POTENTIAL EFFECTS OF THE FIRE PROTECTION SYSTEM SPRAYS AT BROWNS FERRY ON FISSION PRODUCT TRANSPORT*

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INTRODUCTION

During severe nuclear reactor accidents, certain systems which were designed for purposes other than severe accident mitigation might significantly affect the release of fission products to the environment. Traditionally, in source term analyses, the effects of such systems have not been considered. However to estimate realistically radioactive releases for meltdown accidents, the effects of such systems must be addressed. One such possibly important system at Browns Ferry (BF) No. 1 (a Mark I BWR) is the fire protection system (FPS). In this paper, potential fission product mitigation by the portion of that system which uses water to extinguish fires within the reactor building (RB) is discussed, both in general and specifically for postulated accident sequence TW (1), a transient-initiated event accompanied by loss of decay heat removal.

DESCRIPTION OF FIRE PROTECTION SYSTEM

Potential Effects of FPS Sprays During Accidents

The RB sprays of the BF FPS, like any RB sprays, could potentially affect the amounts of many radionuclides released to the environment in a number of ways. Spraying could directly scrub both gaseous and aerosol species from the RB atmosphere and thus generally make their release to the environment less probable. Condensation of steam and cooling of all gases could lower the rate of turnover of the RB atmosphere to the environment and thereby permit more time for scrubbing, as well as natural removal processes, to be effective in the RB. Furthermore, cooling of the gases might result in an inflow of outside air and consequently an alteration in the overall composition of the RB atmosphere, with major concomitant changes in the accident scenario thus being made possible. For example, inflow of oxygen and condensation of steam might permit otherwise prohibited burning of combustible gases within the RB. The sprays could cool not only the RB atmosphere but also the RB itself. Consequently the chemical forms and therefore the fates of some reactive species could be affected.

Basic Characteristics of the FPS at BF

The fire protection system at the Browns Ferry Nuclear Plant (BFNP) is intended to provide fire protection within the plant and includes two aqueous spray systems, two low-pressure carbon dixoide systems, an aqueous film-forming foam system, and some portable fire-protection equipment, as well as plant-wide fire detection systems. Protected buildings include the reactor buildings, the turbine building, the diesel generator building, the service building, and the control building. It is the portions of the two spray systems located in the RB which are considered in this paper.

One of those systems, the fixed or deluge spray system, is designed to provide water to congested electrical cables. Thus its spray nozzles are localized above cable trays. In the reactor building, those trays, and therefore the deluge nozzles, are located primarily in a few areas of the middle two floors (elevations 565 ft and 593 ft) (Figs. 1 and 2). The deluge nozzles are grouped into zones of 5 to 15 nozzles each, with all the nozzles in a zone being actuated simultaneously. Operation of each zone can be initiated either automatically by concurrent detection of both smoke and heat in that zone or else by local manual action.

The other system, the preaction spray system, is designed to cover those areas of concern not necessarily addressed by the deluge system. It can potentially cover most of the middle two floors of the reactor building (Fig. 3). It is initially activated by either detection of smoke or local manual operation, with individual nozzles being actuated and thus allowing water to be released by melting of the fusible links at each of the spray nozzles.

In general, receipt of fire signals from either of the FPS spray systems will automatically start one or more of the plant's four large-capacity (2500 gpm each) fire pumps (unless off-site electricity has been lost). The plant is permitted to generate electricity as long as one fire pump is operable. Once operating, the systems can be shut down either by local actions or by remote shutdown of the fire pumps.

Operation of FPS During Severe Accidents

The operation of the FPS sprays at BF during a severe accident would be highly scenario dependent. Steam and other heated gases, as well as aerosols, could cause the FPS to automatically start to spray water. Inasmuch as the FPS is sized only to handle small electrical fires within BFNP, demand on the system by a large fraction of its nozzles and/or sprinklers could stress it far beyond its intended limits and consequently could result in severely degraded performance of the overall system.

The demand on the FPS during any accident would depend in part on the characteristics of the primary containment failure and any associated releases of heated gases to the RB. For example, rapid depressurization of the primary containment from a high pressure could result in actuation of a relatively large fraction of the RB FPS nozzles and sprinklers. Therefore in such a situation the overall performance of the system might be poor both with respect to condensation of steam and scrubbing of radioactivity from the RB atmosphere. In contrast, relatively slow depressurization of or leakage from the primary containment might result in operation of only a small fraction of the nozzles and sprinklers. However the effect might still be such that both significant condensation and scrubbing could occur.

In any case, most water sprayed by deluge sprays would be wasted with respect to condensation and scrubbing so that effective operation of the FPS with respect to removal of airborne radioactive material would essentially preclude extensive operation of deluge sprays. Likewise effective operation of the FPS would generally be obviated if substantial spraying occurred in portions of the plant outside the RB.

If significant numbers of FPS nozzles and/or sprinklers were actuated, the capacity of the RB drains could be exceeded. Consequently the basement of the RB could flood and safety-related pumps could fail and thus affect the course of the accident.

APPROACH

Accident Sequence

To illustrate the potential effects of the operation of the FPS sprays during severe accidents, a set of calculations has been performed for several plausible versions of the loss of decay heat removal sequence (TW) (1) at BF. In that sequence, the suppression pool (SP) would be predicted to heat up, boil, and after an extended period of time, fail the primary containment (either drywell or wetwell) by overpressurization. If that failure were catastrophic, the pumps required to keep the core covered could also fail at that time. As a result, the fuel could become uncovered and melt. It is likely that catastrophic failure of the primary containment would result in concurrent failure of both the reactor building and the refueling bay blowout panels. Thus all the releases of radioactivity could be into a plant with both primary and secondary containments previously failed. Both the standby gas treatment system (SGTS) and the fire protection system could potentially mitigate the releases to the enviromment.

Plant System Operation Assumptions

For this paper, three alternatives were considered for the FPS: 1) the FPS sprays were assumed not to operate at all; 2) 10% of the preaction nozzles in the RB were assumed to operate; and 3) 40% of the preaction nozzles in the RB were assumed to operate. In the two cases in which sprays were assumed to operate, it was further assumed that only the aforementioned sprays operated, that is, that no deluge sprays anywhere in the plant and no other preaction sprays operated.

The two cases with 10% and 40% spraying might correspond respectively to a situation in which the preaction nozzles function as intended and to one in which their performance is somewhat degraded. The case without spraying would correspond not only to the case in which the RB sprays do not operate but also in many respects to a situation in which a large number of the preaction nozzles function in a severely degraded mode. [The performance of the FPS at BF was estimated by performing hydraulic analyses using plant-specific data obtained from TVA (2,3).]

Inasmuch as the effect of the FPS on radioactive releases would depend strongly upon the SGTS, for each "mode" of operation of the FPS, three alternatives were considered for the SGTS: 1) the SGTS was taken to fail completely; 2) the SGTS was assumed to operate throughout the sequence but its capacity was taken to be inadequate to process all the gases released from the primary containment; and 3) the SGTS was assumed to operate throughout and its capacity was taken to be adequate to process all the released gases.

The SGTS at BF, if operating as intended, would process gases from both the RB and the refueling bay. The second SGTS case was defined to represent the situation at BF with refueling bay gases not being processed. The third case was defined to correspond roughly to the situation at BF with refueling bay gases also being processed.

Fission Product Transport Assumptions

Due to the wide range of possible modes of functioning of the FPS during accidents and the large uncertainties associated with modeling some aspects of the problem, relatively simple models were used to estimate the potential impacts of the FPS sprays on radioactive releases to the environment. Modeling was performed at a level consistent with the assumptions employed in the CORRAL code (1,4). The removal of aerosols and gases by natural processes in the RB at BF was taken to be adequately described by the models implemented in CORRAL for natural removal in a large containment PWR. Likewise, the removal of radioactive materials by sprays was taken to be adequately modeled by the basic PWR expressions employed in CORRAL (5), with the estimated removal rate constants used for this work being given in Table 1. The condensation of steam by sprays was estimated using assumptions previously employed by Parsly (6). Mixing within the reactor building was assumed to be uniform. Basic thermal-hydraulic input was based on recent MARCH (7) code calculations for sequence TW (8,9).

Releases into the RB were taken to be at uniform rates over time intervals comparable to those used in CORRAL. Releases from the core materials before reactor vessel (RV) failure and releases after RV failure were followed separately. Passage through either the suppression pool or the SGTS was accounted for by a decontamination factor of 100. Ten percent of the aerosols formed within the coolant system were assumed to escape into the drywell without passage through the suppression pool. It was assumed that there was no permanent retention in the coolant system. In addition, losses due to residence in the primary containment were ignored.

Nonstandard pathways to the environment, for example, via leakage through the main steam isolation valves, were neglected. The altered likelihood of hydrogen burning was not considered, although altered efflux rates from the RB (caused by condensation and cooling) were taken into account.

RESULTS

FPS Sprays

The aerosol escape fractions resulting from the calculations for sequence TW are given in Table 2. As can be seen, if the SGTS capacity were sufficient to process all the gases released from the primary containment and the SGTS did not fail, then the reduction by that system alone in the aerosols released to the environment could be substantial. If the FPS sprays also operated, the impact due directly to scrubbing would be noticeable but typically would cause a smaller relative reduction of the released aerosol mass - at most a factor of 2 to 3.

The largest impacts of the FPS sprays would be found in those situations in which the SGTS was inadequate to process all the gases if no spraying occurred. Then if spraying were sufficient to permit the SGTS to process all or most of the gases, the reduction in the source term by spraying could be relatively much larger. Thus, contrary to what might be expected, the majority of any such large reduction by the FPS sprays would not be due to direct radionuclide scrubbing by the sprays. Instead such reduction would be due to the lowering of the RB turnover rate by both condensation of steam and cooling of gases; by lowering the amount of materials bypassing the SGTS, the amount of aerosols escaping from the RB would be reduced.

In contrast to the assumptions employed in the calculations, it seems unlikely that the SGTS would function adequately throughout any core-melt accident. For example, the system could fail as a result of aerosol plugging. Thus the estimates given in Table 2 for SGTS operation are in some sense bounding estimates, as the SGTS might not be that effective throughout the accident. In addition, there would probably always be some leakage which would bypass the SGTS (for example, leakage directly from the RB and/or refueling bay to the atmosphere) even if its rated size were nominally large enough to process all the gases and it could withstand the aerosol loadings imposed by the accident.

The releases to the environment of the various radionuclides associated with the aerosols would depend upon the timing of their initial releases from the core materials, as well as on the functioning of both the SGTS and the FPS. For the magnitudes and rates of releases from core materials assumed in the Reactor Safety Study (1), the aerosol release fractions given in Table 2 would result in the radionuclide release fractions given in Table 3. Because the more volatile radionuclides such as cesium would tend to be released from the core materials before RV failure, any releases of these species during sequence TW would generally be mitigated first by scrubbing by the suppression pool. The SGTS and the FPS sprays would serve only to lower the already low releases. In contrast, because the less volatile radionuclides such as ruthenium and strontium would tend to be released primarily after RV failure and therefore would bypass the suppression pool, releases of these species would depend much more directly on the behavior of the SGTS and the FPS sprays.

Comparison to PWR Containment System Sprays

Previous work on the effects of spray systems during severe core-damage accidents has concentrated on containment spray systems (CSSs) in PWRs.

One such spray system (at Surry) is compared in Table 4 to the preaction portion of the FPS located in the RB at BF.

As can be seen by comparing the PWR CSS removal rate constants given in Table 5 with the BWR FPS rate constants given in Table 1, the removal rate constants for the FPS at BF are much smaller than those for the CSS at Surry. In particular, the BWR FPS removal rate constant for an aerosol of any given size is estimated to be approximately 1/60 to 1/10 times that for the same size particle by the CSS in a large containment PWR. The differences between the removal constants for elemental iodine for the two systems are even larger. The differences for all the rate constants are due to much smaller fall heights, larger average drop sizes, and smaller effective spray flow rates for the BWR FPS. The difference for iodine is also due to the lack of spray additives for the BWR FPS.

Extension of Results to Other Situations

The results presented here can be used on a limited basis to consider other accident scenarios and sequences. In particular, the calculations indicate that the adequacy of the SGTS with respect to processing all the gases released from the primary containment would be a major factor in determining the potential impact of the FPS. Likewise, the volume and the composition of all the gases released to the RB, as well as the rates of those releases, would be important. In addition, the operational characteristics of the FPS, especially those features which dictate the extent and distribution of spraying within the RB, would be significant in determining the effect of the FPS.

UNCERTAINTIES

The uncertainties in this analysis and their potential impact on the estimated fission product mitigation by the FPS during severe core damage accidents must be acknowledged to be substantial. Among the factors affecting the results are a number of somewhat arbitrary assumptions of the type involved in all accident analyses. First, the results are very dependent on the exact scenarios assumed and for any given sequence a wide variety of scenarios can be postulated. Of particular importance are those factors affecting the operation of the FPS sprays, for example, the factors affecting the release of steam and other heated gases into the RB. Second, the results depend on the circulatory patterns within the RB and these are not known. Third, the results depend on the uncertain timing and mode of failure of the SGTS.

Among the factors affecting the results are also a number of calculational problems. First, the hydraulic analysis of the FPS has necessarily been of very limited scale. A number of unaddressed possibilities, such as activation of the spray nozzles in other parts of the plant and time dependent changes in the operation of the FPS during the accident, have not been considered. Second, not all of the information needed to perform a detailed analysis, for example, spray drop sizes, was available and some inputs had to be approximated. Third, the state-of-the-art of thermal-hydraulic analysis for the RB, as well as for the rest of the plant, for any given scenario includes large areas of uncertainty.

SUMMARY AND COMMENTS

The fire protection system sprays within any nuclear plant are not intended to mitigate radioactive releases to the environment resulting from severe core-damage accidents. However, it has been shown here that during certain postulated severe accident scenarios at the Browns Ferry Nuclear Plant, the functioning of FPS sprays could have a significant impact on the radioactive releases. Thus the effects of those sprays need to be taken into account for realistic estimation of source terms for some accident scenarios. The effects would include direct ones such as cooling of the reactor building atmosphere and scrubbing of radioactivity from it, as well as indirect effects such as an altered likelihood of hydrogen burning and flooding of various safety-related pumps in the RB basement. Thus some of the impacts of the sprays would be beneficial with respect to mitigating releases to the environment but some others might not be. The effects of the FPS would be very scenario dependent with a wide range of potential effects often existing for a given accident sequence.

Any generalization of the specific results presented here for Browns Ferry to other nuclear plants must be done cautiously, as it appears from a preliminary investigation that the relevant physical and operational characteristics of FPS spray systems differ widely among even otherwise apparently similar plants. Likewise the SGTS systems, which substantially impact the effects of the FPS, differ significantly among plants. More work for both Mark I plants and other plants, BWRs and PWRs alike, is indicated so the potential effects of FPS spray systems during severe accidents can be at least "ball-parked" for more realistic accident analyses.

ACKNOWLEDGMENT

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Table 1. Approximate BWR FPS removal rate constants

	$\lambda_{aerosol}$ $(sec^{-1})^{a}$			λ_{I_2} $(sec^{-1})^{a,b}$
	aerosol diameter (μ)			
	0.1	1.0	10	
No sprays	3×10^{-7}	3×10^{-5}	3×10^{-3}	1×10^{-4}
10% preaction	1×10^{-4}	1×10^{-4}	2×10^{-2}	5×10^{-5}
40% preaction	3×10^{-4}	3×10^{-4}	3×10^{-2}	2×10^{-4}

[a] Full height = 25 ft; 10% of the preaction sprinkers is taken to correspond to approximately 750 gpm and 40% of the preaction sprinklers is taken to correspond to approximately 3000 gpm.

[b] Partition coefficient = 100.

Table 2. Aerosol escape fractions for sequence TW[a]

A. Escape fractions for aerosols released before RV failure[b]

	No SGTS	RB SGTS[c]	Perfect SGTS[d]
No sprays	0.11	0.09	0.001
10% preaction	0.10	0.08	0.001
40% preaction	0.07	0.04	0.0007

B. Escape fractions for aerosols released after RV failure[e]

	No SGTS	RB SGTS[c]	Perfect SGTS
No sprays	0.90	0.60	0.009
10% preaction	0.60	0.24	0.006
40% preaction	0.40	0.16	0.004

[a]Escape fractions here are based on amounts released from core materials and are estimated separately for materials initially released from core materials before RV failure and those released after RV failure. These escape fractions are probably conservative inasmuch as they do not include the effects of retention in either the coolant system or the drywell.

[b]Escape fraction for complete release to environment of all materials reaching RB would be 0.11. (See discussion in text.)

[c]Assumes that the RB SGTS operates as intended throughout accident.

[d]Assumes that the SGTS processes all released gases.

[e]Escape fraction for complete release to environment of all materials reaching RB would be 1.0.

Table 3. Radionuclide escape fractions for sequence TW

	Escape fraction[a]					
	I[b]	Cs-Rb	Te-Sb	Ba-Sr	Ru[c]	La[d]
No SGTS						
No sprays	0.2	0.3	0.8	0.02	0.05	0.01
40%	0.1	0.1	0.4	0.01	0.02	0.004
RB SGTS						
No sprays	0.1	0.2	0.5	0.02	0.03	0.006
40%	0.05	0.06	0.2	0.006	0.01	0.002
Perfect SGTS						
No sprays	0.002	0.003	0.008	0.0002	0.0005	0.0001
40%	0.001	0.001	0.004	0.0001	0.0002	0.00004

[a]These escape fractions are probably conservative inasmuch as they do not include the effects of retention in either the coolant system or the primary containment.

[b]Denotes escape fraction assuming that all the iodine is transported unreactively with the aerosols.

[c]Includes Ru, Rh, Co, Mo, Tc.

[d]Includes Y, La, Zr, Nb, Ce, Pr, Nd, Np, Pu, Am, Cm.

Table 4. Comparison of the FPS sprays at a Mark I BWR (Browns Ferry) and the containment spray system at a large containment PWR (Surry)

Characteristic	BWR FPS sprays[a]	PWR CSS
Purpose	Provide fire protection in reactor building	Suppress pressure in reactor building; remove radioactivity from reactor building atmosphere
Water	Taken from river; no additives	Initially taken from refueling storage water tank (350,000 gal); borated with NaOH added
Fate of water	Accumulates in RB basement - can flood pumps	Recycled from reactor building sump to sprays
Delivery of water	Up to four pumps - up to 2500 gpm each; total head = 300 ft; numerous headers throughout middle two floors, especially over electrical cables	Two pumps - 3200 gpm each; two 360° headers located near top of reactor building
Volume directly affected	At most, middle two floors of RB; most of upper two floors and basement not sprayed	Bulk of reactor building volume; compartments at bottom not sprayed

[a]The FPS spray at BF may not be representative of the FPS sprays found at other Mark I plants.

Table 5. Approximate large containment PWR CSS removal rate constants

	$\lambda_{aerosol}$ (sec^{-1})[a]			λ_{I_2} (sec^{-1})[a]
	aerosol diameter (μ)			
	0.1	1.0	10	
No sprays	5×10^{-8}	5×10^{-6}	5×10^{-4}	4×10^{-4}
Sprays	1×10^{-3}	1×10^{-3}	1	$\geq 1 \times 10^{-2}$[b]

[a]Fall height = 100 ft and spray flow rate = 6400 gpm.

[b]For example, 1×10^{-2} corresponds to a partition coefficient of 1000 and 8×10^{-2} corresponds to a partition coefficient 10,000; value of partition coefficient depends on spray additives.

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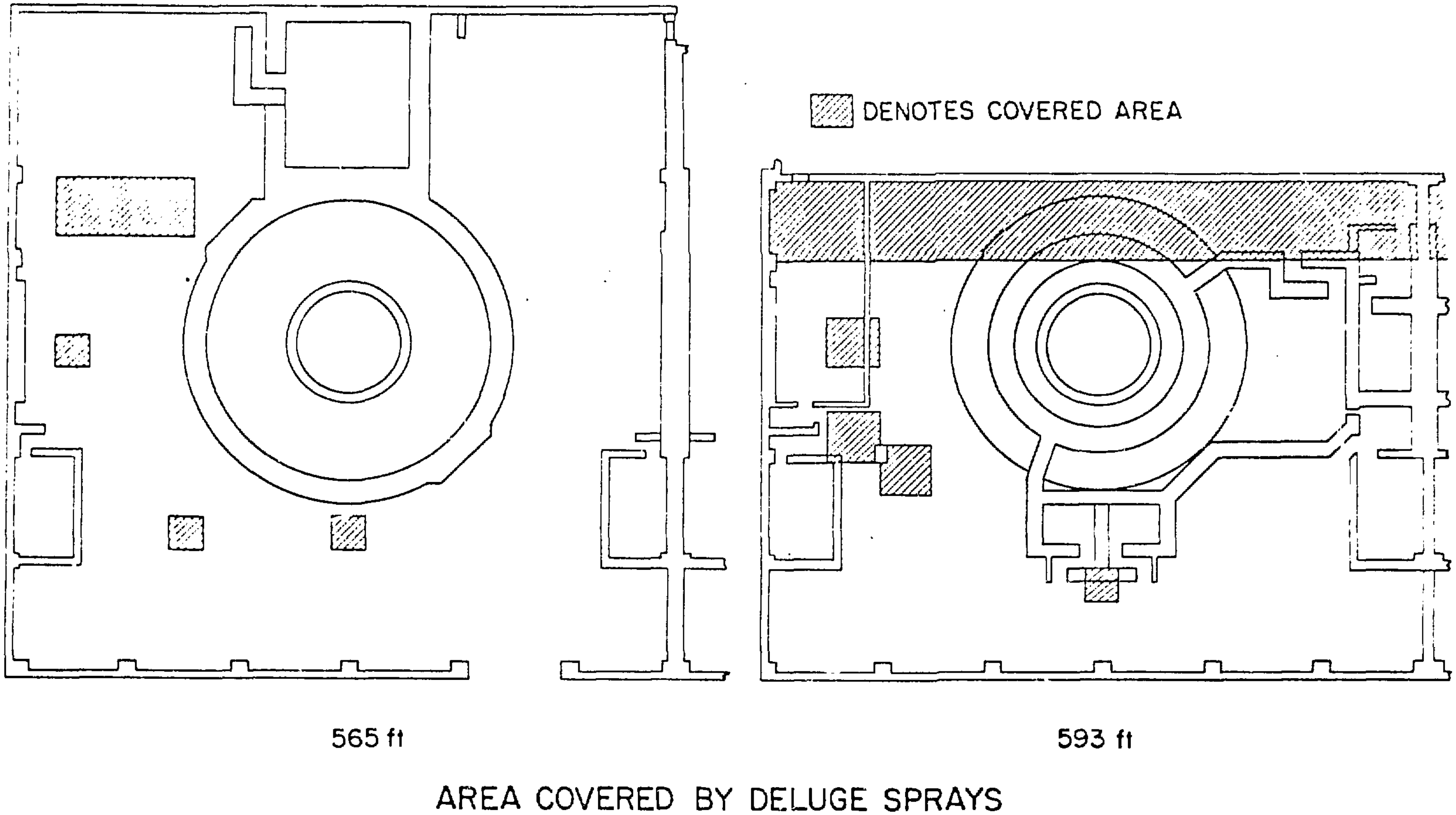
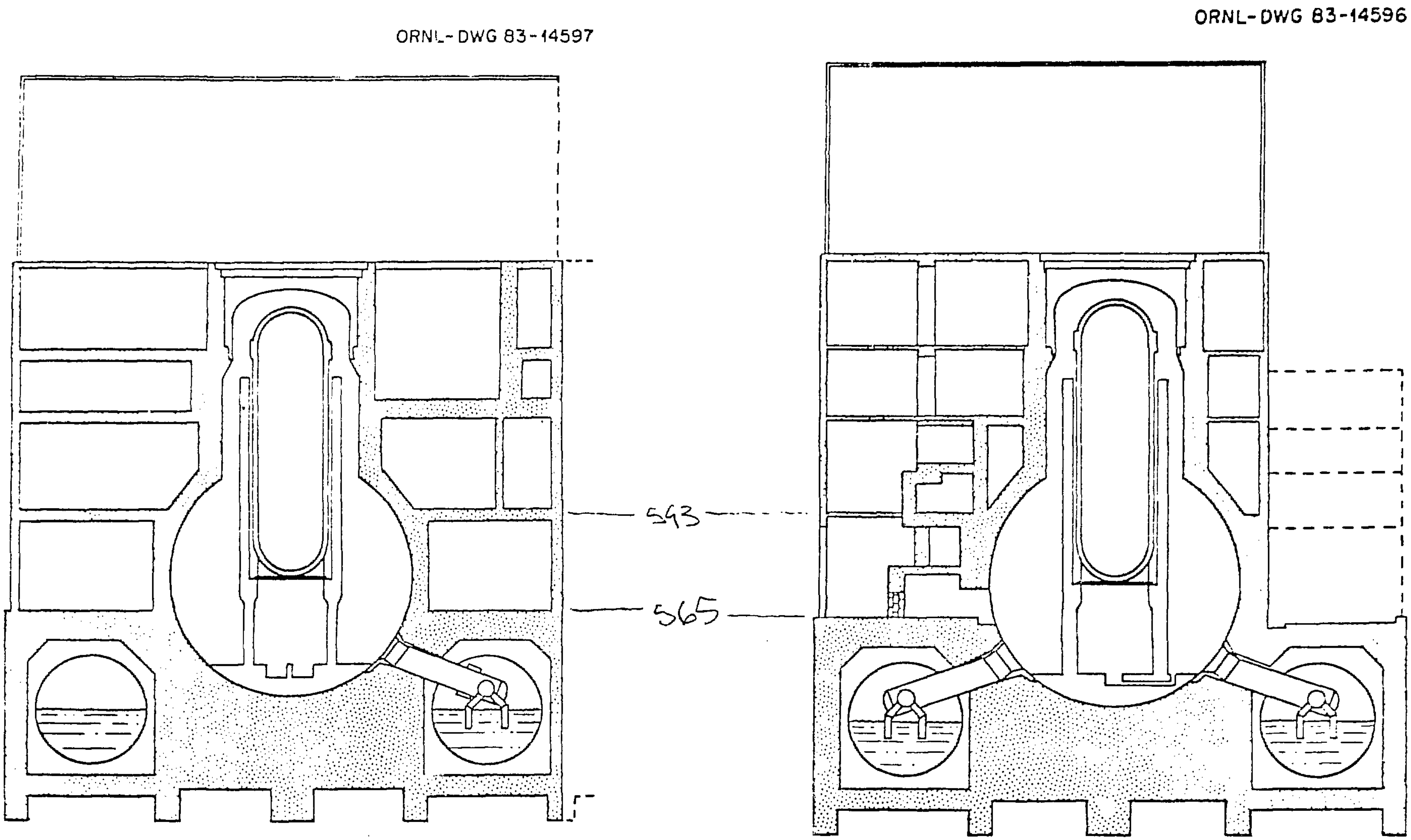


1. Main floor areas of reactor building at Browns Ferry potentially covered by deluge sprays



2. Cross-sections of one unit at Browns Ferry, including both the primary containment (drywell and wetwell) and the secondary containment (reactor building and refueling bay)

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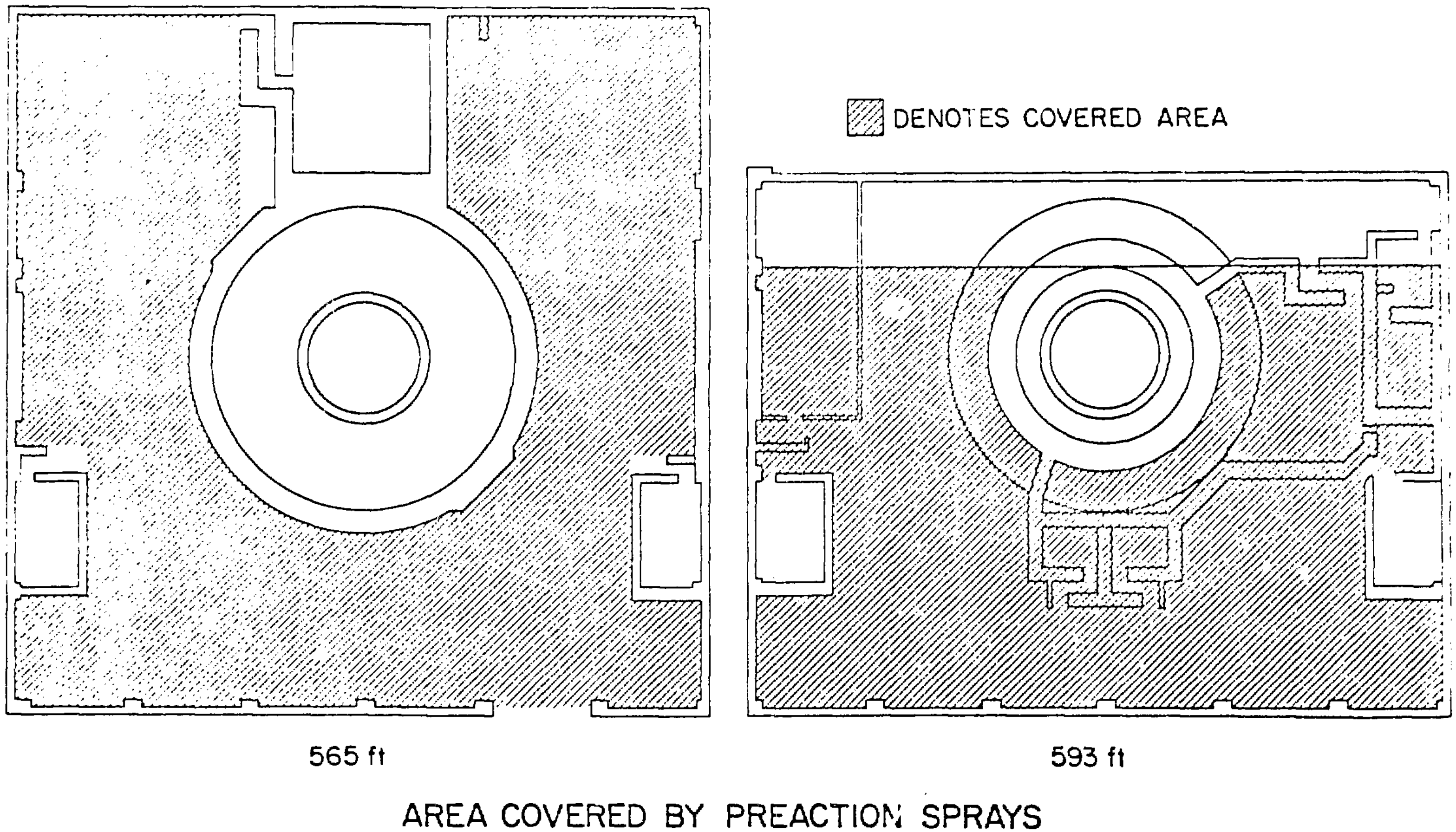

3. Main floor areas of reactor building at Browns Ferry potentially covered by preaction sprays