CONF-8806153--1

THE ROLE OF BWR SECONDARY CONTAINMENTS IN SEVERE ACCIDENT MITIGATION: ISSUES AND INSIGHTS FROM RECENT ANALYSES[*]

Sherrell R. Greene
Oak Ridge National Laboratory

CONF-8806153--1

DE88 011837

ABSTRACT

All commercial boiling water reactor (BWR) plants in the U.S. employ primary containments of the pressure suppression design. These primary containments are surrounded and enclosed by a secondary containment consisting of a reactor building and refueling bay (MK I and MK II designs), a shield building, auxiliary building and fuel building (MK III), or an auxiliary building and enclosure building (Grand Gulf style MK III). Although secondary containment designs are highly plant specific, their purpose is to minimize the ground level release of radioactive material for a spectrum of traditional design basis accidents. While not designed for severe accident mitigation, these secondary containments might also reduce the radiological consequences of severe accidents. This issue is receiving increasing attention due to concerns that BWR MK I primary containment integrity would be lost should a significant mass of molten debris escape the reactor vessel during a severe accident.

Failure of the primary containment pressure boundary during a severe accident may result in the discharge of large quantities of hydrogen into the secondary containment atmosphere. Deflagration of this hydrogen within the secondary containment would result in pressure loadings which might threaten secondary containment structural integrity. The fission product retention capability of an intact secondary containment will depend on several factors. Recent analyses indicate that the major factors influencing secondary containment effectiveness include: the mode and location of the primary containment failure, the internal architectural design of the secondary containment, the design of the standby gas treatment system, and the ability of fire protection system sprays to remove suspended aerosols from the secondary containment atmosphere. Each of these factors interact in a very complex manner to determine secondary containment severe accident mitigation performance.

This paper presents a brief overview of domestic BWR secondary containment designs and highlights plant-specific features that could influence secondary containment severe accident survivability and accident mitigation effectiveness. Current issues surrounding secondary containment performance are discussed, and insights gained from recent ORNL secondary containment studies of Browns Ferry, Peach Bottom, and Shoreham are presented. Areas of significant uncertainty are identified and recommendations for future research are presented.

---

[*] Research sponsored by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, under Interagency Agreement DOE 0551-0551-A1 with the U.S. Department of Energy under Contract DE-AC05-84OR21400 with the Martin Marietta Energy Systems, Inc.

MASTER

DISCLAIMER

1. INTRODUCTION

All commercial boiling water reactor (BWR) plants in the U.S. employ primary containments of the pressure suppression design. These primary containments are surrounded and enclosed by a secondary containment consisting of a reactor building and refueling bay (MK I and MK II designs), a shield building, auxiliary building and fuel building (MK III), or an auxiliary building and enclosure building (Grand Gulf style MK III). Although secondary containment designs are highly plant specific, their purpose is to minimize the ground level release of radioactive material for a spectrum of traditional design basis accidents. While not designed for severe accident mitigation, these secondary containments might also reduce the radiological consequences of severe accidents. This issue is receiving increasing attention due to concerns that BWR MK I primary containment integrity would be lost should a significant fraction of the reactor core become molten and escape the reactor vessel during a severe accident.

During the past eight years ORNL has been heavily involved in BWR severe accident analysis efforts, as the lead analysis center for the Nuclear Regulatory Commission's BWR Severe Accident Sequence Analysis (SASA) and BWR Severe Accident Technology (BWRSAT) programs.[1-24] The goal of these programs has been to provide the NRC with a best-estimate, deterministic analysis capability for BWR severe accidents (ie accidents which progress through core-uncovery, core melting, and reactor vessel failure). Through this period, ORNL has benefited from the cooperation of the utilities that own and operate the plants that have been studied: the Tennessee Valley Authority for Browns Ferry studies, and the Philadelphia Electric Company for Peach Bottom studies. Additionally, ORNL has had access to and extensively applied state-of-the-art severe accident simulation codes such as CONTAIN and MELCOR.[25,26]

2. BWR SECONDARY CONTAINMENT CONCEPT

Exhibit 1 is a simplified representation of the multi-barrier containment concept and the manner in which it is implemented in the domestic BWRs. The fission product inventory of the plant is contained within the Zircaloy-clad fuel pins which, with the channel boxes, collectively constitute the reactor core. The second barrier to fission product release during an accident is the reactor vessel (BWR reactor vessels would be isolated behind closed main steam isolation valves during severe accident sequences). The third barrier to fission product release is provided by the primary containment, which (in a MK I plant) consists of the inverted light bulb-shaped drywell and the toroidal-shaped wetwell (which is housed in the basement of the reactor building). The final barrier to fission product release is the secondary containment (reactor building and refueling bay), which completely surrounds and encloses the primary containment. BWR secondary containment reactor buildings are massive, multi-floored structures with reinforced external concrete walls. Secondary containment above the top of the reactor building is provided by a refueling bay constructed of corrugated sheet metal walls that contain large blowout panels to provide protection from the effects of tornados and internal reactor building pressurization due to steam line breaks. Blowout panels are also provided in the steam tunnel which connects the reactor and turbine buildings.

3. SEVERE ACCIDENT PHENOMENOLOGY

One scenario for a BWR severe accident begins with the failure of all normal and emergency core cooling systems. (It should be noted that this is an extremely unlikely event because BWRs employ as many as thirteen different systems capable of injecting water into the reactor vessel.) This loss of injection capability is followed by a gradual boiloff of the reactor coolant inventory, and uncovery of the reactor's core. As the water level drops within the core, fuel temperatures increase significantly, leading to oxidation of the Zircaloy fuel cladding - a highly exothermic reaction which generates substantial quantities of hydrogen and dramatically increases the fuel heatup rate. This hydrogen is either vented to the pressure suppression pool via the safety/relief valves, or escapes to the primary containment upon reactor vessel failure. The continued heating of the core materials eventually leads to the release of fission products from the fuel, and the subsequent melting and downward relocation of core material into the bottom (lower head) of the reactor vessel. The hot core debris (continually heated by nuclear decay heat and the exothermic Zircaloy oxidation reaction) thermally attacks the lower head, leading to reactor vessel failure and expulsion of hot core debris onto the concrete floor of the primary containment.

The reaction of the hot core debris with the primary containment concrete would proceed in a very complex manner, releasing fission product vapors, fission product-laden aerosols, additional hydrogen, carbon dioxide, carbon monoxide, and water vapor. The exact mix of gases generated by the core/concrete reaction is a function of the type of concrete employed, and the amount of un-oxidized Zircaloy leaving the reactor vessel. It should be noted that in an unmitigated BWR severe accident the entire Zircaloy inventory of the reactor would eventually oxidize (either in the reactor vessel or on the drywell floor), generating as much as 6000 lb (2722 kg) of hydrogen (plant specific value). These reaction products heat and pressurize the primary containment, and the debris might directly attack the steel primary containment shell (MK I design) or drywell downcomers (MK II). The primary containment boundary would ultimately fail, releasing fission products, aerosols, steam, and combustible gases into the surrounding secondary containment. The aerosols and fission products would migrate through the reactor building and some of the fission products would eventually escape to the surrounding environment via the refueling bay blowout panels (which would open to relieve the internal reactor building pressurization generated by the primary containment blowdown and the deflagrations).

4. INSIGHT: BWR SECONDARY CONTAINMENT DESIGNS ARE HIGHLY PLANT SPECIFIC

The secondary containments of domestic BWRs were designed and/or constructed by ten different architect/engineering firms (Table 1), and vary considerably in basic design characteristics such as volume, number of floors, the arrangement of stairways and elevator shafts, etc. Table 2 presents a comparison of the secondary containment design characteristics for the Browns Ferry (MK I), Peach Bottom (MK I), and Shoreham (MK II) plants. Browns Ferry and Peach Bottom employ very similar reactors. Browns Ferry is a three-unit, 3293 MWt BWR 4/MK I plant which utilizes a single common refueling bay to service all units. Peach Bottom is a two-unit 3293 MWt BWR 4/MK I plant, but each unit is serviced by an independent refueling bay. Shoreham is a single unit, 2436 MWt BWR 4/MK II plant.

A review of the data in Table 2 will reveal that Browns Ferry's reactor building volume is 23 % larger than that of Peach Bottom (1411800 ft^3 [429 ft^3/MWt] versus 1146800 ft^3 [348 ft^3/MWt]). Interestingly, Shoreham's reactor building volume is almost as large as that of Browns Ferry, and is larger than either Browns Ferry or Peach Bottom on a pro-rated basis (563 ft^3/MWt). Refueling bay volumes also vary significantly, with Browns Ferry's refueling bay volume greatly exceeding that of the two other plants. Browns Ferry has by far the largest total secondary containment volume and heat sink area, due primarily to its large common refueling bay.

Another important feature of the three plants which may be compared is the Standby Gas Treatment System (SGTS) and Reactor Building Standby Ventilation System (RBSVS) exhaust flow rates. Browns Ferry and Peach Bottom both utilize an SGTS design which features "once-through" filtration and exhaust of the secondary containment atmosphere. SGTS flow rates at Browns Ferry and Peach Bottom are quite high, with flow rates sufficient to exchange an entire reactor building atmosphere in 67 minutes at Browns Ferry and 46 minutes at Peach Bottom. Shoreham employs an RBSVS (rather than an SGTS) which recirculates the bulk of the reactor building atmosphere through filter trains, while exhausting only minor fractions of the RBSVS flow. Consequently, Shoreham's system requires 19.7 hours to exhaust one reactor building atmosphere.

Finally, as can be seen from Table 2, Browns Ferry utilizes an extensive pre-action fire protection spray system, while Peach Bottom and Shoreham employ very limited pre-action spray systems. The significance of SGTS and fire protection spray system design differences will be discussed in the following sections.

5. INSIGHT: INTRINSIC FISSION PRODUCT RETENTION CAPABILITY OF INTACT SECONDARY CONTAINMENTS CAN BE SUBSTANTIAL

During the past four years, studies at ORNL have revealed that the aerosol retention capability of intact BWR secondary containments may be quite substantial for some accident scenarios in some plants. Plant-specific studies of the aerosol retention capability of the Browns Ferry and Peach Bottom designs have revealed that as much 90% of the aerosols which escape the primary containment may be retained in the secondary containments of these plants.[27] Aerosol decontamination factors, or DFs, (the ratio of the mass of aerosols which escape the primary containment to the mass of aerosols which escape the secondary containment) of 10 to 40 have been calculated for some scenarios. It should be noted that secondary containment decontamination factors are time dependent parameters (Exhibit 2). A single-valued estimate for containment DF does not convey sufficient information to provide insight into the time-dependent nature of containment performance.

6. INSIGHTS: PRIMARY CONTAINMENT FAILURE MODE AND LOCATION ARE VERY IMPORTANT

Since both the refueling bay and steam tunnel blowout panels are typically predicted to open following primary containment failure, the mode and location of the primary containment failure are the dominant factors influencing the residence time of the blowdown in the secondary containment and the fraction of the secondary containment volume and area available for the various heat transfer and fission product removal processes.

Historically, the dominant primary containment failure mechanism considered in BWR severe accident analyses was over-pressure failure of the steel primary containment shell.[28,29] The pressure and location at which failure would occur are plant-dependent. Failure pressures have been predicted to range between 130 and 160 psig (896 and 1103 kPa gauge)[30,31] The most probable over-pressure failure location in MK I plants appears to be the upper half of the pressure suppression pool torus. The most probable over-pressure failure location for MK II plants appears to be the primary containment liner in the wetwell airspace above the surface of the pressure suppression pool. A common feature of both of these failure locations is that primary containment blowdown would enter the lowest portions (basement) of the reactor building. This is a fortuitous characteristic, because the basement zones of the reactor building are below grade and can withstand high pressures. A second very important advantage of this failure location is that it affords the maximum opportunity for scrubbing of fission products and aerosols, since the blowdown must flow through major portions of the reactor building prior to escaping to the environment.

Great concern has recently been voiced about the possibility of MK I drywell shell failure due to direct attack by core debris.[32] Recent work by ORNL has revealed that the probability of this failure mode is a strong function of the type of concrete employed for the drywell floor, with limestone-common sand concrete affording more protection than high-limestone concrete.[23] The limestone-common sand concrete ablates at lower temperatures than high-limestone concrete, leading to greater dissolution of the core debris by concrete oxides and lower debris temperatures than would result in the case of high-limestone concrete. This depression of debris temperatures is gained, however, at the expense of higher containment pressures and temperatures produced by the accelerated degassing of the limestone-common sand concrete. In the event that shell failure does occur near the level of the drywell floor, the drywell blowdown would be expected to enter the lower regions of the reactor building via the annular gaps surrounding the vent pipes leading to the torus room.[27,33]

A third potential mechanism for BWR primary containment failure is primary containment shell or penetration failure due to collapse of the reactor vessel caused by ablation of the reactor's concrete support pedestal. Recent ORNL studies have revealed that more than 75% of the reactor pedestal wall thickness may be eroded due to concrete ablation in some cases.[23] The probability of this failure mode is a strong function of the amount of zirconium metal available for oxidation on the drywell floor. It should be noted that the weight of the reactor vessel and internals would be decreased prior to pedestal failure due to expulsion of the core and core support materials following reactor vessel failure. The resulting load on the reactor pedestal would, therefore, be significantly reduced. Unfortunately, the most probable location for primary containment failure following pedestal collapse has not been determined (and is probably plant-specific).

A fourth type of primary containment failure in MK I and MK II plants is failure of the drywell head flange seals.[30] The Idaho National Engineering Laboratory (INEL) recently conducted a series of thermal performance tests of seals similar to those employed in BWRs.[34] The INEL experiments indicate that these seals would fail catastrophically at a differential pressure of 160 psi (1103 kPa) when flange temperatures reach 730 degrees F (661 K). Recent ORNL calculations indicate that drywell head temperatures of 900 to 1068 degrees F (756 to 849 K) may be reached in some MK I accident sequences. Failure of these head flange seals is a particular concern, since drywell blowdown via this pathway would enter the region between the drywell head and the drywell shield plugs located in the floor of the refueling bay - and then directly into the refueling bay itself. This is a particularly undesirable path, because the reactor building and the various reactor building fission product retention mechanisms would be bypassed.

7. INSIGHT: SECONDARY CONTAINMENT FISSION PRODUCT RETENTION CAPABILITY IS ENHANCED BY FIRE PROTECTION SYSTEM SPRAYS

Some BWR secondary containments incorporate comprehensive fire protection systems which utilize fused-link water sprinklers for fire suppression. The Browns Ferry plant utilizes a system that employs fused-link sprinklers which cover the first three floors of the reactor building (soon to be upgraded to cover all floors). The system consists of two 10000 gallon (37.8 m^3) raw service water (RSW) storage tanks (located atop the reactor building), four RSW pumps which maintain the tank inventory during normal operation, four fire system pumps (one of which is diesel-driven), and the sprinkler system. The RSW storage tanks provide a 20000 gallon (75.7 m^3), gravity-fed sprinkler supply reservoir, and no power is required for actuation of the fused-link sprinklers. ORNL first identified the secondary containment fire protection system as a potential severe accident mitigation system during a previous SASA study.[27]

Although not designed for severe accident mitigation, the fused-link sprinklers would actuate following primary containment failure due to increased reactor building atmospheric temperatures. While major portions of the first three floors of the Browns Ferry reactor building are covered by the current spray system, during station blackout conditions the spray system would be fed only by the roof-top RSW storage tanks, and the single diesel-driven fire pump. Under these circumstances, water is available to the third floor sprinklers only until the RSW tanks are depleted. The first and second floor sprinklers are continuously fed, however, by the single diesel-driven pump.

Exhibit 3 displays the results of two Browns Ferry short-term station blackout calculations in which (a) operation of the spray system was inhibited, and (b) the spray system was assumed to function in its normal manner. The ordinate of Exhibit 3 is the fraction of the total aerosol inventory (that has escaped the primary containment) retained in the reactor building, the turbine building, and the environment at one hour after primary containment failure. The impact of spray system operation can clearly be seen by noting the difference in the environmental aerosol inventory. Fractional aerosol releases are decreased from 33% to 10% by (limited) spray operation. It is apparent, therefore, that secondary containment fire protection systems can significantly enhance the secondary containment aerosol decontamination factor. Unfortunately, many plants do not employ pre-action sprinklers, while other plants utilize systems with extremely limited coverage.

8. INSIGHTS: ROLE AND EFFECTIVENESS OF SGTS/RBSVS ARE HIGHLY VARIABLE

All BWR secondary containments incorporate a system designed to filter (through charcoal and high efficiency particulate absolute [HEPA] filters) and exhaust primary containment purge gas during normal startup and shutdown operations. These systems are also employed to process the secondary containment atmosphere during accident conditions. Most MK I plants utilize high capacity standby gas treatment systems (SGTS), which are of the once-through design. These systems draw suction on the reactor building and refueling bay (typically 20000 cfm [9.4 m^3/s] total), filter the entire gas stream, and exhaust it through an elevated stack to the atmosphere. Secondary containment makeup air is provided via infiltration and controlled inleakage from the environment.

Some MK II plants (Limerick) utilize a low capacity SGTS in conjunction with a reactor enclosure recirculation system (RERS). The RERS mixes, filters, and recirculates 60000 cfm (28.3 m^3/s) between the reactor building and refueling bay. The independent SGTS filters and exhausts much smaller flows (3000 cfm or 1.4 m^3/s) to the environment. The Shoreham plant utilizes a reactor building standby ventilation system (RBSVS) which draws suction on the reactor building (45000 cfm or 21.2 m^3/s) and discharges (without filtration) to the refueling bay. Less than 1200 cfm (0.6 m^3/s) of this flow is filtered and exhausted to the environment. The major impact of SGTS operation on the secondary containment atmosphere is filtration and dilution. The major effect of the RERS is filtration and mixing, and the major impact of the RBSVS is mixing.

The effectiveness of plant Standby Gas Treatment Systems and Reactor Building Standby Ventilation Systems during severe accidents will be plant and accident sequence-dependent. The SGTS and RBSVS fans would not be operable in station blackout sequences (in which offsite a.c. power and on-site diesels would not be available), so that the potential benefit of these systems is minimal. For other accident sequences in which the system fans are operable, the effectiveness of the systems will be a function of overall system design and capacity, and the primary containment failure location and blowdown rate. During severe accidents, the exhaust capacity of the SGTS, RERS, or RBSVS (if operating) could have a major impact on secondary containment fission product retention, since primary containment blowdown rates in excess of the system exhaust capacity can result in secondary containment pressurization and direct leakage from the secondary containment to the environment. The operational characteristics of these systems can significantly influence the probability of secondary containment combustible gas deflagrations, and the nature of the threat that such deflagrations pose to secondary containment integrity. (This issue will be discussed in the following section). RBSVS operation might actually decrease secondary containment fission product retention capability for cases in which the primary containment blows down into the lower region of the reactor building, because the system would actively transport fission products from the lower regions of the building to the refueling bay (which would be the secondary containment failure location in many accidents).

9. INSIGHT: COMBUSTIBLE GAS DEFLAGRATIONS MAY THREATEN SURVIVABILITY OF SECONDARY CONTAINMENTS

While the aerosol and fission product retention capability of an intact secondary containment may be quite substantial, the overall credibility of the secondary containment function can be compromised if deflagration-induced pressure pulses fail portions of the secondary containment boundary (exterior reactor building walls). Exhibit 4 depicts the results of a series of Browns Ferry short-term station blackout simulations in which the primary containment shell was assumed to fail due to direct contact with the hot core/concrete debris at a time when the primary containment pressure was 85 psia (586 kPa). Five different primary containment hole sizes, ranging from 5.38 to 0.01 ft^2 (0.5 to .0005 m^2), were assumed, and the primary containment blowdown was assumed to enter the torus room in the basement of the reactor building (elevation RB1 in Exhibit 4). The abscissa of Exhibit 4 is reactor building elevation (floors one [RB1] through five [RB5] and the refueling bay [RF]), and the ordinate is the maximum calculated internal secondary containment pressure occurring in each floor throughout the course of the accident. While peak internal pressures as high as 32 psia (221 kPa) were observed in the basement (elevation RB1) of the reactor building, peak above-ground reactor building pressures range from 20 to 27 psia (138 to 186 kPa) in this series of calculations. The maximum pressure differentials observed in these calculations are as much as four times the 3 psid (20.7 kPa differential) design pressure rating of the Browns Ferry reactor building and would probably challenge the integrity of the secondary containment.

The tendency to achieve the atmospheric composition necessary for deflagration is a function of many factors. The two most important factors are the degree of secondary containment compartmentalization (or connectivity) and the impact of the SGTS/RERS/RBSVS system operation. Low connectivity tends to promote localized deflagrations, while high connectivity tends to result in fewer, but larger and more severe, deflagrations. The impact of the larger number of small burns on secondary containment fission product retention is much less severe than that of a few global burns, in which higher peak pressures are developed, and the entire building vents to the outside environment over a short time period.[27] Deflagrations in highly compartmentalized structures usually result in lower peak pressures than do global burns in large open volumes. Additionally, the involved region in the compartmentalized structure vents to other regions of the reactor building, rather than into the environment as is the case when large portions of the secondary containment are involved in a single global deflagration event. SGTS/RERS/RBSVS operation may influence combustibility by (a) mixing the secondary containment volume and (b) importing air from outside the secondary containment. The mixing function tends to increase the amount of hydrogen necessary to reach combustible conditions, while the impact of air infiltration is sequence dependent. In some cases (hydrogen-lean environments), the impact of the air infiltration is to dilute the hydrogen concentration below combustible limits, while in other cases (oxygen-lean environments), the infiltration results in an increase in oxygen concentrations to combustible limits.

10. ISSUE: IMPROVED SECONDARY CONTAINMENT SEVERE ACCIDENT MITIGATION CAPABILITY

The evidence presented in Sections 4-9 above supports the contention that existing BWR secondary containments can play a significant role in mitigating the effects of severe accidents if (a) the secondary containment is not bypassed due to failure of the drywell head flange seals, and (b) a means is found to reduce the threat to the secondary containment integrity from combustible gas deflagrations. Two potential methods for accomplishing these goals are (a) primary containment sprays, and (b) primary containment venting. These two accident mitigation approaches are discussed in this section.

Containment Sprays: Any discussion of the use of containment sprays for severe accident mitigation must be preceded by a reminder that (in current BWR designs) the containment spray and reactor vessel injection system water supplies and piping are (or can be) interconnected such that containment spray availability is concomitant with reactor vessel injection capability. The argument can therefore be made that all available water should be (and would have been) injected into the reactor to halt the accident prior to vessel melt-through. The discussion of the potential benefits of containment sprays is, therefore, realistic only in conjunction with the assumption of late recovery of sprays, or the installation of dedicated containment spray systems.

Operation of drywell sprays during a BWR severe accident might result in several phenomena: (a) aerosol scrubbing [via direct spray removal and pool scrubbing if a water pool is maintained above the core debris], (b) steam condensation, (c) debris freezing, and (d) accelerated metal/water reactions. Perhaps most importantly, it is possible that spray operation will reduce the drywell pressure and upper drywell atmosphere temperature sufficiently to avoid failure of the drywell head flange seals. (Drywell head flange seal failure would allow the primary containment to vent into the refueling bay, bypassing the majority of the secondary containment.) Interaction of the spray water with the core debris could possibly result in preservation of the steel drywell shell (MK I) or drywell downcomers (MK II). Unfortunately, current inadequacies in experimental data and computational models inhibit resolution of this issue. It should also be noted that the impact of primary containment failure-induced flashing and boiling of water pools which overlie core debris (and the associated potential for resuspension of previously deposited aerosols) cannot be adequately evaluated at the present time.

Containment Venting: Existing BWRs employ primary containment venting systems to provide the venting capability necessary for containment inerting prior to reactor startup and de-inerting prior to personnel entry into the primary containment. Most existing plant emergency operating procedures call for containment venting when containment pressure reaches or exceeds the design value (48 to 60 psig or 331 to 414 kPa gauge). [35-37] Failure of the vent system ducting is likely under these circumstances, since the systems were not designed for such pressure differentials. Such ducting failures would allow the vented material to discharge directly into the reactor building, flooding the building with steam and combustible gases, and effectively eliminating further access to the secondary containment. Backfitting of dedicated "hard" vent systems (which employ high-pressure ducting throughout the entire system but no filters) has been suggested as one mechanism for improving vent reliability. It should also be noted that, existing containment venting systems would not be functional during station blackout sequences. Power (d.c. or a.c. or direct human manipulation) is required for vent valve operation.

Containment venting from the wetwell air space in a MK I containment is desirable primarily as a mechanism for reducing combustible gas concentrations in the secondary containment subsequent to drywell shell failure (melt-through), thereby increasing the probability of secondary containment survivability. Containment venting is feasible in a MK I (via either the existing vent system or a dedicated "hard" vent system) because the probability of pressure suppression pool bypass (in the vent system) is very low. It is important to note, therefore, that wetwell venting via either the existing system or a hardened vent system in the MK I design (a) is a mechanism for preservation of secondary containment integrity, and (b) is unlikely to discharge a significant quantity of aerosols into the environment.

Containment venting in MK II plants is (in contrast to MK I plants) desirable primarily as a mechanism for preserving primary containment integrity by preventing excessive primary containment pressures (since drywell shell failure via direct attack by core debris appears unlikely). MK II containment venting (via existing systems or simple "hard" systems) appears to be infeasible however, since drywell downcomer failure (and associated pressure suppression pool bypass) due to direct attack from core debris appears probable in some designs. It is much more probable that operation of simple "hard" venting systems in MK II plants would result in the discharge of aerosols directly into the environment. It should be noted, therefore, that wetwell venting via either the existing system or a hardened vent system in a MK II design (a) is a mechanism for control of primary containment pressure but (b) is likely to discharge aerosols into the environment.

One potential solution to the problems associated with use of existing containment venting systems is the installation of hardened filtered venting systems, such as the FILTRA system in use at the Barseback BWR plant in Sweden.[38] While the Long Island Lighting Company had intended to install a similar filtered vent system at the Shoreham Plant, such systems have traditionally been viewed by U.S. utilities as having unacceptably low cost/benefit ratios.[39]

11. UNCERTAINTIES AND UNRESOLVED ISSUES

While recent efforts have yielded new insights into the role and significance of BWR secondary containments in severe accident mitigation, many uncertainties persist and much work remains to be done.

Secondary containment simulation capability: Although great advances in our secondary containment simulation capability have occurred in recent years, there are still several areas in which significant uncertainties exist. Some of these uncertainties are a result of inadequacies in our experimental database, while others are due to a lack of model implementation in existing codes. Some of the more important problems of this nature include the simulation of deflagration and detonation dynamics and the chemical kinetics of fission product species. New codes such as MELCOR and CONTAIN are, for the first time, providing the integrated simulation capability required for realistic severe accident containment analyses.

Primary containment failure mode and location: Much is yet to be learned regarding the various modes of primary containment failure, the conditions under which each failure mode would occur, and location of the various failure points. As previously mentioned, analyses completed to date indicate that the primary containment failure mode and location is a plant-specific and accident sequence dependent characteristic. The current emphasis of such studies is evaluation of the probability of MK I shell failure due to direct attack by core debris.

Impact of plant-specific design features on secondary containment performance: There are forty BWR units under construction or in operation in the U. S. The vast majority of secondary containment work that has been done to date has focused on station blackout transients at Browns Ferry and Peach Bottom. Recently, some additional work has been done to evaluate the secondary containment performance of the La Salle and Shoreham plants. Detailed secondary containment decontamination factor studies have only been completed for the Peach Bottom design. Since containment designs are highly plant-specific, the results of these studies should not be extrapolated to other facilities. Should a consensus evolve within the regulatory community that secondary containment severe accident performance is important, a great deal of effort would be required to develop an understanding of plant-specific design features and the plant-specific severe accident performance of these containments for a range of accident sequences. During the next two years the ORNL BWRSAT Program will be conducting a survey of domestic BWR secondary containments. The goal of this effort is to (a) develop a database for BWR secondary containment design information, (b) identify potentially important plant-specific design features, and (c) perform severe accident response studies for a limited number of secondary containment designs. Additionally, the BWRSAT Program will be expanding the focus of its overall sequence analysis effort to include BWR MK II and MK III plants.

Secondary containment performance enhancements: Work performed to date indicates that existing BWR secondary containments could play an important role in the mitigation of severe accidents. The reliability and effectiveness of the secondary containment function might be significantly increased via improvements to (a) prevent secondary containment bypass, (b) insure secondary containment integrity, and (c) maximize the fission product retention capability of an intact secondary containment building.

Secondary containment bypass can be precluded by ensuring that the primary containment blowdown is directed into the lowest regions of the reactor building, and that drywell head flange seal failure does not occur. The potential benefit of dedicated drywell spray systems for reduction of drywell head temperatures is currently under investigation at ORNL. Another potential technique for reducing the probability of secondary containment bypass in MK I and MK II plants is to incorporate a rupture diaphragm in the pressure suppression pool air space, to ensure that the primary containment blowdown would be directed to the basement of the reactor building. Such a failure location would enhance the reliability of the pool scrubbing function, and maximize the fraction of the reactor building volume and surfaces available for the various fission product removal processes should a severe accident occur. Such an approach demands intensive scrutiny, however, since it is unlikely that use of the rupture diaphragm system would preclude primary containment failure due to pedestal failure or direct attack of the MK I drywell shell by core/concrete debris.

The major threat to secondary containment integrity is hydrogen and carbon monoxide deflagrations. Primary containment venting to the outside atmosphere can reduce the severity of the secondary containment challenge from such deflagrations by directing combustible gases around the reactor building. This benefit would be gained, however, at the expense of an earlier noble gas release than might otherwise occur. Much work remains to be done to evaluate various candidate venting systems and strategies. The use of both simple hardened venting systems (which do not employ filters) and filtered venting systems should be examined carefully to determine if such systems are practical for MK II designs (in which pressure suppression pool bypass appears more probable than in MK I designs).

Two systems have the potential to significantly enhance secondary containment fission product retention capability. The addition of gravity-fed pre-action fire protection sprays to plants which do not currently have them would seem to offer dual benefits of reduced vulnerability to fires, and enhanced severe accident performance. Analyses should be conducted for a range of secondary containment designs to investigate the costs and benefits of such systems. As previously mentioned, existing gas treatment systems (SGTS/RERS/RBSVS) have the potential to both enhance and decrease secondary containment severe accident performance. Additional evaluations are necessary to (a) identify the various systems currently installed, and (b) determine which operating modes are desirable under severe accident conditions.

Role of the turbine building: The turbine building is normally isolated from the reactor building by the blowout panels in the steam tunnel. As previously discussed, these blowout panels are generally predicted to open following primary containment failure in a severe accident sequence, allowing the reactor building atmosphere to communicate with the turbine building atmosphere. The potential therefore exists for significant quantities of fission products to be passed from the reactor building to the turbine building. While some preliminary analyses have been conducted, the importance of this fission product transport path has not been fully evaluated.[27] It is probable that the degree to which the turbine building participates in the accident will be plant- and accident sequence-dependent.

12. SUMMARY

Severe (core melt) accidents are extremely improbable events. Never the less, the experiences of Three Mile Island and Chernobyl are forceful reminders that the improbable is not the impossible. "*The main difference between TMI-2 and Chernobyl was the survival of the containment in the first case and the almost complete destruction of the containment in the latter case.*"[40] BWR secondary containments completely surround and enclose the primary containment. Although many uncertainties persist, the results of recent analyses indicate that BWR secondary containments can play a significant role in reduction of the offsite consequences of severe accidents in which primary containment failure occurs. Efforts are underway to address many of the identified uncertainties, and to provide added insight into the potential role and effectiveness of BWR secondary containments in severe accident mitigation.

REFERENCES

1. M. H. Fontana, "Severe Accident Sequence Assessment and Time-Line Charts for Boiling Water Reactors - Program Overview," NUREG/CR-2008, May 1981.

2. D. H. Cook et al., "Station Blackout at Browns Ferry Unit One - Accident Sequence Analysis," Vol. 1, NUREG/CR-2182, November 1981.

3. R. P. Wichner et al., "Station Blackout at Browns Ferry Unit One - Iodine and Noble Gas Distribution and Release," Vol. 2, NUREG/CR-2182, August 1982.

4. W. A. Condon et al., "SBLOCA Outside Containment at Browns Ferry Unit One - Accident Sequence Analysis," Vol. 1, NUREG/CR-2672, October 1982.

5. D. D. Yue et al., "BWR4/MARK I Accident Sequences Assessment," NUREG/CR-2825, October 1982.

6. D. H. Cook et al., "Loss of DHR Sequences at Browns Ferry Unit One - Accident Sequence Analysis," NUREG/CR-2973, May 1983.

7. R. P. Wichner et al., "SBLOCA Outside Containment at Browns Ferry Unit One - Iodine, Cesium, and Noble Gas Distribution and Release," Vol. 2, NUREG/CR-2672, September 1983.

8. R. M. Harrington and L. J. Ott, "The Effect of Small-Capacity, High-Pressure Injection Systems on TQUV Sequences at Browns Ferry Unit One," NUREG/CR-3179, September 1983.

9. M. Z. Podowski et al., "Mechanistic Core-Wide Meltdown and Relocation Modeling for BWR Applications," NUREG/CR-3525, December 1983.

10. S. R. Greene, "Realistic Simulation of Severe Accidents in BWRs - Computer Modeling Requirements," NUREG/CR-2940, April 1984.

11. R. M. Harrington and S. A. Hodge, "ATWS at Browns Ferry Unit One - Accident Sequence Analysis," NUREG/CR-3470, July 1984.

12. R. P. Wichner et al., "Noble Gas, Iodine, and Cesium Transport in a Postulated Loss of Decay Heat Removal Accident at Browns Ferry," NUREG/CR-3617, August 1984.

13. D. H. Cook, "Pressure Suppression Pool Thermal Mixing," NUREG/CR-3471, October 1984.

14. R. M. Harrington and L. C. Fuller, "BWR-LTAS: A Boiling Water Reactor Long-Term Accident Simulation Code," NUREG/CR-3764, February 1985.

15. B. R. Koh et al., "The Modeling of BWR Core Meltdown Accidents - For

Application in the <u>MELRPI.MOD2</u> Computer Code," NUREG/CR-3889, April 1985.

16. M. F. Albert, "The Adsorption of Gaseous Iodine by Water Droplets," NUREG/CR-4081, July 1985.

17. R. M. Harrington and S. A. Hodge, "Loss of Control Air at Browns Ferry Unit One - Accident Sequence Analysis," NUREG/CR-4413, April 1986.

18. G. E. Mueller and A. Sozer, "Thermal-Hydraulic and Characteristic Models for Packed Debris Beds," NUREG/CR-4689, (December 1986).

19. C. R. Hyman and C. F. Weber, "Effects of Lateral Separation of Oxidic and Metallic Core Debris on the BWR MK I Containment Drywell Floor," NUREG/CR-4610, January 1987.

20. R. M. Harrington, "Containment Venting as a BWR ATWS Mitigation Technique," presented at the Fourteenth Water Reactor Safety Research Information Meeting, Gaithersburg, Maryland, October 1986.

21. L. J. Ott, "Advanced Severe Accident Response Models for BWR Application," presented at the Fifteenth Water Reactor Safety Research Information Meeting, Gaithersburg, Maryland, October 1987.

22. G. E. Mueller, "Analytical Solution for the Transient Thermal Response of Volumetrically Heated Fixed Porous Nuclear Debris Beds," <u>Nuclear Engineering and Design</u> 106 (1988) 231-241.

23. S. A. Hodge, C. R. Hyman, and L. J. Ott, "Primary Containment Response Calculations for Unmitigated Short-Term Blackout at Peach Bottom," letter report to Dr. Thomas J. Walker, Accident Evaluation Branch, Division of Reactor Accident Analysis, RES, USNRC, dated May 2, 1988.

24. S. H. Kim et al., "The Development of <u>APRIL.MOD2</u> - A Computer Code for Core Meltdown Accident Analysis of Boiling Water Nuclear Reactors," NUREG/CR-5157, July 1988.

25. K. D. Bergeron, et al., "User's Manual for CONTAIN 1.0, A Computer Code for Severe Nuclear Reactor Accident Containment Analysis," NUREG/CR-4085, May 1985.

26. F. E. Haskin et al., "Development and Status of MELCOR," presented at the Fourteenth Water Reactor Safety Information Meeting, Gaithersburg, Maryland, October 1986.

27. S. R. Greene, "The Role of BWR MK I Secondary Containments in Severe Accident Mitigation," presented at the Fourteenth Water Reactor Safety Information Meeting, Gaithersburg, Maryland, October 28, 1986.

28. Reactor Safety Study, WASH-1400, Appendix VII, U. S. Nuclear Regulatory Commission, October 1975.

29. L. G. Greimann, et al., "Reliability Analysis of Steel Containment Strength," NUREG/CR-2442, Ames Laboratory, Iowa State University,

June 1982.

30. "Mark I Containment Severe Accident Analysis," CBI NA-CON, Inc., for the BWR MK I Owners' Group, April 1987.

31. "Request For Authorization To Increase Power To 25%," Long Island Lighting Co., Appendix 3.

32. T. Walker, S. Hodge, G. Greene et al., "BWR MK I Drywell Shell Melt Through," NRC BWR Task Group Report, February 10, 1988.

33. S. R. Greene, "The Impact Of BWR MK I Primary Containment Failure Dynamics On Secondary Containment Integrity," presented at the Fifteenth Water Reactor Safety Information Meeting, Gaithersburg, Maryland, October 29, 1987.

34. T. L. Bridges, "Containment Penetration Elastomer Seal Leak Rate Tests," NUREG/CR-4944, Idaho National Engineering Laboratory, July 1987.

35. Procedure LGA-03, La Salle County Station, 10/14/86.

36. "Request For Authorization To Increase Power To 25%," Long Island Lighting Co., Appendix 4.

37. "Individual Plant Evaluation for Susquehanna Steam Electric Station," Chapter 7, NPE-86-003, Pennsylvania Power & Light Company, April 1986.

38. E. Soderman, "Mitigation of Severe Accidents in Swedish Nuclear Power Plants," Nuclear Europe, 11-12/1987.

39. "Shoreham Nuclear Power Station Probabilities Risk Assessment With the Supplemental Containment System," Long Island Lighting Company, February 1988.

40. Joop F. van de Vate, "Safety Containment Buildings As Barriers Against Particulate Radioactivity Release Under Accident Conditions," Nuclear Technology, Vol. 81, May 1988.

Table 1. Domestic BWR Secondary Containment Designers

ARCHITECT/ENGINEER	PLANT
Bechtel Corporation	Dresden 1 Humboldt Bay Big Rock Point Monticello Peach Bottom 2 & 3 Pilgrim 1 Duane Arnold Limerick 1 & 2 Hope Creek 1 Susquehanna 1 & 2 Grand Gulf 1 & 2
Sargent & Lundy	Dresden 2 & 3 Quad Cities 1 & 2 Fermi 2 Zimmer 1 La Salle 1 & 2 LaCrosse Clinton 1
Stone & Webster	Shoreham Fitzpatrick Nine Mile Point 1 & 2 River Bend 1
Burns & Roe	Oyster Creek 1 Cooper WNPS 2
Tennessee Valley Authority	Browns Ferry 1, 2, & 3
Ebasco Services	Millstone 1 Vermont Yankee
Gilbert Associates	Perry 1 & 2
Southern Services	Hatch 1 & 2
United Engineers & Constructors	Brunswick 1 & 2
Niagara Mohawk Power	Nine Mile Point 1

Table 2. Comparison of Browns Ferry, Peach Bottom, and Shoreham Secondary Containment Designs

PARAMETER	BROWNS FERRY	PEACH BOTTOM	SHOREHAM
Rated Power (MWt)	3293	3293	2436
Number of Units	3	2	1
Common Refueling Bay ?	yes	no	
Reactor Bldg. Volume (ft^3)	1411800	1146800	1372600
Refueling Bay Volume (ft^3)	2745000	1096400	717700
Total Sec. Cont. Volume(ft^3)	4156800	2243200	2090300
Reactor Bldg. Structural Surface Area (ft^2)	239300	213100	196800
Refueling Bay Structural Surface Area (ft^2)	161300	69300	46100
Total Sec. Cont. Heat Sink Area (ft^2)	400600	282400	242900
Reactor Bldg. Floor Area (ft^2)	54700	42400	45700
Refueling Bay Floor Area (ft^2)	48700	14700	10700
Total Sec. Cont. Floor Area (ft^2)	103400	57100	55400
SGTS Exhaust Filter Train Flow (cfm)	21500	25000	1160[a]
Pre-action Fire Protection Spray Coverage Area (ft^2)	21000	100	800

[a] Shoreham RBSVS circulates 45000 cfm between the reactor building and refueling bay, but filters and exhausts only 1160 cfm.

SECONDARY CONTAINMENT DECONTAMINATION FACTORS ARE TIME DEPENDENT

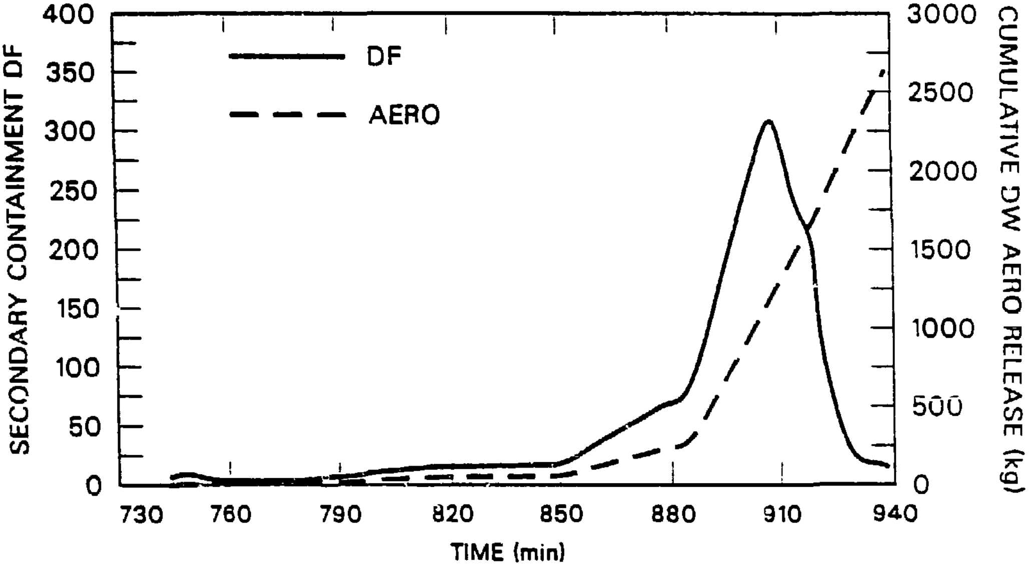
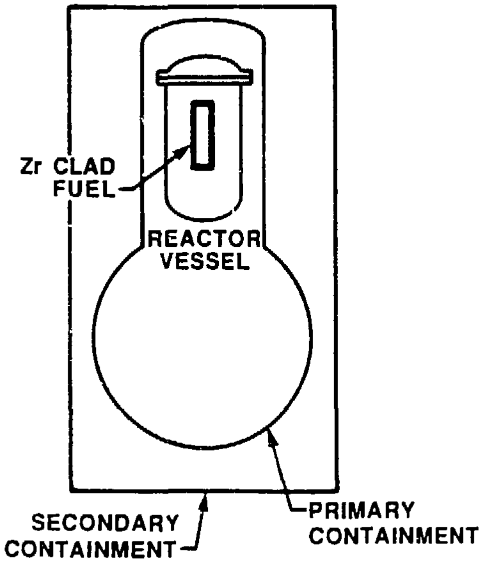


Exhibit 2

SECONDARY CONTAINMENT PROVIDES FINAL BARRIER TO FISSION PRODUCT RELEASE



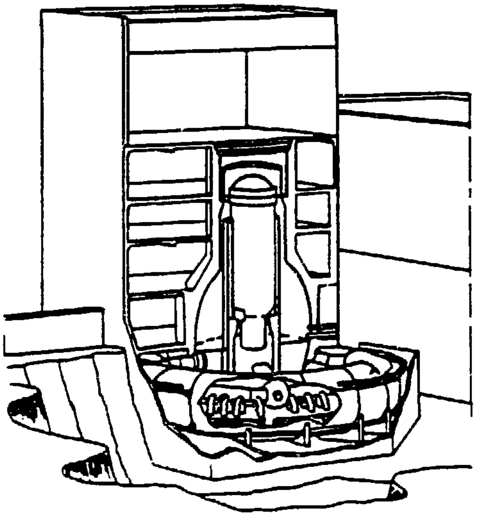


Exhibit 1

COMBUSTIBLE GAS DEFLAGRATIONS THREATEN SURVIVABILITY OF SECONDARY CONTAINMENT

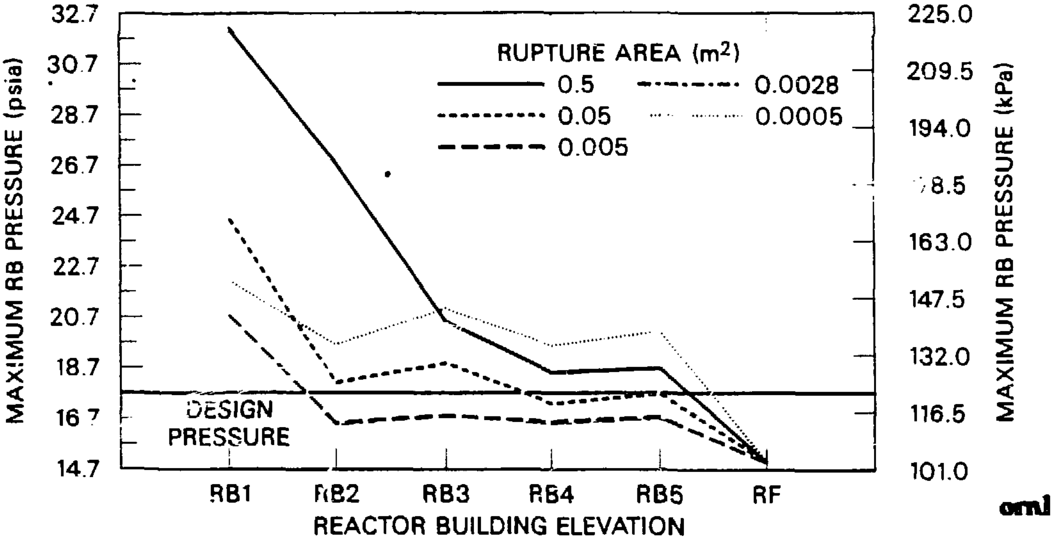


Exhibit 4

SECONDARY CONTAINMENT FISSION PRODUCT RETENTION INCREASED BY SPRAY OPERATION

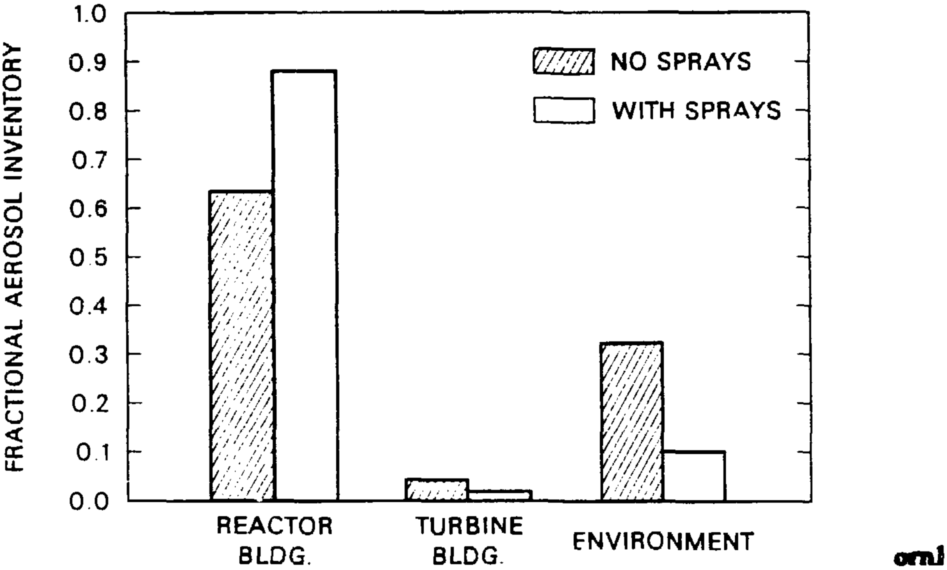


Exhibit 3