BWRSAR CALCULATIONS OF REACTOR VESSEL DEBRIS POURS FOR PEACH BOTTOM SHORT-TERM STATION BLACKOUT

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S. A. Hodge
L. J. Ott

Boiling Water Reactor Severe Accident
Technology (BWRSAT) Program*
Oak Ridge National Laboratory

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S. A. Hodge L. J. Ott

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831

ABSTRACT

This paper describes recent analyses performed by the BWR Severe Accident Technology (BWRSAT) Program at Oak Ridge National Laboratory to estimate the release of debris from the reactor vessel for the unmitigated short-term station blackout accident sequence. Calculations were performed with the BWR Severe Accident Response (BWRSAR) code and are based upon consideration of the Peach Bottom Atomic Power Station. The modeling strategies employed within BWRSAR for debris relocation within the reactor vessel are briefly discussed and the calculated events of the accident sequence, including details of the calculated debris pours, are presented.

I. Introduction

Boiling Water Reactors (BWRs) and their primary containments have unique features for which special models must be provided if best-estimate severe accident calculations are to be performed. The Boiling Water Reactor Severe Accident Technology (BWRSAT) Program at Oak Ridge National Laboratory (ORNL) has developed and incorporated into its Boiling Water Reactor Severe Accident Response (BWRSAR) code several advanced response models for application to BWR severe accident analyses. Major features of these advanced in-vessel models include representation of (1) heat transfer to all in-core structures including channel boxes and control blades, (2) the effect of safety/relief valve (SRV) actuations, (3) structural/steam reaction chemistry effects, (4) progressive relocation of core structures including candling of the fuel rod cladding, (5) failure of the core plate and formation of a debris bed in the reactor vessel bottom head, (6) bottom head dryout and reheating of the quenched debris, (7) failure of the bottom head penetrations, and (8) the time-dependent egress of molten core debris from the reactor vessel. These models have been discussed in the paper "Advanced Severe Accident Response Models for BWR Application," given at the Fifteenth Water Reactor Safety Information Meeting in October 1987 and to be published in a forthcoming topical issue of Nuclear Engineering and Design. Nevertheless, because of the important effects that the method of modeling of core plate failure, bottom head debris bed formation and melting, bottom head penetration failure, and the release of molten materials from the reactor vessel has upon subsequent conclusions regarding the characteristics and the timing of contact of the released core debris with the Mark I drywell shell, these models for events occurring in the bottom head are here discussed in greater detail than in the previous paper.

This paper also provides a discussion of the results of recent analyses performed by the BWRSAT Program to estimate the debris pours from the reactor vessel during an unmitigated short-term station blackout severe accident sequence. This work was performed at the request of Dr. Thomas J. Walker, Leader of the Task Group on the BWR Mark I Shell Melt-Through Issue established by the Accident Evaluation Branch of the Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research. The Task Group was formed in support of an ongoing effort to determine the response of the drywell shell in the unlikely event that a severe accident were to proceed to the point of release of molten core debris from the reactor vessel.

The specific calculations performed in this work are based upon the short-term station blackout accident sequence at the Peach Bottom Atomic Power Station, which has been determined by the Accident Sequences Evaluation Program (ASEP) to provide about 20% of the total risk of core melt at this facility.[1] The specific case analyzed is based upon the existing plant configuration, where it is assumed that the Automatic Depressurization System (ADS) is actuated in accordance with the BWR Owners Group Emergency Procedure Guidelines. It was assumed for these calculations that the core debris in the reactor vessel bottom head forms two separate mixtures during heatup after bottom head dryout: a single metallic eutectic with a melting temperature of 2750°F (1783 K) and a single oxidic eutectic with a melting temperature of 4350°F (2672 K).

In general, the calculations whose results are represented in this paper were carried out on a best-estimate basis. This includes the representation of the decay heat power as a function of time. The fuel models are appropriate for conventional GE 8X8R BWR fuel assemblies.

II. BWRSAR Models for Events After the Onset of Core Degradation

A. Core plate failure

The primary alignment function of the BWR core plate is to provide lateral guidance for the upper portion of the control rod guide tubes, as shown in Fig. 1. Each of the 185 control rod guide tubes supports four fuel assemblies grouped around a cruciform opening for the control rod blade. The core plate, which is two inches (5.1 cm) thick and weighs 20,500 lb (9300 Kg) supports only the outermost 24 assemblies of the 764 assemblies that make up the total core. [Dimensions pertain to the 251-in. ID BWR 4 reactor vessel installed at 1067 MW_e plants such as Peach Bottom or Browns Ferry.] The core plate is characterized by large holes provided for passage of the control rod guide tubes and smaller holes for the in-core instrument guide tubes as shown in the plan view of Fig. 2. In the BWRSAR models, molten materials moving downward during the early period of the core relocation phase of a severe accident attack and fail individual radial regions of the core plate, opening pathways for follow-on relocating debris to fall directly into the reactor vessel bottom head. Debris relocation and the effect upon the core plate are described in detail in the following paragraphs.

The models for candling of fuel rod cladding that have been incorporated into BWRSAR are essentially identical to those developed by R. M. Summers[2] for MELCOR and discussed by Dingman et al.[3] In the BWRSAR code, the candling of molten clad and its associated mass of dissolved UO_2 leaves the upper portions of the fuel pellet stacks standing encased in thin ZrO_2 sheaths after all of the Zr metal has relocated downward. As the downward-moving candled material freezes, remelts, and freezes again on subsequently lower nodes, the lower portion of the core undergoes a thermal escalation due to the associated energy transport and to the increased metal/steam reaction, enhanced by the continual presentation of a fresh, unoxided material surface to the steam in the local environment. Eventually, the candling material contacts any remaining water above the core plate causing increased steaming, buildup of a quenched mass upon the core plate surface, and, after core plate dryout, rapid core plate heatup.

Since calculations and available experimental evidence[4] indicate that the control blade and channel box material of the BWR core would relocate uniformly and rapidly over a time scale of seconds once the stainless steel and zirconium metal melting points are reached under severe accident conditions, candling models are not employed in the BWRSAR code for the molten control blade or channel box nodes. Rather, upon reaching the molten state, the nodal control blade or channel box material is transferred immediately downward onto the core plate. As long as water remains above the core plate, the molten material is quenched, causing an increased steaming rate. Eventually, if there is no water injection into the reactor vessel, core plate dryout will occur and there will be a temporary cessation of steam generation into the core region.

After core plate dryout, mass continues to build up on the core plate from the candling process and from relocated molten canister or control blade nodes, with associated core plate heatup. Each radial region of the core plate is predicted to fail due to the accumulated load and loss of strength when the regionally calculated mass-averaged debris/core plate temperature exceeds a user-specified temperature, usually 2000°F (1367K). In practice, the mass-averaged temperature increases so rapidly after core plate dryout that adjusting the assumed failure temperature has little effect on the calculated time of failure.

Each failed core plate region and its accumulated debris fall into the lower plenum producing a burst of steam as the fallen material is quenched. However, it is expected that the fuel pellet columns, encased in ZrO_2 sheaths, would remain standing since the weight of the fuel is supported by the control rod guide tubes, not by the core plate. After failure of a core plate region, additional relocating material in that region falls directly into the lower plenum. During the relocation process, material balances are performed to keep track of chemical species (such as Fe, Cr_2O_3, Zr, UO_2) as they accumulate on the core plate and in the lower plenum.

The rationale for the BWRSAR code methodology with respect to core debris relocation onto the core plate is supported by the results of the DF-4 experiment[4] conducted in the Annular Core Research Reactor (ACRR) at Sandia National Laboratories in November 1986, which confirm the predictions of earlier calculations with the BWRSAR models. In the experiment, the control blade melted first (as predicted in pretest calculations by BWRSAR models) and progressively and rapidly relocated to the bottom of the test section. In a post-test cross-section, the relocated control blade material was found in the form of an ingot cast in the shape of the zircaloy channel box at the very bottom of the test section, which is below the bottom of active fuel. Both the control blade and channel box wall portions of the DF-4 test section were more than 90% destroyed due to melting and relocation during the experiment, but the fuel pellet stacks are predominantly still standing. Relocated cladding blocks the base of the fuel rod regions of the experiment.

The DF-4 experiment, which had to fit within the ACRR, was designed to represent a short (0.5-m) length of uncovered fuel, channel box, and control blade in the upper region of a BWR core undergoing an unmitigated severe accident. It can be argued that in a full-length test section, the relocating molten control blade and channel box material might not travel all of the way to the experiment base before freezing. However, BWRSAR code predictions indicate that all axial sections of the control blades above the core water level would reach their melting points almost simultaneously as the temperature of the uncovered region of the core increases, and the same is true for the axial sections of the channel box walls. (It is a matter of relatively low-melting-point material sandwiched between higher-melting-point materials whose temperatures are rapidly rising: the very low thermal capacitance of the thin channel box walls also contributes to the observed phenomena.) There is no question, however, that the execution of an experiment using full length representation of BWR control blade, channel box, and fuel rods is highly desirable to confirm these calculated results. If much of the relocated molten core debris were to not reach the core plate, but instead were to form a frozen crust above the plate, subsequent debris bed formation and melting above the core plate would lead to an accident event sequence more like the Three Mile Island experience (PWR) than the sequence predicted by BWRSAR. Thus, the question of core plate survival in the BWR severe accident sequence is pivotal.

It should be noted that the BWRSAR models do predict retention and buildup of a debris bed above the core plate for cases in which the core plate is sufficiently cooled by reactor vessel water injection to forestall dryout, heatup, and structural failure. The required water injection rate is small if continuous, larger if the flow is intermittent and in both cases the integrated effect must be sufficient to prevent core plate failure but insufficient to terminate the accident. This scenario seems most unlikely for prolonged BWR severe accident sequences since any injection system, if available, is capable of injection rates ample to recover the core and terminate the accident although operator action (specified in existing written procedures) would be necessary to enhance the flow in some cases. For this reason, the BWRSAR models for the progression of the unmitigated severe accident are based upon the assumption of a total loss of injection such as would occur in short-term station blackout.

B. Debris bed formation in the BWR bottom head

After regional failures of the core plate structure occur, 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 ZrO_2 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 of 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 Browns Ferry 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. 3) 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 head by the accumulated debris is modeled by BWRSAR. Depending on the accident sequence, this displacement can result in water being forced into the core region even 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 mostly metallic debris (control blades, canisters, candled clad and dissolved fuel) that either had originally accumulated on the core plate before failure, or had subsequently relocated within the failed core plate regions 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 relocated 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. This results in a rapid continuous boiloff of the lower head 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 6 to 9 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 structures 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 calculation (prior to oxidation) that are normally included in the formation of the bottom head debris bed are outlined in Table 1.

With control rod guide tube failure and collapse of the outer regions of the core, the formation of the bottom head debris bed is complete. As described, it is discretized on formation into three layers separated vertically; additionally, each layer is discretized into radial nodes resulting in the debris bed nodalization illustrated in Fig. 4. 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 the chemical reaction of steam from the vessel atmosphere 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 transfer. Additionally, radiation and convection from the surface nodes to the vessel gaseous contents and to 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.

C. Reactor vessel bottom head penetration failure

As the temperature of the debris bed increases, materials begin to melt, migrate, freeze, and remelt. 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.

There are more than 200 reactor vessel bottom head penetrations in a BWR reactor vessel of the size employed at Browns Ferry, where there are 185 control rod drive mechanism assembly penetrations, 55 instrument guide tube penetrations, and a drain line near the low point in the bottom head. It seems certain that the initial pressure boundary failure under the conditions of bottom head debris 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 penetrations are stainless steel. Cross sections of the control rod drive mechanism assembly and instrument tube penetrations and their weldments are illustrated in Fig. 5. The assumed method of failure of the penetration structure is by 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 is initiated by failure of the in-core housing guide tubes associated with the local power range detectors (Fig. 6) and the source and intermediate range detectors (Fig. 7). 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 assumed 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 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 penetrations, 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 penetration 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 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 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 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.

II. The Short-Term Station Blackout Accident Sequence

Much of the impetus for these new studies of Peach Bottom Station Blackout has derived from the most recent findings of the NRC-sponsored Accident Sequence Evaluation Program (ASEP) in support of the NUREG-1150 effort.[1] The final results of the ASEP Program provide the estimate that 60% of the overall risk of core melt for Peach Bottom can be attributed to the overall threat of Station Blackout. (The remaining risk is allocated as 31% for ATWS and 9% for all other possible accident sequences.) Historically, the station blackout accident sequence has been considered to be loss of offsite power and reactor scram combined with failure of the station diesels to start and load. In this (long-term) accident sequence, water is injected into the reactor vessel by the steam turbine-driven HPCI or RCIC systems as necessary to keep the core covered for as long as dc power for turbine governor control remains available from the unit batteries, a period of about six hours. However, the definition of Station Blackout implemented by the ASEP Program has been expanded to include two cases that heretofore would have been classified as Loss of Injection, or TQUV in WASH-1400 parlance. In these short-term station blackout sequences, the capability for water injection to the reactor vessel is lost at the inception of the accident sequence. (The short-term designation derives from the fact that the core is uncovered relatively quickly in these sequences.)

The early total loss of injection hallmark of Peach Bottom Short-Term Station Blackout might be initiated in either of two ways. First, there might be independent failures of both the HPCI and RCIC systems when they are called upon to keep the core covered during the period while dc power remains available. Second, there might have been a common-mode failure of the dc battery systems that, upon loss of offsite power, had precluded starting of the diesel generators and thereby was the cause of the Station Blackout; without dc power for valve operation and turbine governor control, the steam turbine-driven injection systems also would not be operable. The ASEP program results assign 17% of the overall core melt frequency for Peach Bottom to the case of Short-Term Station Blackout with independent failure of HPCI and RCIC and 3% of the frequency to the case initiated by common-mode failure of the station batteries. The calculations discussed in the remainder of this paper are based upon the case with independent failure of HPCI and RCIC.

III. The Calculated Sequence of Events

The sequence of events and event timing for the Peach Bottom short-term station blackout with ADS actuation accident sequence as calculated by the BWRSAR code are provided in Table 3. It is assumed that the reactor had been operating at 100% power at the time of scram and that no injection source is ever recovered.

Plots of key parameters representing events within the reactor vessel as predicted by the BWRSAR code are provided in Fig. 8. These plots represent events from time 35 minutes when the BWRSAR calculation is initiated until time 300 minutes, which is about 45 minutes after reactor vessel bottom head penetration failure. As indicated in Fig. 8a, the ADS system is activated at time 80.0 min, when the reactor vessel water level is near the bottom of the core; this causes the opening of five safety/relief valves (SRVs). The open SRVs subsequently close whenever the reactor vessel falls to within 20 psi (0.138 MPa) of the drywell pressure and then reopen when the reactor vessel pressure has increased to 50 psi (0.345 MPa) above drywell pressure. The corresponding relief valve flows are shown in Fig. 8d.

The swollen reactor vessel water level, the calculation of which includes consideration of the effects of voids, is shown in Fig. 8b. The calculated water level rapidly falls below the core plate as a result of the water loss by flashing when the ADS valves are opened. Small temporary increases in level occur because of displacement of water in the bottom head when large masses of core debris are introduced after core plate failure. The decay heat associated with the fuel pellets relocated into the bottom head at time 222.8 min causes a boiloff of the remaining water in the reactor vessel; bottom head dryout occurs at time 254.9 min.

Plot 8c shows the extent of hydrogen generation by metal-steam reaction in the core region. Approximately 23% of the clad, 12% of the channel box walls, and 3% of the control blade stainless steel is predicted to be oxidized during the accident sequence, producing about 1137 lb (516 kg) of hydrogen in the core region within the reactor vessel.

Selected primary containment response characteristics predicted by the BWRSAR code for the period up to one-half hour after reactor vessel bottom head penetration failure are provided in the individual plots provided in Figs. 9 and 10. As indicated in Fig. 9a, ADS actuation causes a small pressure increase, but this pressure increase is erased as the containment heat sinks soak up energy after core plate dryout. The containment pressure increases significantly in response to debris relocation into the reactor vessel bottom head and after collapse of the central fuel pellet stacks. Bottom head penetration failure does not significantly increase the containment pressure because the reactor vessel was previously depressurized by means of the ADS actuation.

The drywell atmosphere temperature, shown in Fig. 9b, increases due to increased heat transfer from the reactor vessel whenever flow is initiated from the safety/relief valves (Fig. 8d), then decreases as the drywell heat sinks absorb the energy to the atmosphere. The effect of bottom head penetration failure is slight. At the completion of the reactor vessel blowdown, neither the drywell pressure nor the calculated drywell shell temperature (Fig. 9c) is of sufficient magnitude to threaten the integrity of the drywell shell pressure boundary.

The temperatures of the wetwell atmosphere and the torus shell respond to events within the reactor vessel as shown in Figs. 10a and 10b, but do not increase to threatening values. The wetwell atmosphere temperature increases after reactor vessel bottom head penetration failure because of the hot gases entering the pressure suppression pool from the drywell via the vent lines and downcomers. (The pool remains subcooled, however. Its response is shown in Fig. 10d.)

A large amount of hydrogen has accumulated within the wetwell airspace (Fig. 10c) and the drywell (Fig. 10d) at the time of reactor vessel bottom head penetration failure. Some additional hydrogen [about 247 lb (112 kg)] is generated by the passage of steam through the bottom head debris bed during the first 60 minutes after penetration failure. A slow rate of hydrogen generation by this mechanism continues as long as water remains in the downcomer region of the reactor vessel. This water is boiled by radiative and conductive (through the vessel wall) heat transfer from the bottom head debris; the steam passes through the debris bed on its way out of the vessel.

The characteristics of the debris pours from the reactor vessel bottom head as calculated by the BWRSAR code are shown in Fig. 11. Figure 11a indicates the rate of molten material release from the reactor vessel as a function of time. Although bottom head penetration failure occurs at 255 minutes, the initial pour does not occur until time 263 minutes because of the time interval required for the metallic debris to heat to its assumed melting temperature of 2750°F (1783 K). The mass-averaged temperature of the release is shown in Fig. 11b.

The integrated mass of debris released from the reactor vessel is indicated in Fig. 12a, where it is shown that about 875,000 lbs (397,000 kg) has left the vessel by the end of the calculation, at time 900 min. This is equivalent to about 98% of the total mass of bottom head debris. The decay heat (proportional to the mass of UO_2) included in the released debris is shown in Fig. 12b.

It should be noted that the BWRSAR code predicts that the portion of the reactor vessel bottom head beneath the point of attachment of the support skirt is completely melted through at time 483 minutes. There are no specific models within BWRSAR to address this phenomenon since it is believed that the 340,000 lbs (154,000 kg) of debris remaining within the vessel at this time would merely relocate downward about three feet (0.91 m) onto the control rod drive housing support structure (see Fig. 13). After relocation, the debris would continue to melt, with the molten portion flowing down onto the drywell floor in the same manner as if the reactor vessel had remained intact. Heat transfer from the debris to the reactor vessel by convection and conduction is discontinued at the time of debris relocation.

IV. CONTAIN Calculations of Primary Containment Response

The reactor vessel debris pours shown in Figs. 11 and 12 have been used to drive CONTAIN code calculations to estimate the primary containment response. The results of these primary containment calculations are presented at this meeting by C. R. Hyman in the paper "CONTAIN Calculations of Debris Conditions Adjacent to the BWR Mark I Drywell Shell During the Later Phases of a Severe Accident."

V. References

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Table 1. BWR reactor vessel structures included in bottom head debris bed formation

	Initial Masses kg	Initial Masses 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 control blades	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 2. Default values for eutectic mixture and constituent melting points provided within the BWRSAR code

Constituent/Eutectic	Melting Temperature K	Melting Temperature °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

Table 3. Calculated sequence of events for Peach Bottom Short-Term Station Blackout with ADS Actuation. The bottom head debris is modeled to separate into a mixture of metals melting at 2750°F and a mixture of oxides melting at 4750°F

Event	Time (min)
Station blackout-initiated scram from 100% power. Independent loss of the steam turbine-driven HPCI and RCIC injection systems	0.0
Swollen water level falls below top of core	40.2
Open one SRV	77.0
ADS system actuation	80.0
Core plate dryout	80.9
Relocation of core debris begins	132.4
First local core plate failure	132.7
Collapse of fuel pellet stacks in central core	222.8
Reactor vessel bottom head dryout; structural support by control rod guide tubes fails; remainder of core falls into reactor vessel bottom head	254.9
Bottom head penetrations fail	255.0
Pour of molten debris from reactor vessel begins	263.1
First UO_2 leaves reactor vessel	355.0
Bottom head melt-through	483.0

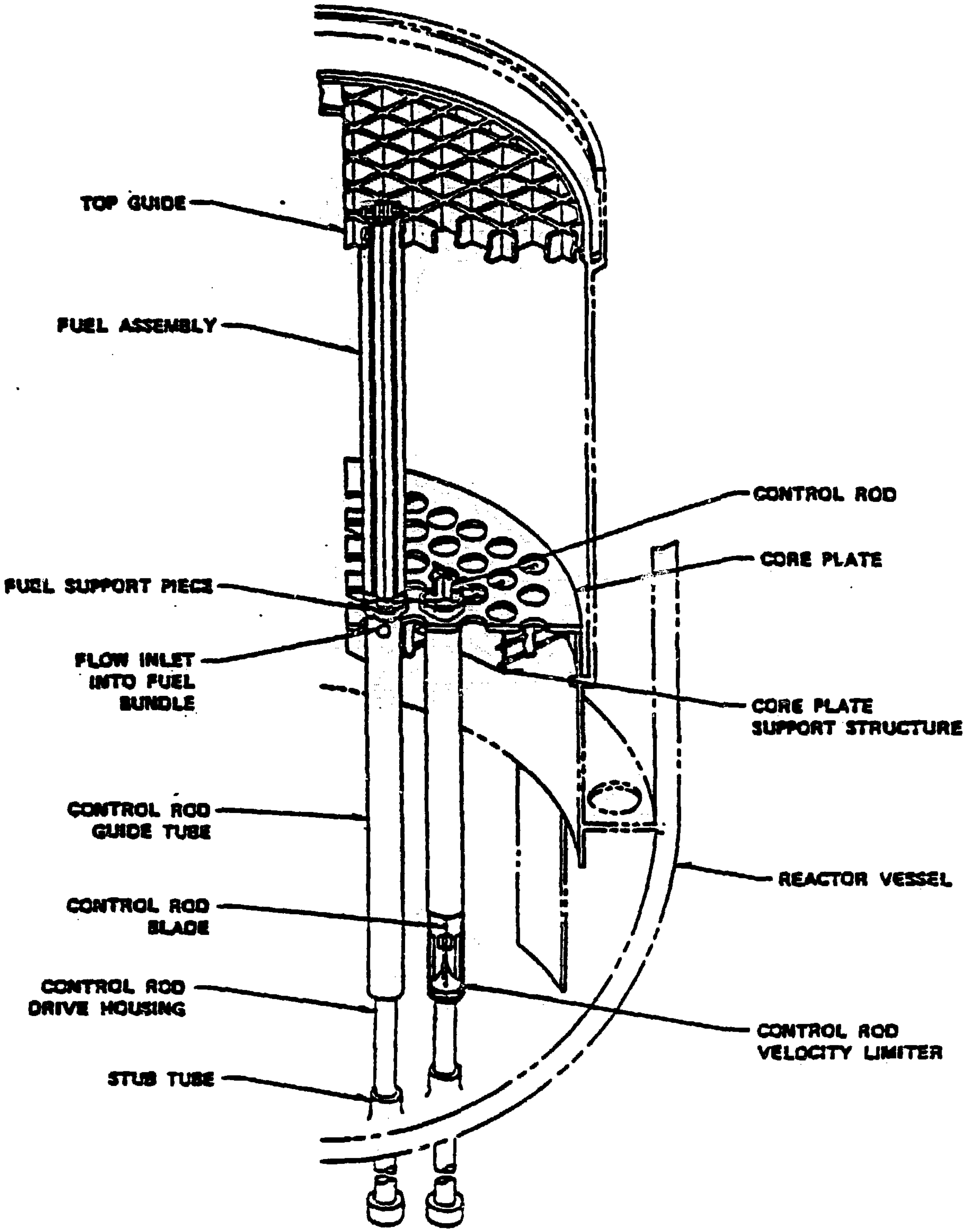

Fig. 1. The BWR core plate separates the core region from the reactor vessel bottom head. The core fuel assemblies are supported by the fuel support pieces, the control rod guide tubes, the control rod drive housings, and the stub tube welds.

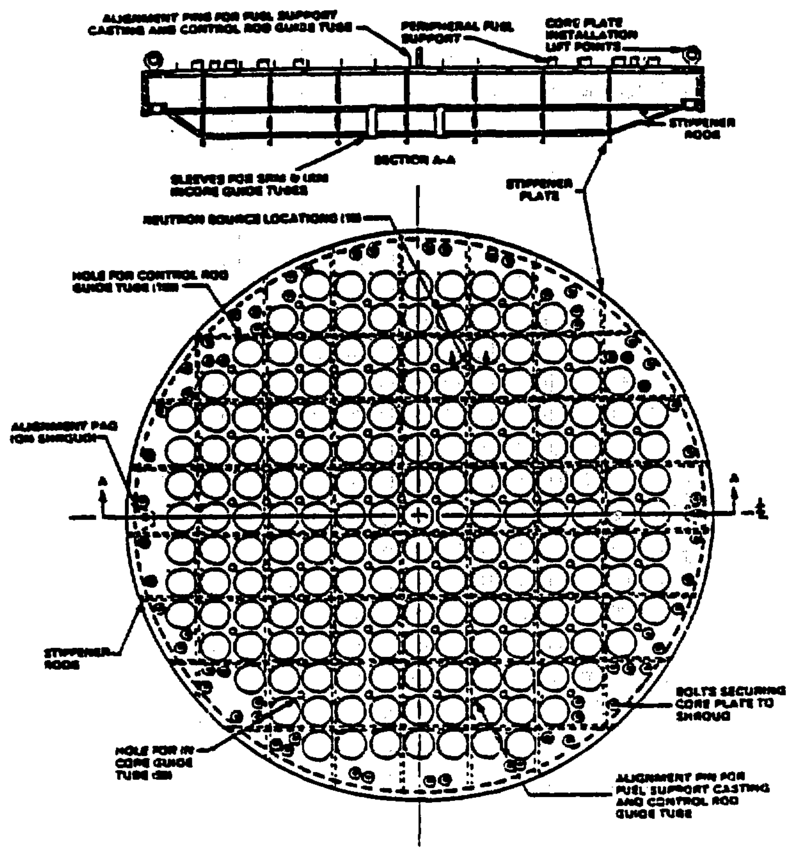

Fig. 2. Elevation and plan views of the core plate.

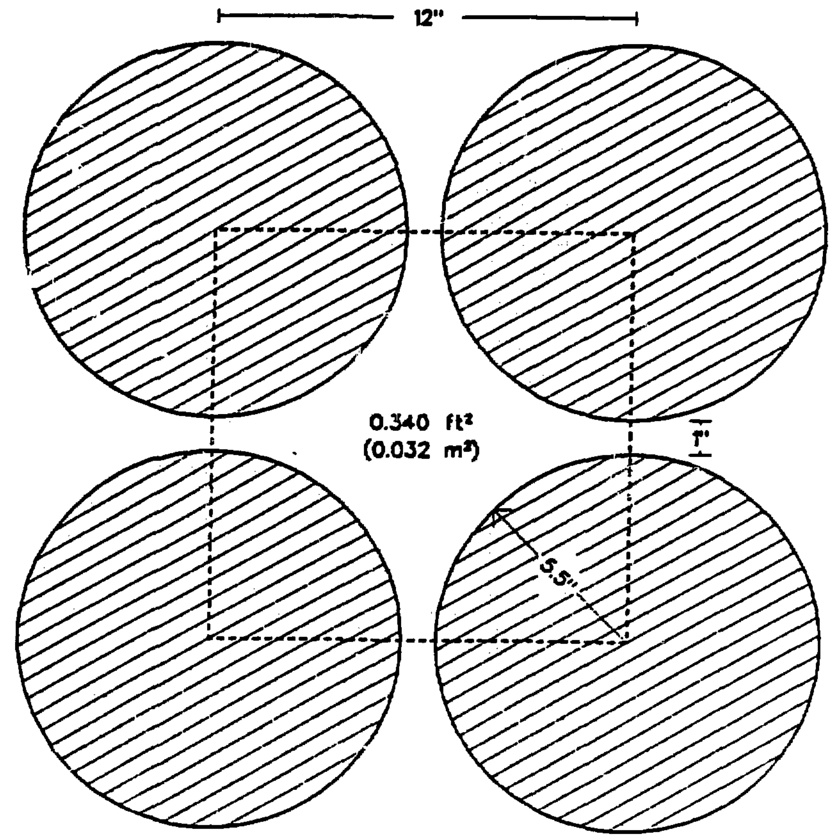

Fig. 3. Control rod guide tube spacing and available open flow area in the BWR reactor vessel bottom head.

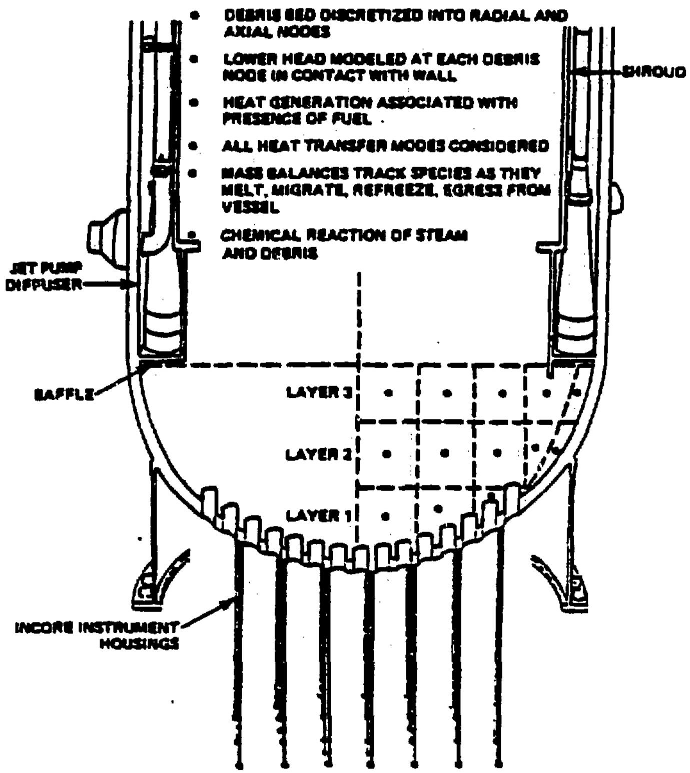

Fig. 4. Description of models and illustration of noding employed for the BWR reactor vessel bottom head debris bed.

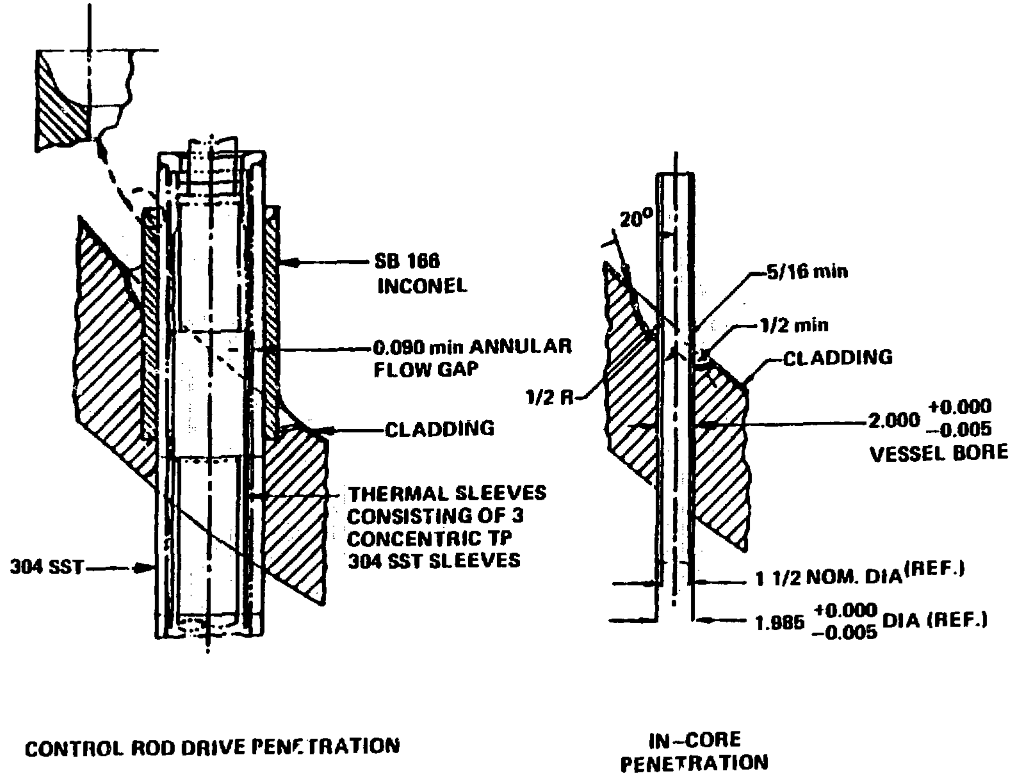

Fig. 5. Control rod drive mechanism assembly and in-core instrument guide tube penetrations through the BWR reactor vessel bottom head. Dimensions are given in inches.

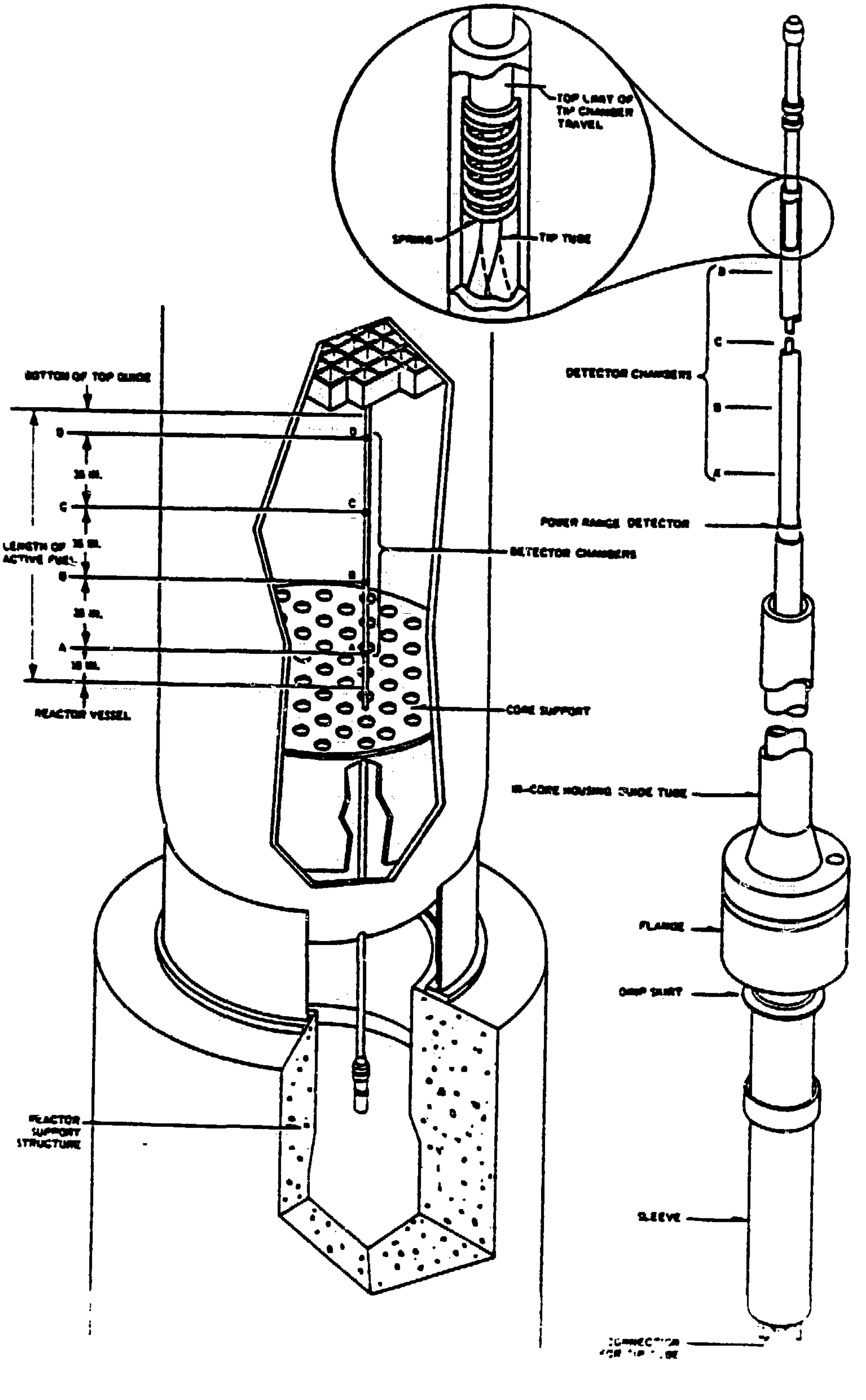

Fig. 6. Mechanical arrangement of one of the 43 Local Power Range Detector assemblies. The annular gap clearance between the in-core housing guide tube and the instrument tube is specified as 0.40 inches.

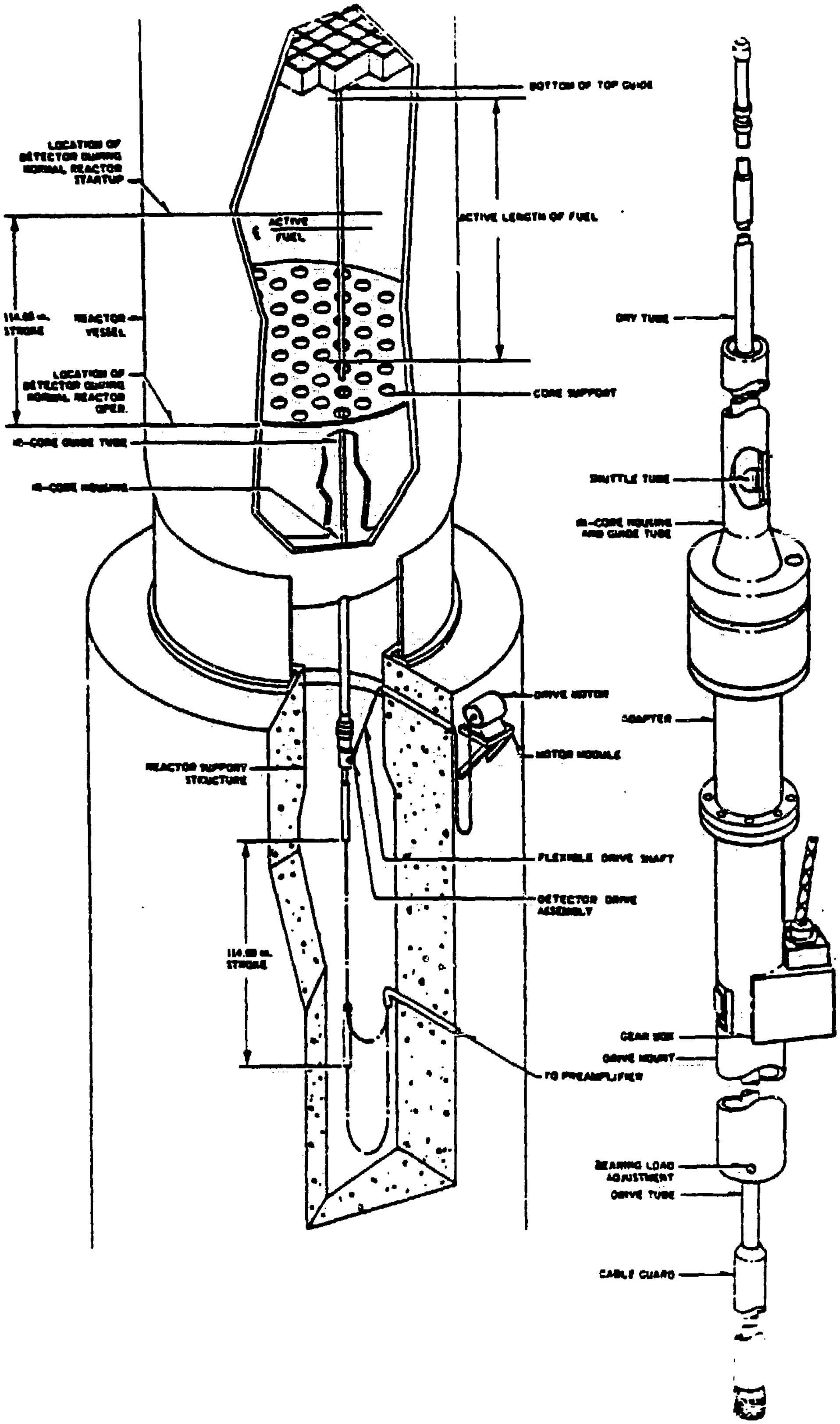

Fig. 7. Mechanical arrangement of the four source range and eight intermediate range detector in-core instrument assemblies.

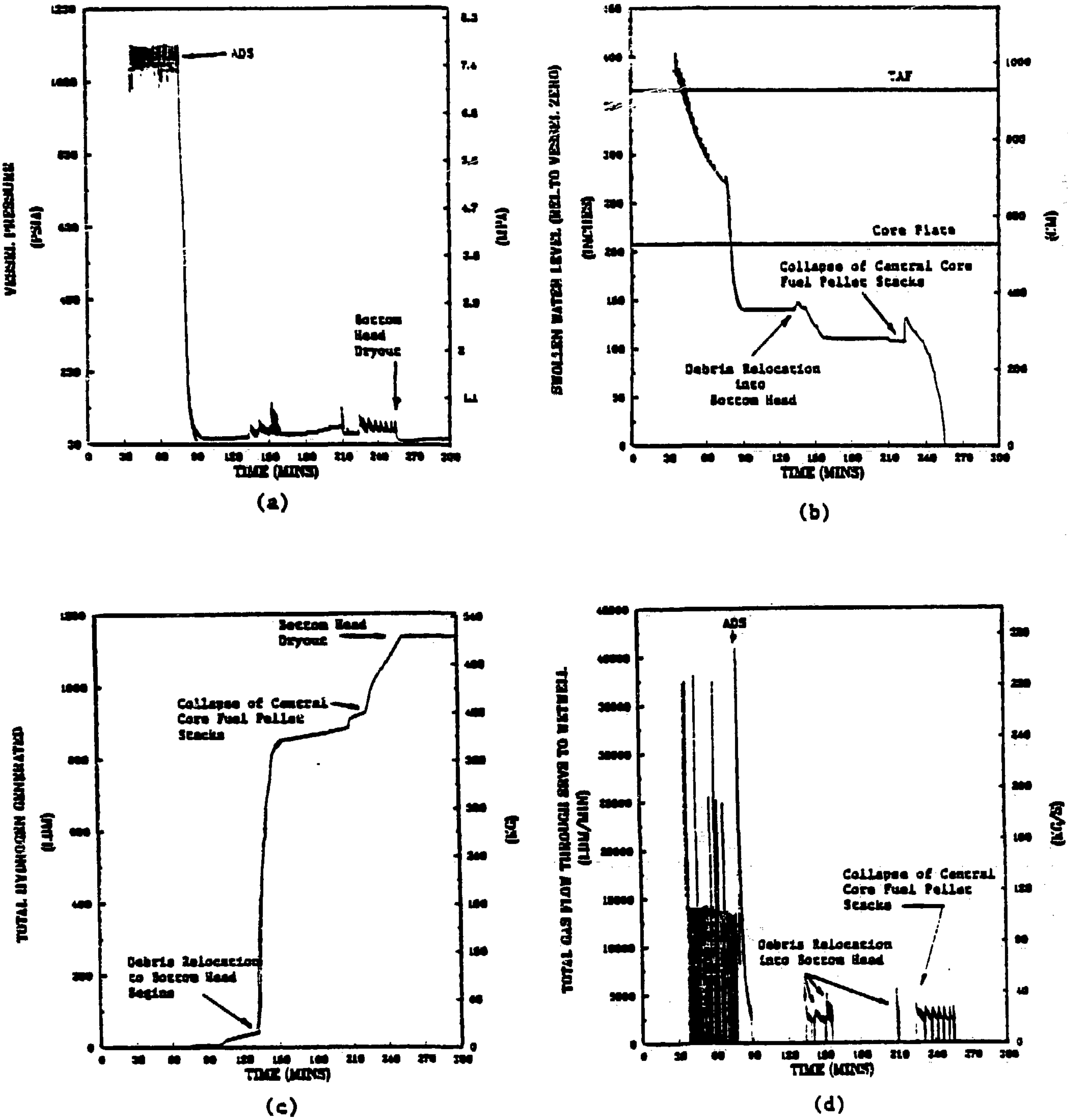

Fig. 8. Accident signatures for events within the reactor vessel as predicted by the BWRSAR code for the Peach Bottom short-term station blackout accident sequence with ADS.

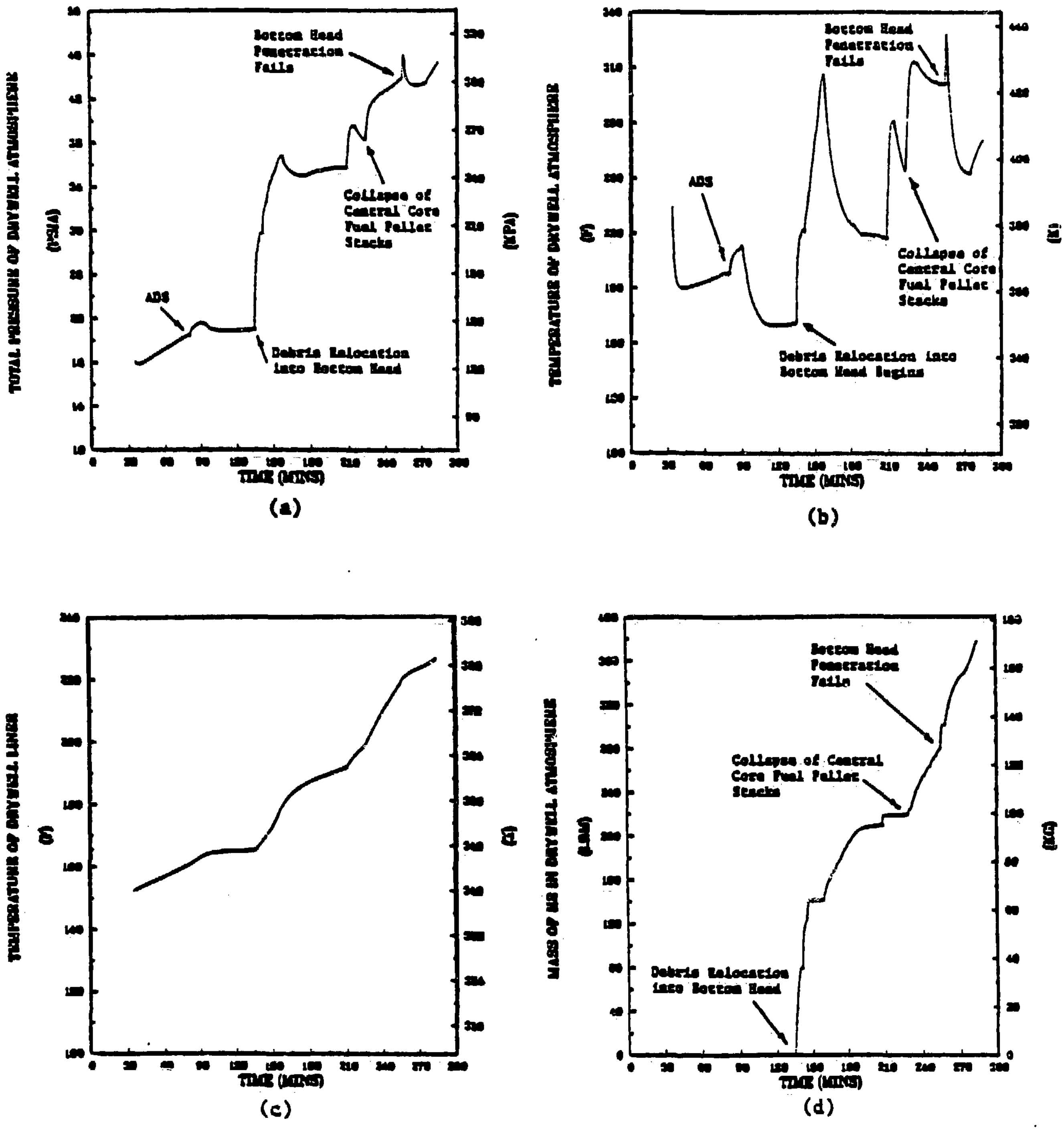

Fig. 9. Accident signatures for response of the drywell as predicted by the BWRSAR code for the Peach Bottom short-term station blackout accident sequence with ADS.

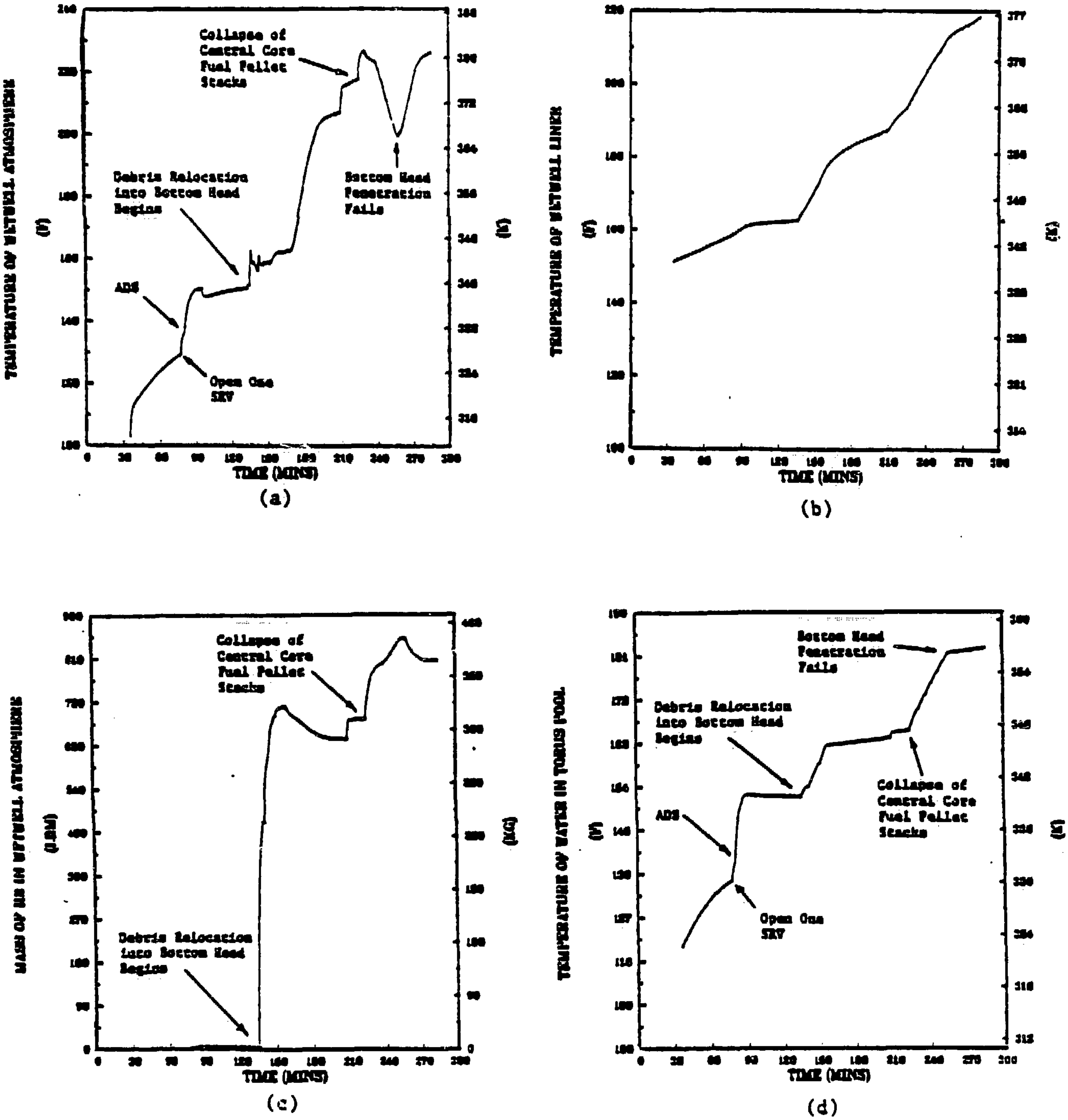

Fig. 10. Accident signatures for response of the wetwell as predicted by the BWRSAR code for the Peach Bottom short-term station blackout accident sequence with ADS.

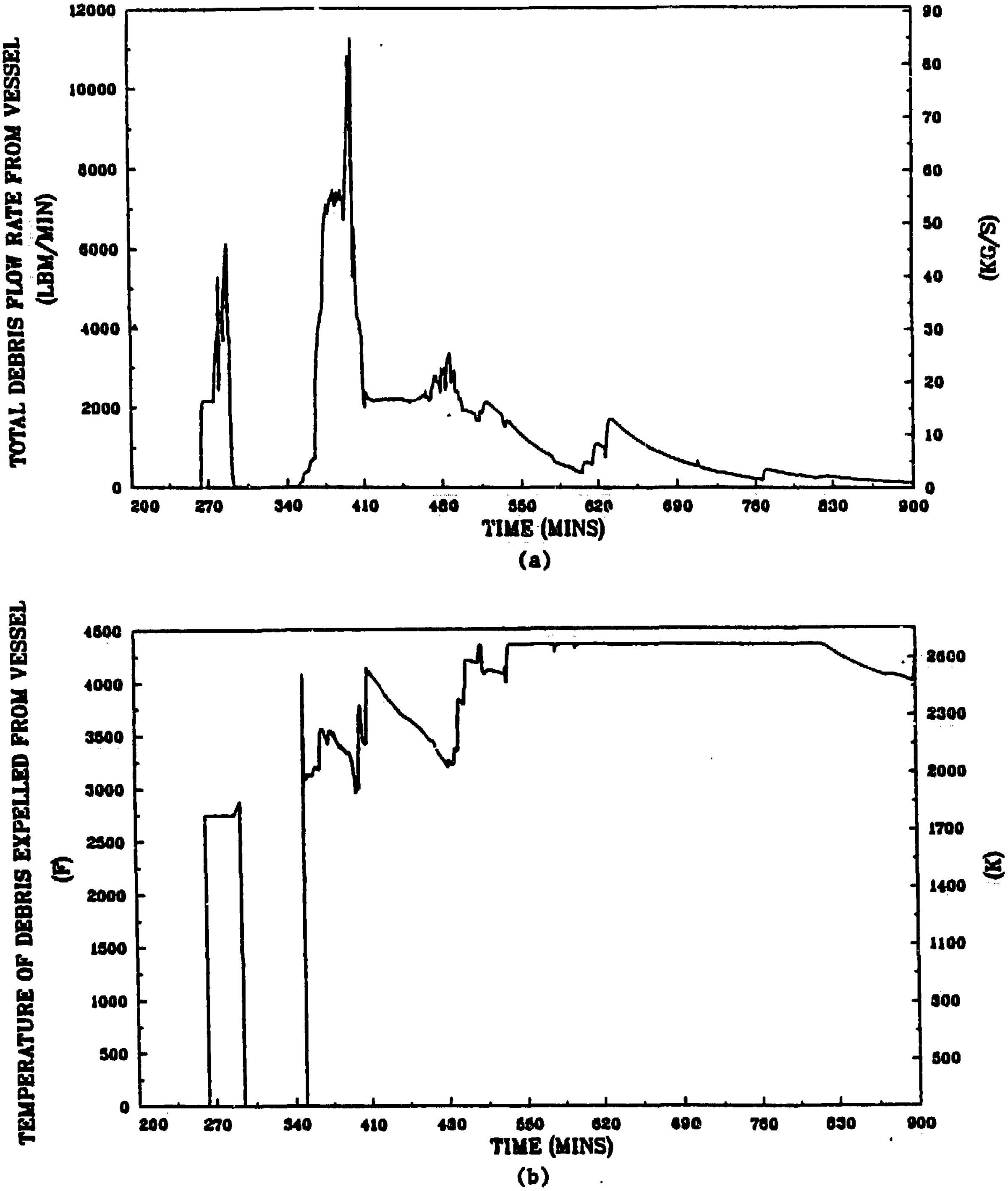

Fig. 11. Flow rates and temperatures of debris pours from the reactor vessel bottom head as predicted by the BWRSAR code for the short-term station blackout accident sequence with ADS at a unit of the Peach Bottom Atomic Power Station.

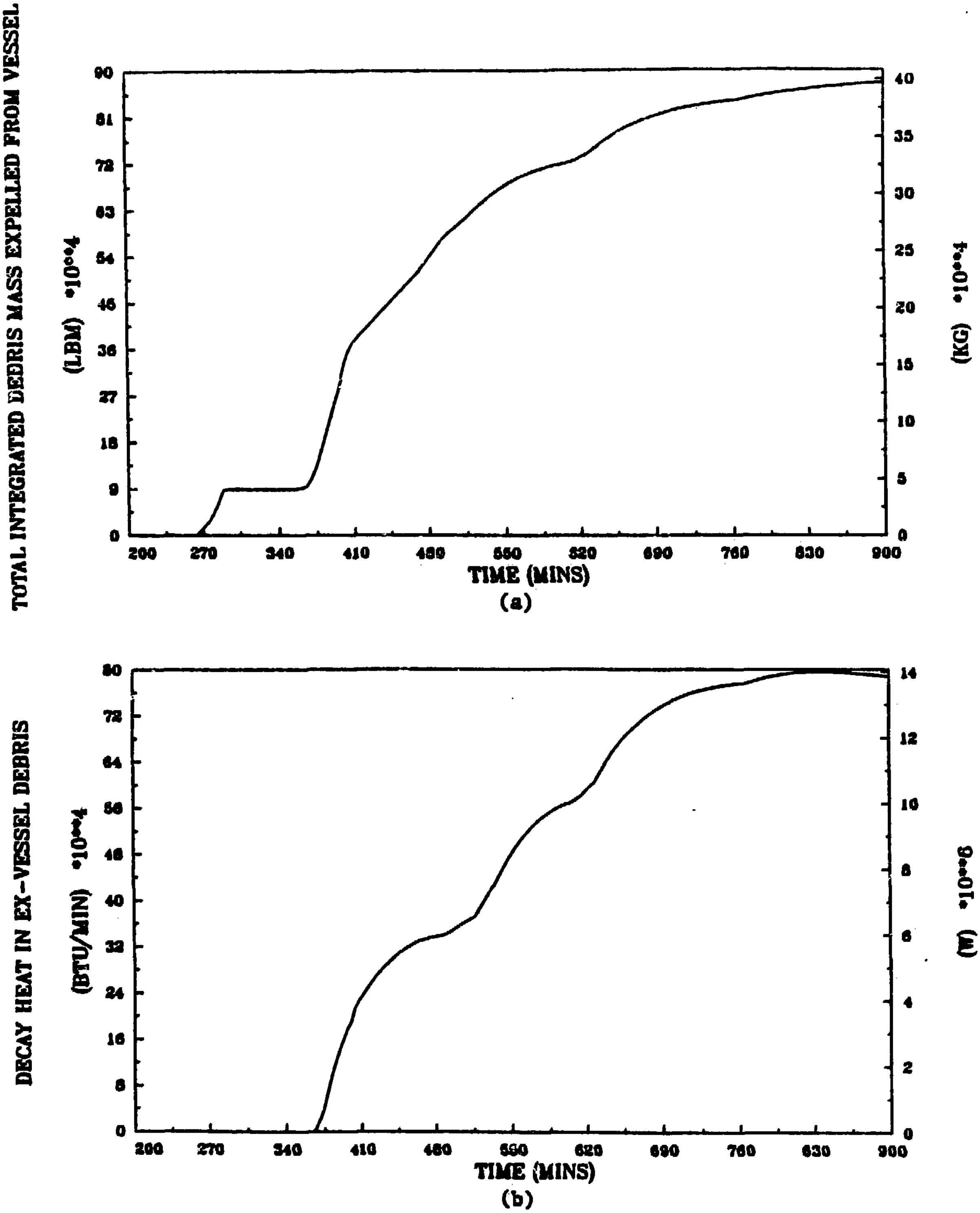

Fig. 12. Integrated debris mass expelled from the reactor vessel and decay heat power in the ex-vessel debris as calculated by the BWRSAR code for the short-term station blackout accident sequence with ADS at a unit of the Peach Bottom Atomic Power Station.

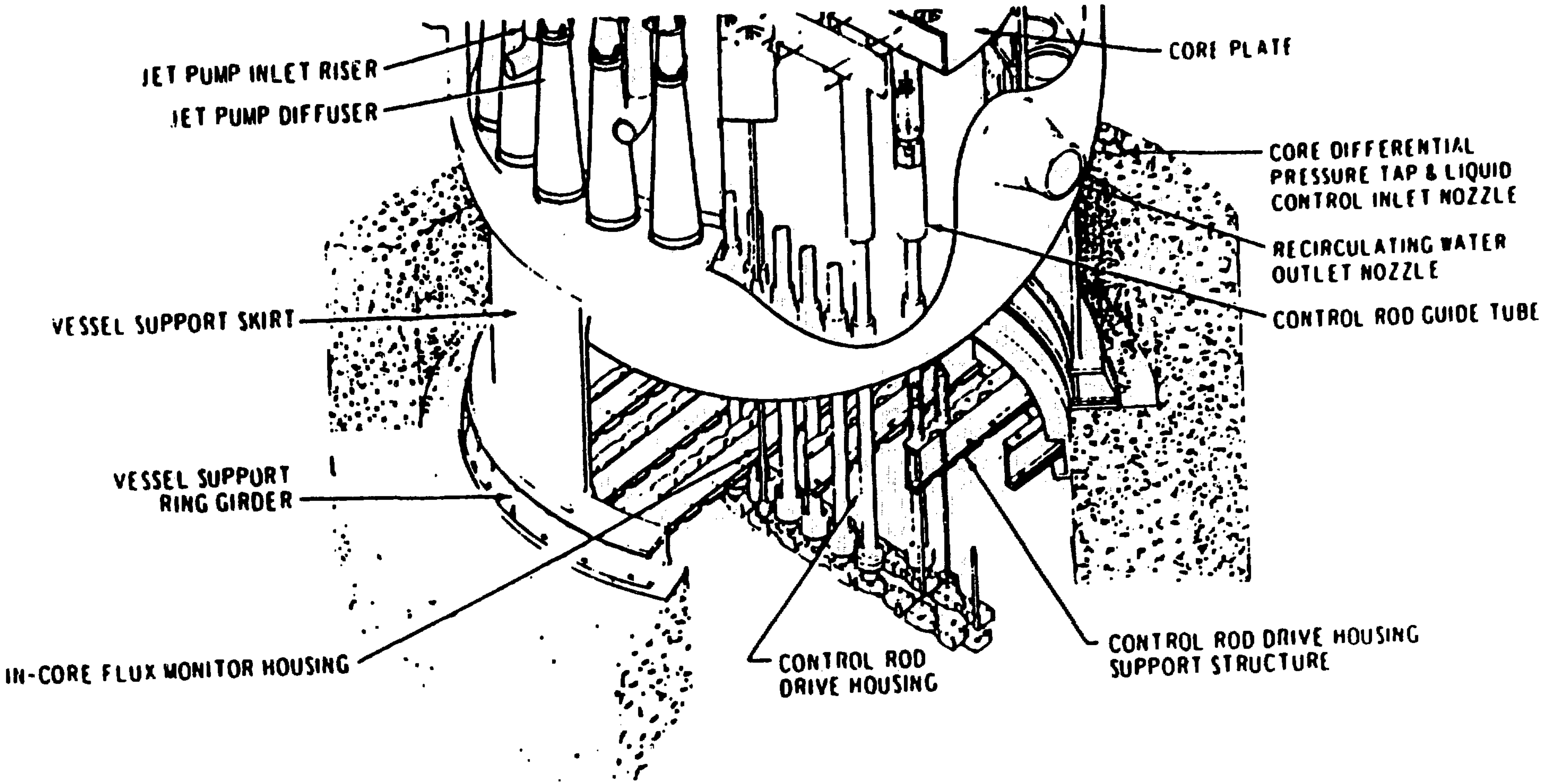

Fig. 13. Downward movement of separated portions of the bottom head beneath the skirt would be limited to about 34 inches by the CRD housing support structure.