Eventually, temperatures near the wall are such that penetrations fail and a path is opened for gas blowdown and passage of molten material from the vessel. In general, most of the debris bed is still solid when penetration failure and vessel blowdown occur, so that relatively little of the debris is expelled during blowdown.

With more than 200 reactor vessel bottom head penetrations in a BWR reactor vessel of the size employed at Peach Bottom, it seems most probable that the initial pressure boundary failure under the conditions of bottom head debris bed dryout would occur through the vessel penetrations, not by melt-through of the bottom head itself. The lower head of a BWR is clad with Inconel 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 Fig. 2. One method of failure of the penetration structure considered by the BWRSAR code is creep/rupture of the Inconel/stainless steel welds by which the penetration assemblies are held within the reactor vessel.

The BWRSAR models also provide for a loss of the reactor vessel pressure boundary that would be initiated by failure of the in-core

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housing guide tubes associated with the local power range detectors (Fig. 7) and the source and intermediate range detectors (Fig. 8). Melting of upper portions of these guide tubes within the bottom head debris bed would provide an annular flow path within the tubes by which molten metals could pour through the reactor vessel wall. Passage of molten metal into the ex-vessel portion of a guide tube is considered sufficient to cause immediate failure of the tube pressure boundary.

Since the bottom layer of debris is comprised almost entirely of metals while $UO_2$ constitutes more than half of the middle layer, the middle layer heats up much more rapidly after bottom head dryout than does the bottom layer. For this reason, melting of the in-core housing guide tubes would occur first in the middle layer. The criteria employed in BWRSAR for initiation of reactor vessel blowdown through the in-core instrument housing guide tubes are first, that the middle layer debris bed temperature be above the melting point of stainless steel and second, that the level of liquid metal within the reactor vessel bottom head has risen into the middle debris layer so that molten metal is available to pour into the failed portion of the tubes.

After failure of the reactor vessel pressure boundary, a leak path from the vessel to the drywell atmosphere is created. Subsequently, the vessel gaseous content blows down if the reactor vessel is at pressure or, if the vessel is depressurized, slowly leaks out as the gas temperature increases and the water in the reactor vessel downcomer region surrounding the jet pumps is boiled off. The leak path for the steam generated from the water surrounding the jet pumps is up through the downcomer region, down through the core region, and out through the debris bed. Thus, the steam available in the vessel at the time of pressure boundary failure would pass through the debris and would react with the zirconium metal during its passage.

Only the steam/zirconium reaction is modeled in the BWRSAR debris bed models, but this is a major heat source in the nodal energy balances, particularly for cases in which the reactor vessel is pressurized at the time of penetration failure. Stainless steel oxidation in the bottom head debris is not modeled since this is expected to be a secondary effect and because the temperatures at which rapid stainless steel oxidation occurs are close to the melting point; thus stainless steel tends to relocate rather than to undergo excessive oxidation. The result is that much of this metal is expected to leave the vessel in a molten state without oxidizing. Obviously, there are uncertainties in this area. These concerns definitely indicate the need for experimental resolution because a great amount of hydrogen is predicted to be generated in the vessel bottom head during blowdown via the BWRSAR modeling approach.

Application of the current BWRSAR models leads to a protracted, time-dependent pour of debris from the reactor vessel. Molten material moves downward from one node to another within the debris bed as long as void space remains within the lower node. Once the interstitial spaces in the lower nodes are filled, the molten liquid can move horizontally
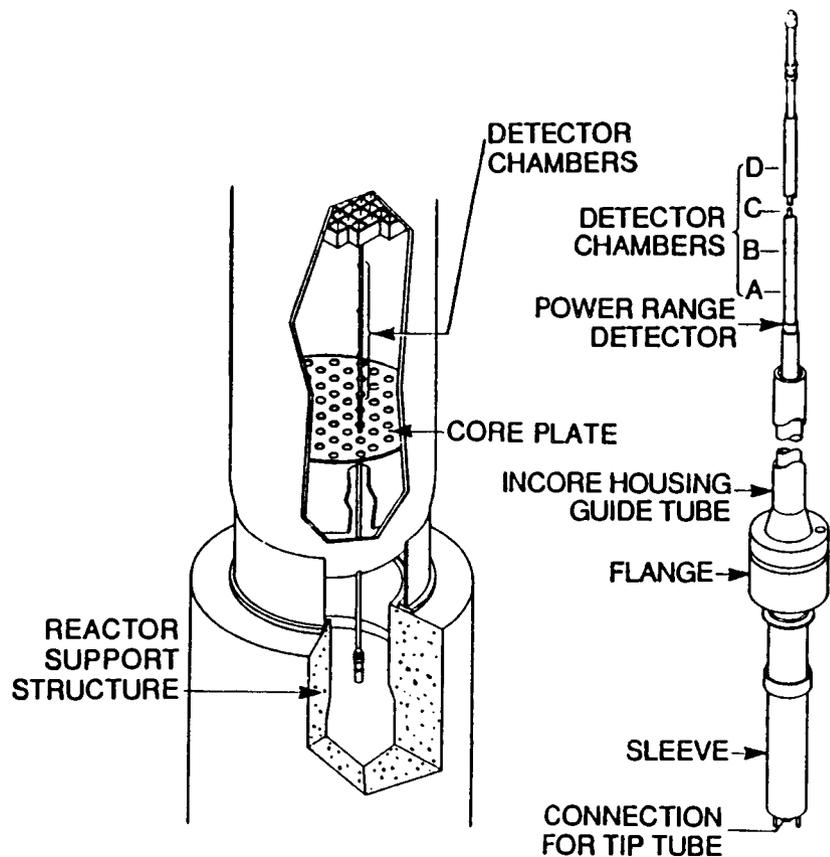
Fig. 7. Mechanical arrangement of one of the 43 Local Power Range Detector assemblies. The annular gap clearance between the in-core housing guide tube and the instrument tube is specified as 0.40 inches.
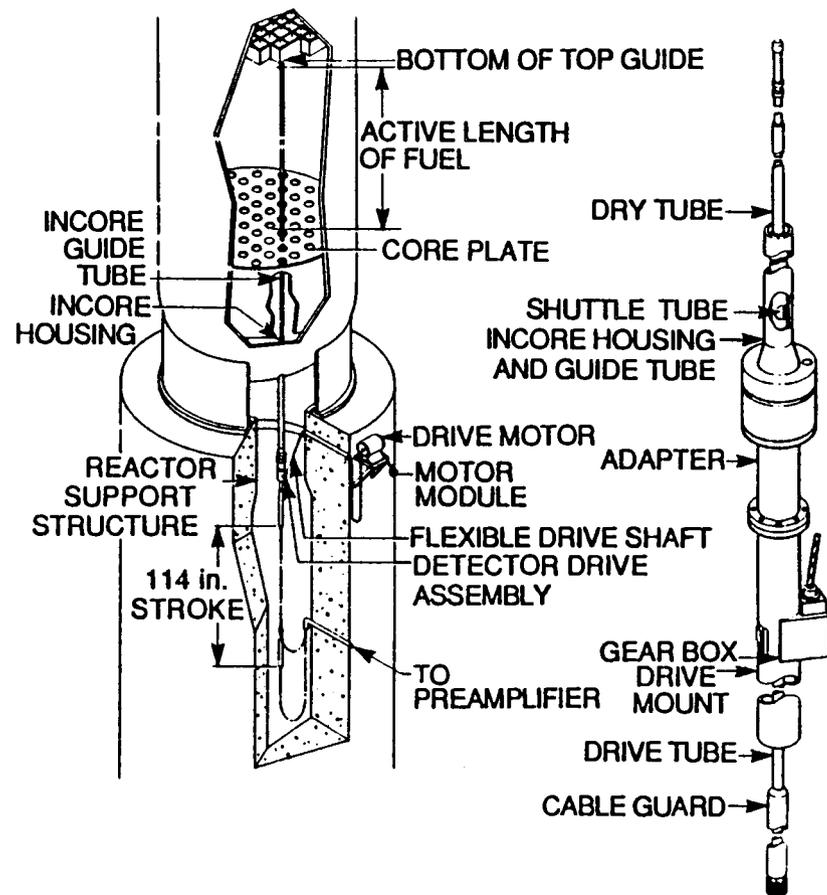


Fig. 8. Mechanical arrangement of the four source range and eight intermediate range detector in-core instrument assemblies.

within the bed as necessary to keep the liquid level approximately constant within a layer. An exception occurs in the case of the two middle layer outermost nodes after penetration failure occurs in this layer; for these two nodes, simultaneous movement downward to the void space in the (single) underlying node and horizontally to exit the vessel through the failed penetration can occur. In all cases, the rate of movement of molten material through the debris bed is controlled by a user-input time constant, usually set at one minute. Thus, for example, if the calculational timestep is 0.2 minute, 20% of the molten material within a node can move horizontally or vertically (or both, for the outermost middle layer nodes) each timestep.

Table 3.1.  BWR reactor vessel structures included
in bottom head debris bed formation

|  | Initial masses | |
| --- | --- | --- |
|  | kg | lbs |
| **Core constituents:** | | |
| a.  Zircaloy | | |
|    1.  Cladding | 37,000 | 81,500 |
|    2.  Channel box | 22,900 | 50,400 |
|    3.  Spacers | 2,700 | 5,900 |
| b.  $UO_2$ fuel | 172,500 | 380,300 |
| c.  Stainless steel | 16,300 | 35,800 |
| d.  $B_4C$ powder | 1,150 | 2,500 |
| | | |
| **Stainless steel structures:** | | |
| a.  Top guide | 6,900 | 15,200 |
| b.  Core plate | 9,300 | 20,500 |
| c.  Control rod guide tubes | 88,680 | 195,500 |
| Total | 357,430 | 787,600 |

Table 3.2.  Default values for eutectic mixture
and constituent melting points provided
within the BWRSAR code

| Constituent/Eutectic | Melting Temperature | |
| --- | --- | --- |
|  | (K) | (°F) |
| SS/B/Zr | 1422 | 2100 |
| SS/Zr | 1589 | 2400 |
| SS | 1672 | 2550 |
| Zr/B | 2033 | 3200 |
| $Zr(O)/UO_2$ #1 | 2125 | 3365 |
| $Zr(O)/UO_2$ #2 | 2673 | 4350 |
| $ZrO_2$ | 2978 | 4900 |
| $UO_2$ | 3070 | 5066 |

# 4.  RESULTS OF BWRSAR CALCULATIONS


As discussed in Chapter 3, the BWRSAR code models do not provide for consideration of reactor vessel bottom head failure modes while the bottom head debris remains covered with water.  The debris is assumed to be quenched upon entry into the lower plenum and the results of recent experiments at Argonne National Laboratory support this assumption.[13,14]  However, after dryout of the bottom head debris bed, the code searches for the conditions necessary for each of three bottom head failure modes each timestep.  These are:

1.  Failure of the penetration welds at the wall,

2.  Failure of the instrument guide tubes within the debris and overflow of molten material into the tubes, and

3.  Failure of the vessel wall itself.

The two modes of instrument tube penetration failure considered by the BWRSAR code are illustrated schematically in Fig. 9.  Failure of the welds that position the instrument guide tubes within the vessel would permit the guide tubes to fall from the vessel.  However, the center of the bottom head debris bed heats up most rapidly after bottom head dryout so the guide tubes might initially fail at a position remote from the wall, permitting local molten material to spill into the tubes and pass from the vessel.  In practice, the BWRSAR code predicts both of these failure mechanisms to occur almost simultaneously (within ten minutes of each other) soon after bottom head dryout.

It should be recognized that passage of molten material within the instrument tubes and through the reactor vessel bottom head is expected to cause failure of the instrument tubes just below the reactor vessel wall.  This is based upon the analysis by L. J. Ott discussed in Section 3.1.2 and upon the observation that BWR bottom head dryout includes dryout of the instrument guide tube housings immediately beneath the reactor vessel.  [The BWR reactor vessel would be depressurized so that the saturation temperature of the water in the housings would be low and, as indicated in Fig. 10, the arrangement of the bottom head insulation assures that the housing temperature immediately beneath the vessel approaches the temperature of the bottom head.]

With regard to failure of the bottom head itself, the BWRSAR code does predict this to occur, but only long after the onset of penetration failures.  As an example, for the recently completed Peach Bottom short-term station blackout studies,[4] both modes of bottom head penetration failure were predicted to occur within ten minutes of bottom head dryout whereas gross failure of the bottom head is not predicted to occur until $3\frac{1}{2}$ hours later.

The reason for the delayed failure of the BWR bottom head can be understood by consideration of the information provided in Fig. 11 and
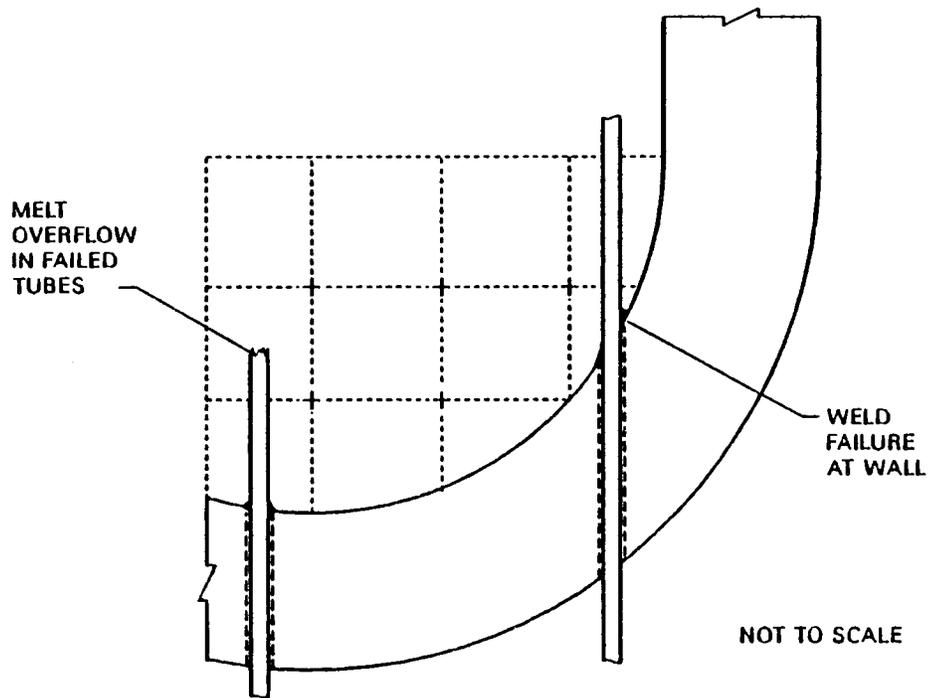
MELT
OVERFLOW
IN FAILED
TUBES

WELD
FAILURE
AT WALL

NOT TO SCALE

VESSEL HEAD
REMOVABLE
INSULATION

TYPICAL
NOZZLE
INSULATION

BIOLOGICAL
SHIELD

7.0 m INSULATION OD

6.7 m Rx VESSEL OD

BOTTOM HEAD
INSULATION
THICKNESS 7.6 cm

Fig. 9.   BWRSAR representation of BWR bottom
head penetration failure includes both models for
weld failure at the vessel wall and models for melt
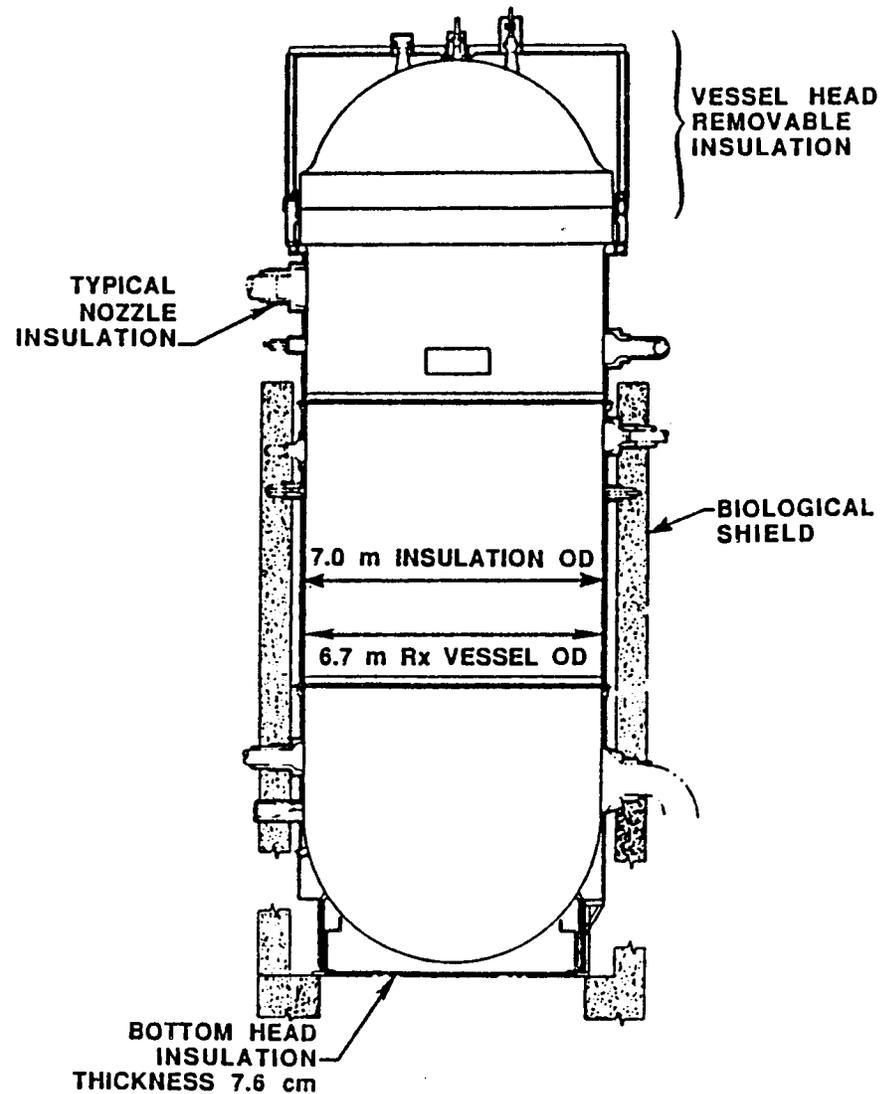overflow into failed tubes within the center of the
debris bed.

Fig. 10.   The volume immediately beneath the
reactor vessel is enclosed by the bottom head in-
sulation.

DIMENSIONS IN CENTIMETERS

HORIZONTAL WALL AREA = 3.434 M$^2$
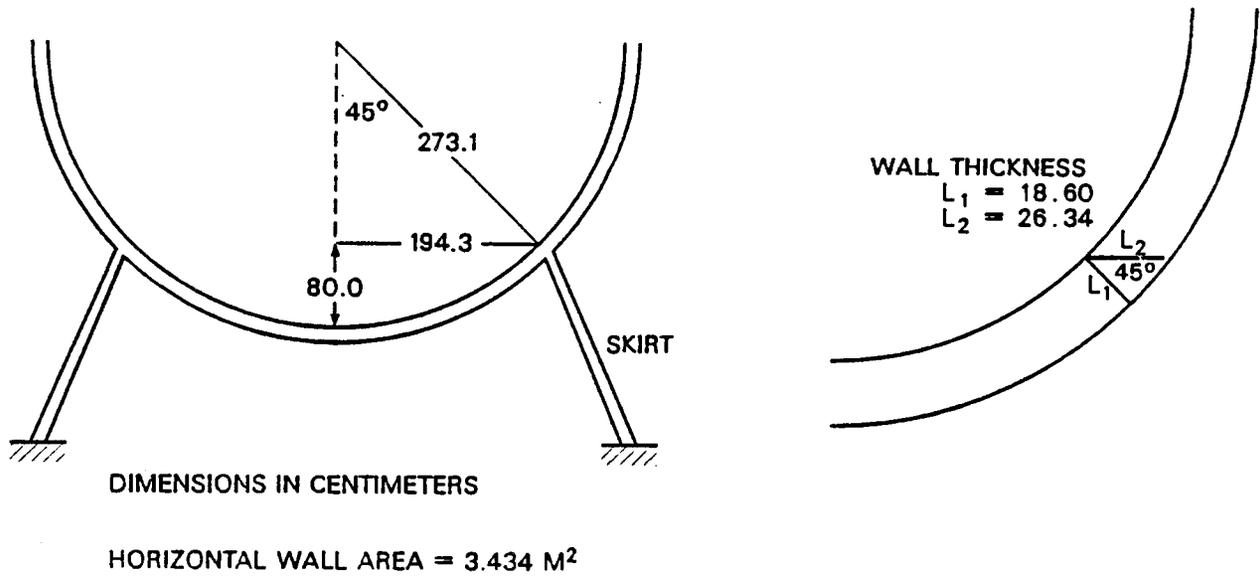
Fig. 11.  The BWR reactor vessel is supported from below by the support skirt.
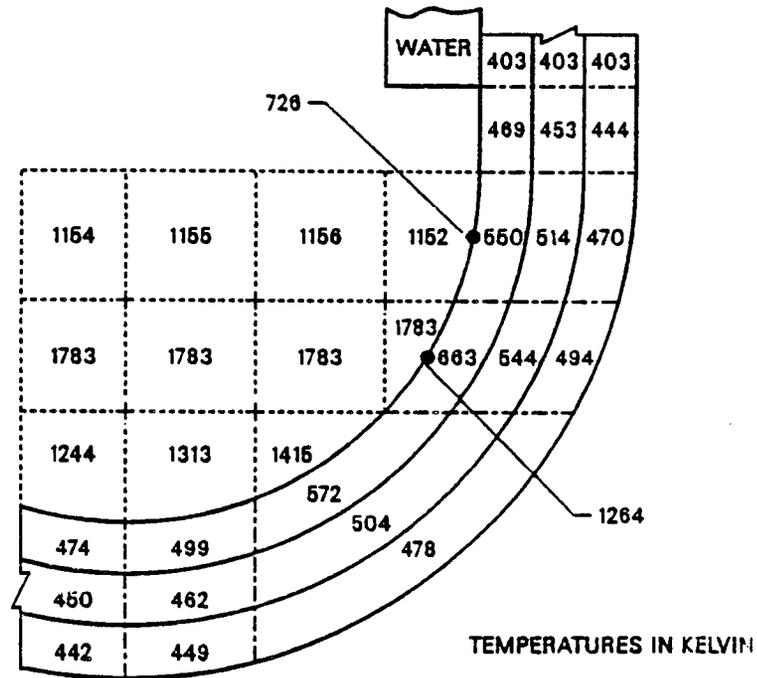


TEMPERATURES IN KELVIN

Fig. 12.  Reactor vessel bottom head wall temperatures at the time of predicted penetration failures are much too low for creep-rupture considerations.

Table 4.1.  The BWR reactor vessel is supported from below, so, with the reactor vessel depressurized under severe accident conditions, only the portion of the reactor vessel bottom head beneath the support skirt would be in tension.  As indicated in Table 4.1, the tensile stress in the lower portion of the bottom head is about 3650 psi (25 MPa) under normal operating conditions, but only 133 psi (0.9 MPa) under severe accident conditions.  Since rapid creep-rupture of the wall could be caused only by a combination of high tensile stress and high temperature, we can rule out early failure based upon stress considerations alone.  However, the reactor vessel wall temperatures are also much too low to support a theory of early creep-rupture of the bottom head.  The calculated wall temperatures at selected locations in the bottom head at the time of predicted penetration failure are shown in Fig. 12.

The creep-rupture curves derived from experimental data for the actual material of the BWR bottom head are shown in Fig. 13.  As indicated in the figure, a wall temperature of 1750°F (1228 K) would be expected to cause failure of the wall at about 5 hours under conditions of normal operating tensile stress [25 MPa].  However, high wall temperatures under the conditions of an ongoing BWR severe accident would be accompanied by low vessel pressures and low wall tensile stress [1 MPa] and creep-rupture of the wall would require hundreds of hours.

What are the consequences when the lower portion of the BWR reactor vessel and its load of oxidic debris does fall?  As shown in Fig. 14, there is a control rod drive housing support structure about three feet (one meter) beneath the vessel that might interrupt and temporarily hold up the fall.  Nevertheless, the remaining steel structure and contained oxidic debris would eventually reach the drywell floor.  At this point, it is important to recognize that the release of molten oxides over the concrete floor of the drywell would continue to depend upon the melting rate, just as it does while the debris bulk remains within the vessel, slowly pouring out via the failed penetrations.  Thus the relocation of a mound of oxidic debris onto the drywell floor is not expected to be a significant event.

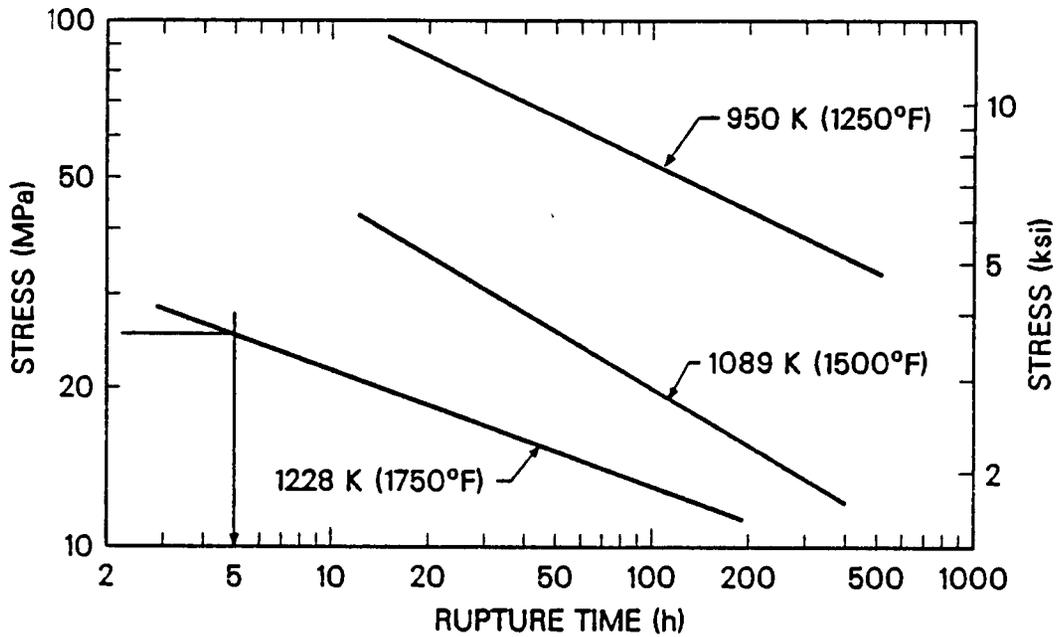Fig. 13. At normal reactor vessel wall stress, creep-rupture would occur after five hours at 1750°F (1228K). With a depressurized reactor vessel under severe accident conditions, the required time would be more than 100 hours.
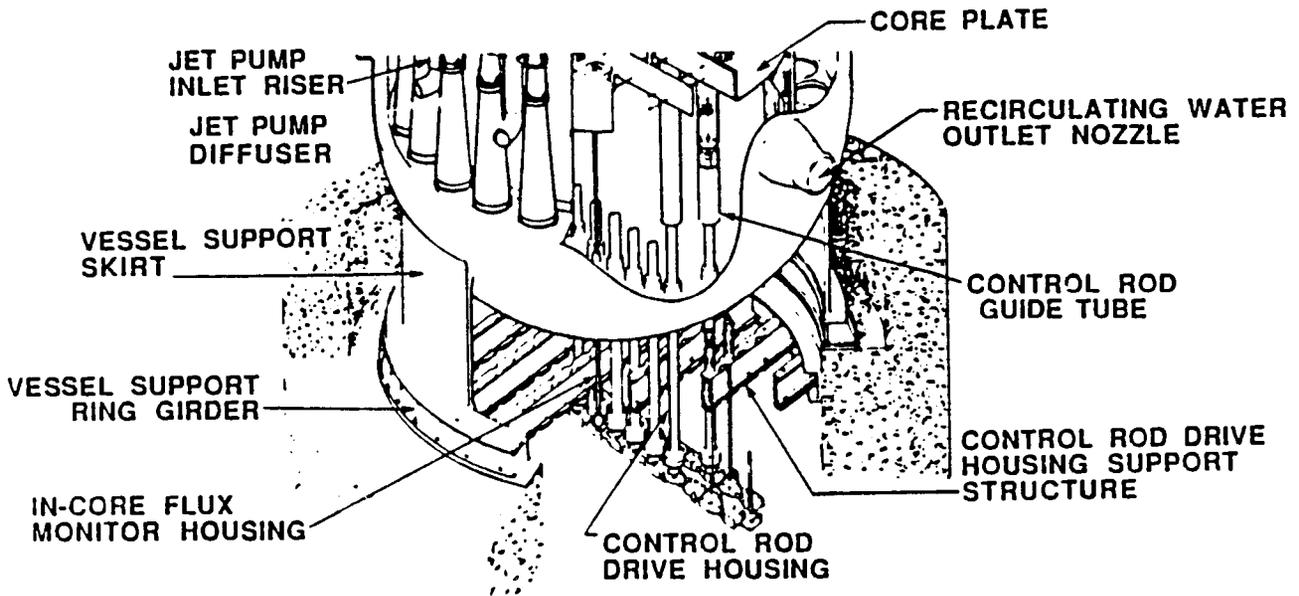


Fig. 14. Downward movement of separated portions of the BWR bottom head may be limited to about three feet (one meter) by the control rod drive housing support structure.

Table 4.1.  Loading of 809 MWe BWR reactor vessel
bottom head underneath skirt attachment

|  |  | Tensile stress | |
|  |  | psi | KPa |
|---|---|---|---|
| A. | Normal operation | | |
|  | Weight of water | 68 | 467 |
|  | Weight of core and structures | 94 | 648 |
|  | Weight of bottom head beneath support skirt | 9 | 61 |
|  | Pressure force | 3,496 | 24,100 |
|  | Total tensile stress at support skirt junction | 3,667 | 25,276 |
| B. | Depressurized and dry | | |
|  | Weight of debris | 124 | 852 |
|  | Weight of bottom head beneath support skirt | 9 | 61 |
|  | Total tensile stress at support skirt junction | 133 | 913 |

# 5. RECOMMENDATIONS

The purpose of this Chapter is to provide recommendations regarding the benefits that might be gained from additional computational analyses beyond those already performed, and the need for the verification of computational models that can only be gained by resort to an experimental approach.

## 5.1 Analyses

It should be recognized that the BWRSAR code currently provides the capability to calculate the temperature profile in the BWR bottom head debris bed and within the reactor vessel wall after bottom head dryout. Obviously, the calculated results are dependent upon certain assumptions regarding the characteristics of the debris bed that are represented by user-input. The most important of these are listed in Table 5.1, together with the best-estimate values used in the current calculations. In addition, the user-specified compositions and melting temperatures of the eutectic mixtures to be formed during debris bed heatup will also affect the calculated wall temperatures.

A parameter study could easily be performed to determine the sensitivity of the calculated temperatures to variations in the user-input over the credible range of values for each parameter. It seems reasonable to recommend that this relatively simple exercise be carried out. However, it is not expected that the results of this study would change the current conclusion that penetration failure would occur long before bottom head temperatures become high enough to threaten the basic integrity of the vessel wall.

## 5.2 Experiments

The Three Mile Island (TMI) experience demonstrated that molten core and structural material can ablate the instrument tubes within the reactor vessel near the wall and that debris can exit the vessel by traveling within the tubes. This happened at TMI although the reactor vessel bottom head remained filled with water throughout the accident sequence. Here we consider the case of a BWR after bottom head dryout, recognizing that the BWR instrument tube wall within the vessel is thinner and the tube internal diameter is larger (compare Figs. 2 and 3). Thus it seems reasonable, based upon the TMI experience, to conclude that molten debris would exit the BWR reactor vessel via the instrument tubes.

The remaining question concerns whether or not the instrument tube would fail external to the vessel so that a flow path would be opened for molten material to flow from the invessel debris bed to the drywell atmosphere. This, of course, did not happen at Three Mile Island. A

simple analysis (discussed in Section 3.1.2) indicates that the BWR instrument tube walls would indeed fail just outside the vessel wall. It seems desirable to check the validity of this analysis by performing a small-scale experiment. This could be done at Oak Ridge in G. W. Parker's experimental apparatus using actual BWR core and structural debris molten materials; these would be poured upon a representative model section of reactor vessel bottom head with the actual wall thickness and properly implanted instrument tube penetrations.

Table 5.1  BWRSAR code user-input parameters affecting
the vessel wall temperature calculation

| | Parameter | Current value | |
|---|---|---|---|
| CONDOX | Thermal conductivity of bottom head debris bed oxides | 2.02 | $\dfrac{Btu}{h\ ft\ °F}$ |
| CONDSS | Thermal conductivity of bottom head debris bed metals | 11.30 | $\dfrac{Btu}{h\ ft\ °F}$ |
| DTHEAD | Time constant for relocation of molten material (vertically or horizontally) within the debris bed | 1.00 | min |
| HRVDW | Coefficient for heat transfer from the reactor vessel bottom head to the drywell atmosphere | 0.625 | $\dfrac{Btu}{h\ ft^2\ °F}$ |
| THKCRS | Thickness of the debris node adjacent to the vessel wall | 0.333 | ft |

## 6. SUMMARY

Failure of the bottom head pressure boundary would almost certainly precede failure of the reactor vessel wall itself in both PWR and BWR severe accident sequences. The more important question from the standpoint of containment response pertains to the method of opening a flow path for molten debris to pour from the vessel. This letter report briefly describes 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. Based upon the results of a recent small-scale BWR core debris eutectics formation and melting experiment performed at ORNL,[15] it is reasonable, for a general analysis of the release of core and structural material from the reactor vessel, to assume formation of two separate molten mixtures during heatup after bottom head dryout. These are a metallic mixture melting at 2750°F (1783 K) and an oxidic mixture melting at 4350°F (2672 K). 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.

The majority of the oxidic debris should be retained within the reactor vessel until the time of gross failure of the lower portion of the bottom head wall and would then be relocated downward onto the control rod drive housing support structure and, if that fails, onto the drywell floor itself. The subsequent release of molten oxides over the concrete of the drywell floor would nevertheless remain controlled by the oxide melting rate, the same as if the vessel bottom head had remained intact.

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