CONTAINMENT VENTING AS A SEVERE ACCIDENT
MITIGATION TECHNIQUE FOR BWR PLANTS
WITH MARK I CONTAINMENT

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Introduction

This report describes the results of analyses performed to assess the effectiveness of containment venting as a Severe Accident mitigation technique for potential accidents at BWR plants with the Mark I containment design. Calculations have been performed for Station Blackout and ATWS, the two accident sequences recently shown by the Accident Sequence Evaluation Program (ASEP) to dominate the BWR Severe Accident risk for core melting. The model plants used for this study are Browns Ferry and Peach Bottom. Differences in plant design that must be considered in severe accident studies are listed in Tables 1 and 2.

Containment Venting for Station Blackout

The sequence of events associated with BWR Station Blackout is listed in Table 3, together with the calculated timing and the concurrent drywell conditions. The calculations were performed with the ORNL Severe Accident Sequence Analysis (SASA) program codes BWR-LTAS and MARCON 2.1B with code input specific to the Peach Bottom plant (Browns Ferry input differs only in the characteristics of the drywell concrete and the results, over the period covered by Table 1, would be virtually identical). It has been conservatively assumed that no action is taken to depressurize the reactor vessel during the early phase of the accident while the opportunity (battery power) to do so remains available. Based upon best available information, it is assumed that the plant batteries would provide DC power for six hours. Reactor vessel injection capability is lost when DC power fails and the core would subsequently become uncovered.

The ORNL SASA program methodology for analysis of the BWR severe accident sequence events that are expected to occur between the onset of core degradation and the failure of the reactor vessel pressure boundary is described in Table 4. It is believed that the reactor vessel would be breached by overtemperature failure of penetration welds while the core debris remained frozen. As the core debris subsequently became liquidus, it would leave the reactor vessel in such quantities as to run out over the drywell floor and fail the drywell shell on contact by direct burn-through.

With the sequence of events described in Tables 3 and 4, containment (wetwell) venting during Station Blackout has limited beneficial potential for BWR MK I Containment plants. This is because venting cannot prevent drywell shell failure (the presence of a deep layer of molten corium on the drywell floor shortly after reactor vessel failure is predicted to fail the drywell shell by direct burn-through). However, early, temporary, venting would be of some benefit by causing a small fraction of the hydrogen generated in-vessel to bypass the reactor building and, more importantly, by reducing the magnitude of the drywell blowdown (and consequent initial rate of flow of fission products through the secondary containment) at the time of drywell shell failure.

If a procedure for early, temporary, wetwell venting is adopted for use in Station Blackout, then the time at which venting should be initiated is plant-specific because of the differing venting paths available. The release of steam and non-condensible gases to the containment atmosphere is relatively low under Station Blackout conditions and accordingly, the venting capacity required to control containment pressure is not large. Since a six-inch, high-pressure venting path exists to atmosphere at Peach Bottom, venting could be delayed for several hours. As indicated on Table 3, the containment pressure would be only about 25 psia (0.17 MPa) at the six-hour point, when the batteries are expected to fail and reactor vessel injection capability would be lost. Temporary venting, if attempted, might begin at this point and be terminated when the first fission products are detected in the venting path.

At Browns Ferry, wetwell venting would have to be through an 18-inch line with interface from high-pressure to low-pressure ducting on the second floor of the reactor building (the 565 level). Consequently, unless the venting is done at a very low pressure, the low pressure portion of the ducting would rupture and a continuous steam source would be introduced into the secondary containment. Fortunately, there is no disadvantage to beginning venting very early since the RCIC pump suction remains on the condensate storage tank (see note 1). The containment pressure can be maintained less than 4 psig (0.1289 MPa) if venting is begun within two hours of the inception of Station Blackout.

If early containment venting is initiated, it should be terminated at the time when significant fission product release begins. For Station Blackout without manual reactor vessel depressurization (Table 3), this would occur about 9 hours after scram and about 4.5 hours before drywell shell failure.

The opening of wetwell vents is difficult under Station Blackout conditions and the potential benefits are limited. Furthermore, there is a distinct possibility that the vents would not be reclosed when significant fission product release begins (thereby advancing the time of significant release by as much as 4.5 hours). Accordingly, it is concluded that containment venting is not practical for BWR MK I Containment Station Blackout. In other words, the small potential benefit is not worth the risk of advanced release.

Containment Venting for ATWS

Calculations have been performed to determine the efficacy of containment venting for the mitigation of postulated ATWS accident sequences at Browns Ferry and Peach Bottom. As noted previously, ATWS has been identified by the ASEP program to be one of the two accident sequences that dominate the BWR severe accident risk of core melt.

It should be recognized that the purpose of containment venting is inherently different for BWR ATWS than for BWR Station Blackout. Internal pressure that threatens the continued integrity of the primary containment does not build up before reactor vessel failure in Station Blackout, but does in ATWS. The only reason to consider wetwell venting in Station Blackout is to attempt to ensure that the pressure suppression pool is placed in the fission product release path from the drywell atmosphere to the surrounding environment. However, significant quantities of fission products do not appear in the drywell atmosphere until reactor vessel bottom head failure, and shortly thereafter, the drywell shell would fail by direct burn-through, opening a direct path to the surrounding environment. Thus wetwell venting cannot accomplish its main purpose in Station Blackout.

In the ATWS accident sequence, however, a great deal of energy is deposited in the pressure suppression pool during the period <u>before</u> permanent core uncovery or core damage of any kind. As the suppression pool temperature increases, so does the associated saturation pressure; the primary containment is pressurized by means of the resultant suppression pool evaporation and steaming. Should the primary containment fail by overpressure, the failure is expected to occur at the juncture of the cylindrical and spherical portions of the drywell shell. The consequent blowdown from the drywell into the secondary containment might incapacitate the reactor vessel injection systems within the secondary containment; without continued injection, the core would be uncovered. Of course, once uncovered, core power would be limited to that provided by decay heat and core damage would progress under the impetus of decay heat as in all other severe accident sequences.

It is important to recognize that core melt might be <u>caused</u> by catastrophic failure of the drywell shell and the associated blowdown of the drywell into the reactor building, if the only available reactor vessel injection systems are failed as a result. Accordingly, containment venting to relieve pressure and preclude catastrophic failure of the drywell shell might be beneficial during ATWS. On the other hand, containment venting, as usual, carries a penalty; the pressure suppression pool would quickly become saturated and would boil. The viability of reactor vessel injection systems with pumps that take suction on the pressure suppression pool would be threatened with failure by means of inadequate net positive suction head. If these injection systems are the only ones available, then core uncovery and melt might actually be <u>caused</u> by wetwell venting.

As discussed above, containment venting for mitigation of an ATWS accident would be initiated before permanent core uncovery or severe fuel damage; therefore, various MSIV-closure ATWS accident sequences, with and without containment venting have been studied by use of the BWR-LTAS code, supplemented as needed by offline codes.

Previous work has shown that containment venting is not necessary under ATWS conditions if the SLC system injection of sodium pentaborate can be initiated within 15 minutes, since containment integrity will not be threatened and the reactor will be safely shut down without it. If, however, some malfunction delays the initiation of the SLC system, then venting might be beneficial. For the purposes of this study, the criteria for success of containment venting are that without venting, severe core damage would occur during the first three hours of the accident sequence, and that with venting, the onset of severe core damage is delayed beyond the three-hour point. Three hours is believed long enough to permit repair of any SLC system malfunctions that might suddenly be revealed at the inception of an ATWS accident sequence.

An event tree (Fig. 1) has been constructed to promote understanding of the various circumstances for which containment venting might prove useful for ATWS mitigation. Venting is unnecessary if the Standby Liquid Control (SLC) system is used to inject sodium pentaborate solution. Other branch points on the tree represent the availability of the RCIC system, the availability of the various low-pressure injection systems, pressure suppression pool cooling, and operator skill in throttling low-pressure injection. It has been assumed in building the tree that pressure suppression pool cooling is lost if the containment is vented, since the Residual Heat Removal (RHR) System pumps take suction on the pressure suppression pool and venting would make the pool saturated. Similarly, injection into the reactor vessel by the core spray pumps is assumed lost if the containment is vented. The condensate booster pumps (CBPs), on the other hand, are fed by the condensate pumps, which take suction on the main condenser hotwell in the turbine building so the continued viability of these condensate system pumps would not be affected by containment venting. The CRD hydraulic system is assumed to be operating in all cases. Where injection by the condensate system is indicated, it is assumed that operator action is taken as necessary to replenish the main condenser hotwell water inventory. Table 5 provides a discussion of the eight situations developed by the tree at which containment venting might be undertaken, and the outcome.

Containment venting appears to be of little value in actually preventing severe core damage. At Browns Ferry, wetwell venting would have to be through 18-inch lines with interface from high-pressure to low-pressure ducting on the second floor of the reactor building (the 565 level). Consequently, unless the venting is done at a very low pressure, the low pressure portion of the ducting would rupture and a continuous steam source would be introduced into the secondary containment. This would preclude personnel access to the reactor building for repair to SLC pumps or other equipment and could greatly impede attempts at system recovery. The situation is the same at Peach Bottom,* except that there the ducting failure would occur in the torus room. In either case, resort to primary containment venting sacrifices access to the secondary containment.

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*The alternate six-inch high pressure vent path at Peach Bottom is inadequate for wetwell venting during ATWS.

Nevertheless, delay of the onset of severe core damage by containment venting does seem feasible in certain narrowly defined cases in which all of the following conditions are satisfied: (1) pressure suppression pool cooling not available, (2) low pressure injection provided by the condensate system pumps via the startup bypass path around the main feed pumps with throttling of the startup bypass valve, and (3) a means for high volume replenishment of main condenser hotwell water inventory is available (see Path 5 on Fig. 1). On the other hand, containment venting would be counterproductive in most cases and therefore is not recommended as a general ATWS mitigation measure. For example, venting would cause the loss of pressure suppression pool cooling and bring on early core melt in Path 6 of Fig. 1, but if pool cooling is maintained instead, permanent core uncovery and severe core damage can be delayed beyond the three-hour criterion.

In spite of the differences in plant design listed in Tables 1 and 2, the responses of Browns Ferry and Peach Bottom to MSIV-closure ATWS are sufficiently similar during the first three hours of the accident sequence that Fig. 1 can apply to Peach Bottom as well as to Browns Ferry. Nevertheless, these plant differences do cause some variation in the details of the response, as discussed in the following paragraphs.

Paths 2 and 3 of the ATWS event tree shown in Fig. 1 represent an intentional steam cooling strategy in which the lower portion of the core is kept covered by RCIC system injection at full capacity while the upper portion of the core is cooled by the resulting steam flow. With suppression pool cooling available (Path 2), there is essentially no difference between the Peach Bottom and Browns Ferry responses and the pool temperature would not exceed 200°F during the first three hours at either plant. Path 3 of the event tree includes independent failure of pressure suppression pool cooling and leads to core melting within three hours at both plants. RCIC system failure would be caused by high containment back pressure (40 psia) at about time 120 minutes.

A seemingly minor difference in plant design has been shown to have an important effect on the calculated plant response for the path indicated by Path 4 of the event tree. In this case, the reactor vessel is depressurized and the operators are supplying reactor vessel injection by means of the condensate system pumps. This is accomplished by isolating the (idle) main feed pumps and injecting via the line normally used to bypass them during reactor startup. As indicated on Fig. 1, core integrity is not threatened during the first three hours, regardless of whether or not venting is employed. Close examination of the calculated results indicates some plant-specific differences, however.

The calculated Peach Bottom response is more favorable for Path 4 because of the smaller startup/bypass line at Peach Bottom, which permits much better operator control of the injected flow under ATWS conditions. (The startup/bypass line is three-inch at Peach Bottom, eight-inch at Browns Ferry; only about 2000 gpm is to be injected.) The effect of this can be recognized by considering how long it takes for the increasing containment pressure to reach the point (75 psia) at which venting might be attempted. This is 90 minutes in the Browns Ferry calculation, 168 minutes for the Peach Bottom calculation. The additional time at Peach Bottom is won because the better controlled and therefore lower average injection rate translates directly into a lower average core power and lower average steam release rate into the pressure suppression pool.

The improved operator control of reactor vessel injection afforded by the smaller feedpump startup/bypass line at Peach Bottom also causes differences in the detailed results for calculated plant-specific response along Path 5 of the Fig. 1 event tree. Again, the calculated Peach Bottom response is more favorable. The pressure (75 psia) at which venting might be initiated is reached after 77 minutes at Peach Bottom and 60 minutes at Browns Ferry. If the containment is not vented, the loss of low pressure injection by reactor vessel repressurization would be delayed until 105 minutes at Peach Bottom, but would occur after only 65 minutes at Browns Ferry.

One of the most important plant-specific equipment differences with respect to impact upon plant response to ATWS is the installed reactor vessel pressure relief system. The Peach Bottom plant employs the three-stage Target Rock safety relief valves, which differ significantly from the two-stage Target Rock valves installed at Browns Ferry with respect to the ability of the valves to remain open in the face of increasing drywell pressure. In the two-stage Target Rock design (Browns Ferry), the reactor vessel-drywell pressure differential and the control air-drywell pressure differential are applied in tandem to reposition the pilot valve and cause the main valve to open. In the three-stage design (Peach Bottom), these two pressure differentials act in opposition. Therefore, these two valve designs respond differently in the face of steadily increasing drywell pressure.

It should be recalled that in MSIV-closure ATWS, several of the SRVs must be open or cycling in order to pass the steam generated within the reactor vessel into the pressure suppression pool. Recognition that different SRV designs are employed at Peach Bottom and Browns Ferry is most important for the calculations that represent Path 6 of the ATWS event tree. For this path, the reactor vessel is depressurized, reactor vessel injection is provided by two core spray pumps, and pressure suppression pool cooling is operational. For both plants, calculations show that, without venting, a balance is reached between the core thermal power and the heat removed by the four RHR system heat exchangers operating in the suppression pool cooling mode. With venting, neither the RHR pumps nor the core spray pumps would have adequate net positive suction head (NPSH) to continue pumping. Even if adequate NPSH did remain, the survival of these pumps would be questionable in the steam environment that would exist in their vicinity after a venting path was opened from the primary containment to the reactor building.

The serendipitous balance between reactor power and pressure suppression pool cooling that automatically comes about in Path 6, without venting, is due to several complex interrelated system characteristics. As the increasing drywell pressure comes within a certain range of the available control air pressure, the SRVs, which were heretofore held open only by the impetus of control air, would begin to close. The steaming rate from the reactor vessel would be correspondingly reduced, slightly increasing reactor vessel pressure. Increased reactor vessel pressure reduces the rate of reactor vessel water injection by the low-pressure systems, which in turn reduces reactor power. With a lower rate of steam discharge from the reactor vessel to the suppression pool through the SRVs, the continued heat removal by the RHR system heat exchangers reduces suppression pool temperature. Lower drywell pressure follows, and soon the available control air pressure is again sufficiently above the drywell pressure so that the SRVs reopen. The cycle repeats, core thermal power averages about 9%, and this energy is removed from the suppression pool, whose bulk-averaged temperature remains in the neighborhood of 300°F, by the RHR system heat exchangers.

The calculated equilibrium drywell pressure for Path 6 without venting is lower for Browns Ferry (80 psia) than for Peach Bottom (103 psia). This is simply because the pressure of the isolated stored drywell control air volume at Browns Ferry would decrease with time, whereas the control air system at Peach Bottom would be vibrant throughout the ATWS accident sequence. [There is an automatic shutdown of the drywell control air compressors when drywell pressure exceeds 2.45 psig at Browns Ferry, such that, after about 24 minutes into the ATWS, the control air pressure would begin decaying at a rate of about 10 psi/hour. There is no such failure of the drywell control air system at Peach Bottom (see note 2); therefore, the Peach Bottom drywell control air pressure should remain approximately constant during the first three hours of the ATWS accident sequence.]

Calculations reveal that the favorable outcome of the no-venting branch of Path 6 at Peach Bottom depends upon the details of how the SRVs are assumed to behave as the control air pressure becomes inadequate to hold them open. Control air pressure must exceed drywell pressure by at least 5 psi in order for an open three-stage Target Rock SRV to remain open (seen Table 1). If all five of the open ADS SRVs are assumed to close at the same instant as soon as the five psid criterion is violated, then the reactor vessel will repressurize and the SRVs will remain closed until the setpoint for automatic actuation is reached. The repressurization would fail low pressure injection and fuel damage would follow as the vessel remains pressurized. If, however, it is assumed that there is a statistical variation among the individual SRVs of as little as 0.1 psi in the control air pressure required to hold an individual valve open, then all of the automatic depressurization system SRVs do not close simultaneously. While some of the valves close, others remain open so that the vessel does not repressurize, and low pressure injection is maintained. This model sensitivity does not occur for the Browns Ferry case, because the two-stage Target Rock SRVs behave differently. Even if all six of the Browns Ferry ADS SRVs closed simultaneously on inadequate control air pressure, they would soon reopen when the reactor vessel reached a slightly higher pressure. For the two-stage valves (see Table 1) reactor pressure and control air pressure act in tandem, so increasing reactor pressure makes it easier for the control air pressure to open or hold open the valves.

Summary

This report concerns the efficacy of containment venting for the BWR MK I containment design. Conclusions are based upon calculated results for the Station Blackout and ATWS severe accident sequences. The analyses are based upon the Browns Ferry and Peach Bottom plant configurations.

A weakness of the BWR MK I containment design is that failure of the drywell pressure boundary would permit escape of any fission products in the drywell atmosphere to the secondary containment without first passage through the pressure suppression pool. This is undesirable, because passage of flow through the pressure suppression pool is very effective in removal of any fission products entrained in the entering flow.

Although containment venting would certainly prevent failure of the drywell shell by overpressure, we believe that if a severe accident sequence were to proceed to the point of emergence of molten corium from the reactor vessel, then the corium would spread over the small drywell floor to the extent that the drywell shell would be failed by direct burn-through. Thus we do not believe that containment venting can prevent the opening of a direct path from the drywell atmosphere to the secondary containment in the BWR MK I design for a severe accident that proceeds to the point of reactor vessel bottom head failure and release of corium onto the drywell floor.

For the Station Blackout accident sequence, the calculated containment pressures do not threaten the integrity of the drywell pressure boundary before reactor vessel bottom head failure, when the drywell shell would be failed anyway. Nevertheless, early containment venting would have some beneficial effect in that the initial rate of blowdown into the secondary containment would be reduced. If opened, the vents would have to be reclosed when significant radioactive noble gas inventories began to appear in the wetwell airspace. Otherwise, the timing of significant release from the plant would be advanced by hours. We do not recommend an attempt at early, temporary, containment venting for the reason that the small potential benefit is not worth the risk that the vents might not be reclosed before significant noble gas release began.

For the ATWS accident sequence, we have the results of other studies that show that no additional operator action, including containment venting, is necessary if the injection of sodium pentaborate solution is initiated within 15 minutes. If, however, the ATWS accident sequence should be compounded by loss of the Standby Liquid Control

(SLC) system, then plant survival would depend on the success of measures taken to delay core damage until the SLC system could be repaired or individual, manual, rod insertion could be effective.

Wetwell venting to atmosphere under ATWS conditions has very undesirable side-effects. First, the pressure suppression pool would immediately become saturated and all pumping systems taking suction on the pool would be threatened by loss of their necessary net positive suction head. Thus reactor vessel injection capability by the core spray or RHR systems and pressure suppression pool cooling would probably be lost if wetwell venting is attempted under ATWS conditions. Second, the price for resort to containment venting includes sacrifice of any personnel access to the secondary containment since the vented steam would be released into the lower levels of the reactor building.

We have examined all of the MSIV-closure ATWS accident sequence scenarios from the standpoint of the effect of containment venting upon them. We have asked whether or not containment venting could play an effective role in staving off severe core damage for the first three hours of the accident sequence. In most cases, venting does not significantly affect the outcome. In one case, containment venting is counterproductive, causing core melt within the three-hour timeframe. In one case, containment venting is beneficial, delaying the core melt beyond the three-hour timeframe.

We do not believe that containment venting should be automatically required by symptom-oriented emergency procedures for BWRs. The integrity of the containment should not be intentionally violated unless there is a clear understanding of the accident sequence in progress and the effect that containment venting would have on the operating pumping systems.

Notes

1. At both Browns Ferry and Peach Bottom, the HPCI booster pump suction is automatically shifted from the condensate storage tank (CST) to the pressure suppression pool upon a low CST level or high suppression pool level signal. The operators can restore the suction to the CST when both signals are cleared, or if the high suppression pool level signal is jumpered.

   There are no automatic shifts of RCIC pump suction at Browns Ferry. At Peach Bottom, the RCIC pump suction is shifted from the CST to the pressure suppression pool only on low CST level.

2. At both Browns Ferry and Peach Bottom, the drywell control air system is automatically isolated upon high drywell pressure or low reactor vessel water level. At Peach Bottom, bypass switches to eliminate this isolation signal are available in the Control Room and the Transient Response Implementation Plan (TRIP) calls for the operators to take this action almost immediately.

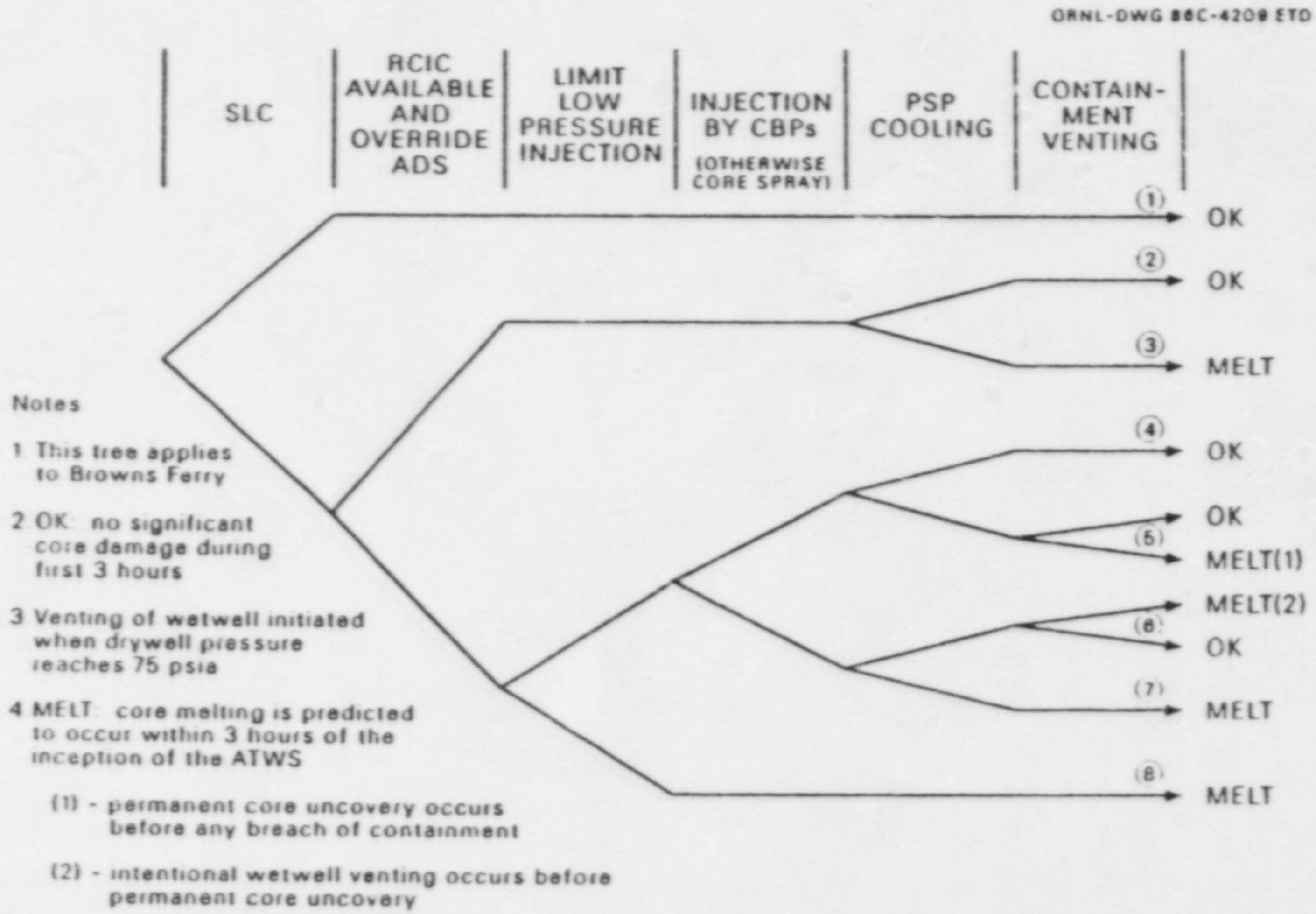

Fig. 1. Event tree to demonstrate the effectiveness of containment venting for mitigation of the MSIV-closure ATWS accident sequence at Browns Ferry.

Table 1. Plant differences affecting primary system and primary containment response to accident conditions

Item	Peach Bottom	Browns Ferry
Safety/Relief Valves (SRV)	11 Three-Stage Target Rock	13 Two-Stage Target Rock
Control Air Requirement for SRV Opening as Function for Reactor Vessel-Drywell Pressure Differential	26 psi at 1150 psid 5 psi at 50 psid	0 psi at 1120 psid 25 psi at 0 psid
Control Air Requirement to Hold an Open Valve Open	5 psi	0 psi at 1120 psid 25 psi at 0 psid
Number of SRVs Assigned to the Automatic Depressurization System (ADS)	Five	Six
Spring-Loaded Safety Valves (Discharge into Drywell)	Two	None
Drywell Control Air System Reliability	Long-term assured supply	Compressors lost at 2.45 psig drywell pressure; accumulators bleed down at 10 psi/hr
RCIC System Pump Suction	Automatically shifted to pressure suppression pool on low CST level	No automatic shift
Size of Feedpump Startup Bypass Piping	3-inch (RFP A only)	8-inch
Condensate System Pumps	Condensate pumps only	Condensate pumps and condensate booster pumps
Location of Control Rod Drive Hydraulic System Pumps	Turbine Building (116 level)	Reactor Building (Basement Corner Room)
Condensate Storage Tank Volume	200,000 gallons	375,000 gallons
Drywell Concrete Weight Fractions		
Al_2O_3	0.016	0.018
CaO	0.454	0.310
CO_2	0.357	0.200
SiO_2	0.036	0.388
H_2O Evap	0.039	0.048
H_2O Chem	0.020	0.017
Other	0.078	0.019

Table 2. Plant differences affecting secondary containment response to accident conditions

Item	Peach Bottom	Browns Ferry
Area of Refueling Bay — Atmosphere Blowout Panels (0.35 psi)	240 ft^2	3200 ft^2
Refueling Bay Free Volume	1.10×10^6 ft^3 (per unit)	2.62×10^6 ft^3 (common to all three units)
Refueling Bay — Reactor Building Separation	None. Equipment shaft is open within reactor building and to refueling bay	Blowout Panels (0.25 psi) Unit 1: On vertical walls enclosing equipment shaft in reactor building Units 2 & 3: On horizontal equipment shaft hatch cover at refueling floor. Equipment shaft is open within reactor building.
Reactor Building Free Volume (One Unit)	1.3×10^6 ft^3	1.8×10^6 ft^3
Reactor Building Compartmentalization	Torus room + three floors, basement corner rooms isolated	Torus room + four floors, basement corner rooms open to torus room and first floor above.
Stairwells Within Reactor Building	Enclosed	Open
Fire Protection System Sprays	None except limited-area spray curtain on 135 level (168 gpm)	Overhead and cable tray
Reactor Building Basement Drains	Corner room drains isolated from torus room and from each other	All basement drains interconnected.
Location of Interface Between High-Pressure and Low-Pressure 18-inch Wetwell Vent Ducting	Torus room	565 level (first floor above torus room)
Alternate High-Pressure Venting Path	Six-inch line direct to atmosphere	None
Location of Reactor Building — Wetwell Vacuum Breakers	Basement corner room	565 level

Table 3. Sequence of events for Peach Bottom station blackout without voluntary reactor vessel depressurization or containment venting

Time (min)	Event	Drywell conditions			
		Psia	°F	MPa	K
0.0	Lose AC power; scram; MSIV closure	15.8	150	0.1089	338.7
360.0	Lose DC power; lose HPCI and RCIC	24.7	236	0.1703	386.5
478.8	Top of core uncovered	31.1	273	0.2144	407.1
530.0	First H_2 in containment	34.4	286	0.2372	414.3
570.0	First fission products in containment	35.8	291	0.2469	417.1
609.8	Start melt	47.6	301	0.3282	422.6
650.0	Core plate dryout	52.0	301	0.3585	422.6
705.5	Core collapse at 50% fuel molten	59.6	306.5	0.4109	425.7
720.0	Bottom head dryout	74.6	326.2	0.5144	436.6
747.4	Bottom head penetration failure	76.2	318.9	0.5254	432.6
760.0	Vessel/containment pressures equalized	112.6	318.2	0.7764	432.2
810.9	Core debris leaves vessel	100.5	325.6	0.6929	436.3
814.7	Burn-through failure of drywell shell	130.2	600.0	0.8977	588.7

Table 4. ORNL SASA program methodology for events between onset of core structural deformation and reactor vessel bottom head failure for BWRs

1. Molten canister and control blade materials relocate onto the core plate which causes: a. temporary steaming increase b. dryout of core plate c. core plate heatup
2. The core plate, loaded and overheated, fails and falls into the reactor vessel lower plenum, causing a steam pulse to enter the core region. Subsequent canister and control blade debris enters the lower plenum directly.
3. All remaining intact portions of the core suddenly collapse into the lower plenum when the calculated UO_2 molten fraction exceeds 50%.
4. The large volume of water in the lower plenum is boiled away. At bottom head dryout, the debris temperature is about 2475°F (1630.4 K). The debris begins to reheat.
5. Several of the reactor vessel bottom head penetration welds fail as the debris temperature rises above 2800°F (1811.0 K). The reactor vessel blows down and its internal pressure equalizes with containment pressure.
6. The core debris leaves the reactor vessel when it becomes liquidus at 3500°F (2200 K).

Table 5. Discussion of branches of Browns Ferry event tree (Fig. 1)

Branch	Description
1.	Containment venting is irrelevant if the SLC system is used to inject sodium pentaborate within 15 minutes. All other branches involve failure of the SLC system.
2.	The RCIC system is used for reactor vessel injection and all four RHR pumps and coolers are employed for pressure suppression pool cooling. The core is partially uncovered, but the upper portion is adequately cooled by steam cooling. The suppression pool temperature does not exceed 200°F during the first three hours, so containment backpressure does not threaten RCIC operation or reach the point where venting would be necessary or considered.
3.	The RCIC system is used for reactor vessel injection but there is no pressure suppression pool cooling. High containment backpressure (40 psia) causes loss of RCIC after about 2 hours. With only CRD hydraulic system injection available, the water level would drop near the bottom of the core and melting would follow. Venting, if attempted, would only threaten the continued operation of the CRD hydraulic system.
4.	The condensate booster pumps (CBPs) are used for low pressure injection to the reactor vessel, with the operators throttling the injection to control reactor power. All four RHR pumps and coolers are used for pressure suppression pool cooling. Without venting, the reactor vessel steaming rate is within the capacity of the pool cooling and the maximum containment pressure is about 77 psia. With venting, suppression pool cooling is lost but this does not threaten continued injection by the condensate booster pumps.
5.	The CBPs are used for controlled low pressure injection to the reactor vessel but pressure suppression pool cooling is not available. Without venting, drywell pressure would exceed available control air pressure and the SRVs could not be held open. As a result, CBP injection would be lost at 65 minutes. In this case, venting is necessary if the reactor vessel is to remain depressurized. Calculations indicate that venting would extend the time of CBP injection well past 3 hours.