PRACTICAL NUCLEAR POWER PLANT CONTAINMENT DESIGNED TO RESIST LARGE COMMERCIAL AIRCRAFT CRASH AND POSTULATED REACTOR CORE MELT

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ABSTRACT

From the inception of light water nuclear power plants, they have required containments to protect the public from potential accidents from or assaults on the nuclear reactor. However, certain accidents such as core melt and large commercial aircraft crash into the containment have been considered beyond the design basis. This has resulted in the identification of a large number of redundant and expensive engineered safety systems, which are designed to prevent core melt. In this paper a conceptual design of a containment capable of resisting core melt and aircraft crash is presented, which provides additional safety with the additional cost of the containment structure being largely offset by the elimination of the need to provide engineered safety systems to resist core melt.

HISTORICAL DEVELOPMENT OF CONTAINMENT STRUCTURE DESIGN REQUIREMENTS

The initial design of large nuclear power plant light water reactor system containments in the U.S. was developed in the early to middle 1960’s and was directed toward protecting the environment and in particular the public from a set of prescribed accident conditions associated with reactor operation. The design basis for the containment structure design was to contain essentially without leakage the result of the instantaneous double ended guillotine rupture of the largest reactor coolant pipe. Other accident conditions were also postulated which included missiles in the form of valve and instrument parts ejected from the high pressure reactor coolant system up to and including the rupture of a control rod drive mechanism. Since there was no practical way to develop containment redundancy, robustness of design and high quality construction practices were developed which essentially treated the Design Basis Accident Loads as normal design loads which included the increased design margins associated with such loads.

Starting in the mid 1960’s a second mission was given to containments and that was to protect the reactor coolant and protection systems from external extreme events. The first of these was extreme earthquake resistant design followed in the late 1960’s by tornado and external extreme flood resistance as design requirements with loads several times those normally considered in conventional industrial facility design.

Initially, the accident design load was not considered mechanistically, but simply as an energy release into the containment volume with a resultant static pressure load on the containment vessel. However, as time progressed the local effects of postulated consequential main coolant pipe rupture, fluid jets and reaction loads at the break location and pipe whip began to be considered as part of the design basis which greatly complicated containment internal design. In the late 1980’s the containment design basis was modified to consider only the reactor coolant system total energy release, and localized effects were limited to branch piping connected to the main reactor coolant system and other high energy piping and then only when leak before break could not be demonstrated.

It should be noted that there remained a number of potential accidents which were not considered as design basis accidents as summarized in Table 1 that could challenge containment integrity that were considered of such low probability as not to be considered a credible design basis.

Table 1 Severe Accident and External Event Scenarios Not Considered in Existing NPP-PWR Containment Design

- Simultaneous Primary Reactor Coolant and Secondary Heat Transport Steam Systems Blowdown
- Reactor Core Melt
- Reactor Vessel Rupture
- Hydrogen Deflagration
- Hydrogen Detonation
- Large Commercial Aircraft Crash at Controllable Flight Speed (400 mph)

RECENT DEVELOPMENTS

Recent developments and experience suggest that some of the extreme load phenomena that have not been considered as a design basis in the past may no longer be considered incredible. In addition, the conventional practice of locating nuclear power plants, NPP away from population centers may have become so expensive so as to justify use of the concept of metropolitan siting. These two new conditions have prompted the consideration of the concept of NPP containment structures and systems which can accommodate the worst possible accident and extreme environmental load phenomena of reactor vessel rupture, core melt, hydrogen detonation, deflagration, and a large commercial aircraft crash.

THE CONCEPT

In Figure 1 is shown the conceptual design of a PWR containment structure designed to resist those postulated failures listed in Table 1 that are not currently considered in containment design. In developing this conceptual design, the material contained in References 1, 2, 3, 4 and 5 were reviewed for applicability to develop input design parameters. Once these input design parameters were defined as shown in Table 2, the containment structure was sized and preliminarily designed in accordance with the requirements of existing standards. [6] It should be understood the design basis defined in Table 2 was based on a review of the current literature as applicable. No attempt was made within the limited scope of this effort to develop a detailed design of the containment structure based on basic detailed NSSS and site dependent input data and detailed calculation. It is hoped that interest in the apparent advantages of a passive containment system capable of withstanding all conceivable accidents and external threats as described herein may promote the funding of such a detailed effort in the near future. In Figure 2 is the application of this proposed design concept to a BWR containment. It should be noted that this concept would eliminate the need for an active pressure suppression type of containment for a BWR reactor system.

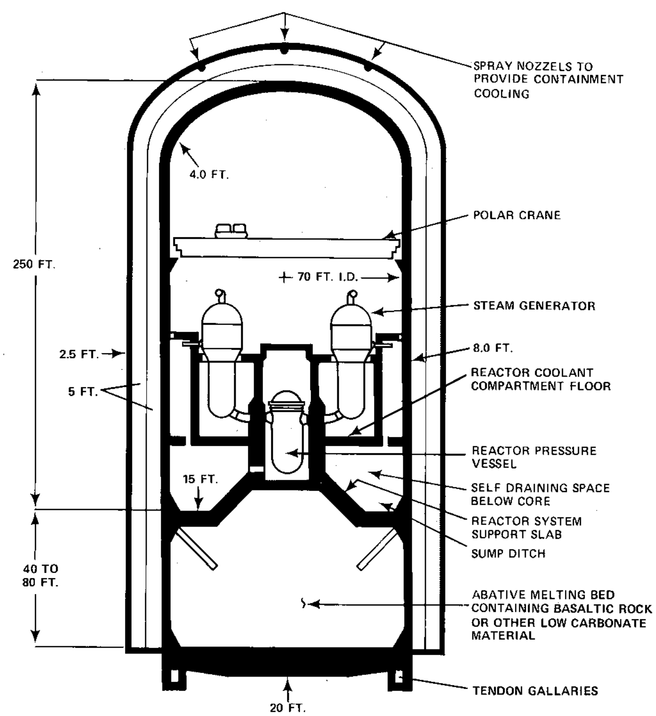

Figure 1 Passive Dry Containment Structure Using Radiator Concept For Containment Cooling Systems for a PWR

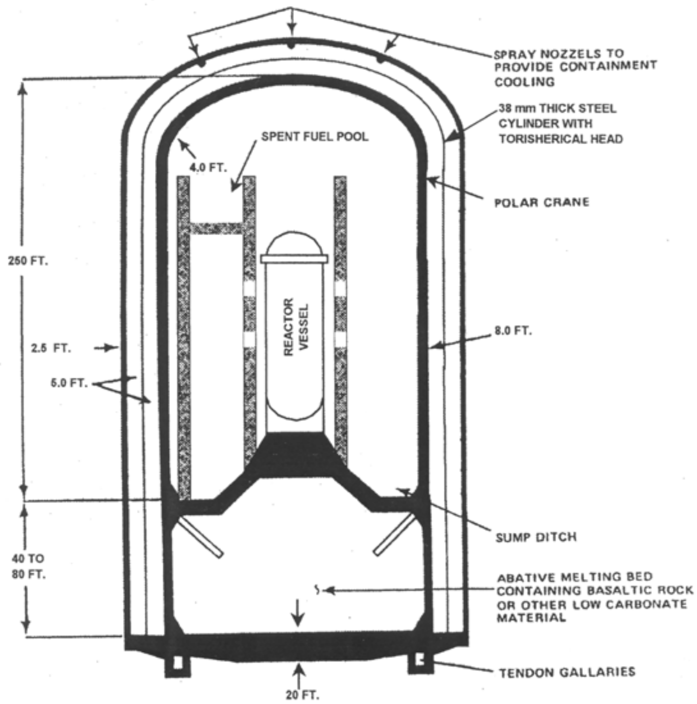

Figure 2 Passive Dry Containment Structure Using Radiator Concept For Containment Cooling Systems for a BWR

Table 2 PWR Passive Containment System Design Parameters

Design Parameter	**Cause**	**Calculated Value**
1. Prompt Pressurization	Simultaneous blowdown of primary reactor coolant and secondary heat transport system in a PWR	105 psi
2. Delayed Pressurization	Vaporization of water by the moltant core after vessel rupture, including:	
	(a) water in reactor cavity	95 psi
	(b) water of crystallization from concrete	5 psi
	(c) hydrogen from zirconium water reaction	
	(d) CO_2 generated from concrete	5 psi
		45 psi
	TOTAL	150 psi
	+20% Design Margin	30 psi
	Design Pressure	180 psi
	Design Temperature	375°F
OR		
3. Hydrogen Deflagration		25 psi
OR		
4. Hydrogen Detonation		150 psi
OR		
5. Large (Boeing 747) Aircraft Crash at 400 mph Not Combined with RCS or Heat Transport System Failure		

This design concept at least would permit the elimination of conventional containment safety related accident heat removal systems in favor of an externally cooled radiator. In this concept the containment atmosphere within the primary prestressed concrete containment could be circulated to an external steel shell through pressure relief valves where external water spray would cool and condense the containment vapors. Surrounding the intermediate steel containment radiator would be a more or less conventional biological shield and environmental protection concrete shield structure. A postulated large airplane crash would first have to penetrate the environmental shield building and the radiator steel shell before it would impact and be stopped by the 8.0 feet thick primary prestressed concrete containment shell.

DESIGN FEATURES

The Containment Structure

The passive containment internal structural design above the reactor coolant compartment floor as shown in Figure 1 and 2 would be very similar to conventional prestressed concrete single barrier containment designs for PWR dry and BWR Mark III type light water reactors. However, the water suppression system for the BWR type reactors would no longer be necessary. The containment cylinder walls and dome would be approximately 8.0 and 4.0 feet thick rather than the current 3.5 and 2.5 feet, respectively. This increased thickness would be required to resist the increased containment design pressure as shown in Table 2. In addition, the 8.0 feet (2.5 m) selected is approximately equal to the 7.75 feet (2.38 m) used for the BASF reactor burst protection structure for the reactor vessel which had a function of containing potential missiles from a burst vessel as developed in Reference 4 and would effectively stop a large commercial aircraft at controllable flight speed impact at 400 mph.

It should be noted that the much simpler so called dry, rather than pressure suppression containment system, could be used for a BWR light water reactor because the basic containment design as described herein is capable of containing both the primary coolant as well as the secondary heat transport system energy releases.

The design pressure selected is 180 psi, which is three times the design pressure typically used in current prestressed concrete 1300 MWe PWR-NPP containments and 2.25 times that developed in a typical pressure suppression BWR dry well. This design pressure was selected based on the analysis presented in References 1 through 5. Also, it should be noted the postulated simultaneous blowdown of the secondary as well as primary systems in a PWR and BWR could give rise to a containment pressure approximately twice that currently considered in design of PWR containments and 1.6 times current BWR dry well design.

The containment section below the reactor coolant compartment floor and above the reactor system support slab is space which does not exist in current PWR containment designs and could be used to house safety related components and systems currently housed in the reactor auxiliary building. For this proposed containment system to be effective, it would be imperative that the amount of water and normal concrete in potential contact with the moltant core be minimized to limit the potential for water moltant core reaction and CO_2 gas generation. In the design, the reactor system support slab would also function as water barrier from the reactor coolant system compartment of the containment from the ablative melting bed compartment.

The containment configuration below the reactor coolant compartment floor is essentially the same as proposed by Van Erp [(2)]. It is anticipated that ablative melting cavity would be steel lined as is the rest of the containment to provide a vapor barrier and refractory baffles used or alternatively, the steel liner would be faced with refractory to insure no melt-through of the liner.

In Figure 1 and 2 a flat bottom, free standing steel shell would be used to act as a giant radiator to provide containment cooling and thereby reduce or eliminate the need to provide containment cooling as an internal engineered safeguard. Practical limits of anchorage of the steel shell to a flat concrete base slab would limit internal design pressure on the steel shell to approximately 15 psi. Essentially this approach has been used on the bell jar hybrid steel and concrete containment concepts used on PWR ice condenser NPP and Mark III type BWR containments.

Emergency Core Cooling Systems

In the passive containment design suggested herein, emergency core cooling system, ECCS would no longer be required to assure public health and safety since the containment system can accommodate a reactor core melt. As such, it would be downgraded to a normal plant operating system whose design would be dictated by economic (potential loss of plant investment) rather than public safety considerations. The ECCS would logically be reduced to a single train instead of three trains with perhaps additional active components so that the systems would still be operative during maintenance outage. Besides the obvious reduction in direct capital costs, the congestion in the reactor building for system support and distribution systems, requirements for in-service inspection, testing, maintenance, control, instrumentation, and emergency power requirements would all be greatly reduced. Finally, the design of the reactor coolant systems, RCS, would be simplified with the reduction of the number of ECCS injection nozzles in the RCS with their attendant effect as a discontinuity and potential for localized stress concentration which could lead to failure.

Containment Cooling System

In the concept shown in Figures 1 and 2, an internal containment cooling system, CCS, including containment spray, would no longer be a safety requirement since the external steel radiator and sprays would provide this function as needed.

Reactor Coolant System Component Supports

Currently, a prime function of, and the one that largely dictates their design in PWR's, is the requirement that the reactor coolant system, RCS, support structures isolates the effects of a postulated rupture of the primary reactor coolant system from the secondary heat transport steam system and vise versa. This criterion in existing designs requires that the RCS support structures as a safety function, be designed for equivalent static reaction loads which vary between 2.5 and 8.0×10^6 pounds. These loads may be as much as an order of magnitude greater than the supports see in normal operation and under earthquake loads.

In the U.S., these extremely large RCS or steam rupture loads also have been combined with the loads associated with the Safe Shutdown Earthquake, SSE, adding even more to the support design load. Such additional seismic loads typically range between 10 to 25 percent of the LOCA load effect taken alone. This new passive containment concept of Figures 1 and 2 would no longer require RCS supports to be designed for postulated RCS pipe rupture loads as a safety issue. Elimination of the LOCA or steamline break isolation requirement combined with SSE would have a significant effect on the reduction in RCS component support capital costs and the congestion caused by the design of massive load resisting supports. Postulated pipe break loads from all high energy systems could all also be eliminated as a design basis.

Elimination Of Pressure Suppression

While the effects on costs associated with elimination of pressure suppression have not been evaluated in this study, it would no longer be necessary to provide a water pressure suppression system for large commercial BWR type reactors since the containment would be able to accommodate both the primary reactor coolant as well as the secondary heat transport systems simultaneous total energy release.

COST COMPARISON

In Table 3 is presented a quantity estimate comparison between conventional prestressed concrete cylindrical containments for a typical 1300 MWe PWR-NPP and the concept suggested in this paper as shown in Figures 1. In Table 4 is presented a relative cost estimate and comparison between current conventional and the passive containment types described in Table 3 with the cost of current containments normalized to 1.0. Credits are also considered associated with reduction in the complexity and redundancy associated with a PWR's emergency core cooling system in down grading such a system from a safety related engineered safeguard to a system whose design is dictated by economic consideration associated with protection against the loss of the power plant investment.

Table 3 Quantity Estimates Conventional Prestressed Concrete Compared to Concrete Passive Containment Design

I. Conventional Containment – 140' I.D. Height to Springline 140' Diameter Prestressed Concrete Wall 3.5 ft. thick and Hemispherical Dome 2.5 ft. thick, Design Pressure = 60 psi

Element	Concrete Cu. Yards	Rebar Tons	Prestressing Ft. of 170 Wire Tendons	Liner Sq. Ft.	Misc.

Reactor Sump	600	125		2,500-1/4" PL	
Base Mat	6,950	2,450		14,000-1/4" PL	
Cylinder	8,380	350	17,000 Horizontal 13,500 Vertical	62,000-1/4" PL	
Dome	2,950	150	10,250	31,000-1/4"PL	
Interior Concrete	8,500	1,600			
TOTALS	27,380	4,675	41,000	109,500	

II. Passive Containment – 140' I.D., Height from Reactor Coolant Compartment Floor to Springline 110', Height from Containment Base Mat to Tope of Reactor Coolant Compartment Floor 120', Primary Containment Wall 8.0 ft. thick and Hemispherical Dome 4.0 ft. thick, Design Pressure = 180 psi. Primary Containment surrounded by Steel Shell Radiator with an average 1.0 inch thickness and Reinforced Concrete Shield Building 2.5 ft. thick walls and 2 ft. thick Dome.

Element	Concrete Cu. Yards	Rebar Tons	Prestressing Ft. of 170 Wire Tendons	Liner Sq. Ft.	Misc.
Base Mat	18,850	8,500		25,500-1/4" PL	
Cylinder	31,700	1,000	85,000 Horizontal 65,000 Vertical	101,200-1/4" PL	
Dome	6,500	500	32,000	34,000-1/4" PL	
Interior Concrete	17,500	3,800			
Basalt Rock					45,600 yd^3
Radiator Shell				163,000-1"PL	
Shield Bldg.	14,300	500			
TOTALS	88,850	14,300	182,000	160,000-1/4" PL 163,000-1" PL	45,600 yd^3

An added significant effect on overall plant costs presented in Table 4 is the reduced requirement for in-service inspection and maintenance during plant life which would be achieved by reducing the complexity of the Emergency Core Cooling System, ECCS, and associated elimination of redundant safety trains and down grading it to a plant operating system since it is no longer necessary for public health and safety.

Table 4 Relative Cost Comparison Between Conventional and Passive Containment, Containment Cooling, and Emergency Core Cooling Systems and Equipment Supports With Conventional Containment Normalized to 1.0

	Total Cost
I. Conventional Containment	1.0 (1)
II. Passive Containment with Steel Radiator 88,850 yd^3 concrete 14,300 tons rebar 182,000 ft. 170 wire tendons 160,000 ft^2 liner PL ¼" 163,000 ft^2 radiator PL 1" 45,600 yd^3 basalt rock 49,000 ft^2 refractory brick	3.68
III. Emergency Core Cooling System Conventional Containment ECCS Maintenance & ISI for 40 yrs. TOTAL Passive Containment ECCS Maintenance & ISI 10/yr x 40 yrs. TOTAL DIFFERENCE	 1.20 0.33 1.53 0.49 0.13 0.62 (0.91)
IV. Containment Cooling System Conventional CCS	 0.50

Maintenance & IS for 40 yrs.	0.17
TOTAL	0.67
Passive Containment CCS	0.14
Maintenance & ISI for 40 yrs.	0.03
TOTAL	0.17
DIFFERENCE	(0.5)
V. NSSS Component Supports	
Conventional Containment	0.21
Maintenance & ISI for 40 yrs.	0.07
TOTAL	0.28
Passive Containment ECCS	0.11
Maintenance & ISI 10/yr x 40 yrs.	0.03
TOTAL	0.14
DIFFERENCE	(0.14)
	Relative Cost
VI. Cost Summary	
Conventional Containment	1.00
Passive Contain with Radiator	3.68
Conventional ECCS	1.53
Passive ECCS	0.62
Conventional CCS	0.67
Passive (Radiator) CCS	0.17
Conventional NSSS Supports	0.28
Passive NSSS Supports	0.11
VII. Cost Differentials	
Containment (3.68 – 1.00)	+2.68
EECS (1.53 – 0.62)	-0.91
CCS (0.67 – 0.17)	-0.50
NSSS Supp. (0.28 – 0.11)	-0.14
TOTAL	1.13
(Net increased in plant cost over conventional containment design. 1.10 times conventional containment design.)	

(1) Times cost of conventional single barrier prestressed concrete 1300 MWe PWR Containment. Assuming total plant costs in 2004 dollars is 2 billion, the conventional containment cost is
0.06 x 2000,000 = $120,000,000.00.

Also presented in Table 4 is the estimated significant reduction in the cost of major PWR component supports which are designed to accommodate the extremely large loads induced in the reactor coolant system when isolation of the primary RCS and secondary heat transport system is no longer a safety issue.

SUMMARY AND CONCLUSIONS

Based on the cost estimate summarized in Section 5.0 of this paper, it would appear the passive containment concept and revised design bases presented in Section 3.0 would add about 1.1 times the containment structure cost to an overall 1300 MWe PWR NPP costs. Given that the containment structure adds about 6.0 percent to overall plant costs the total increase in PWR plant cost for a passive containment system design for all severe accident scenarios, plus large airplane crash suitable for metropolitan siting, would be about 6.7 percent. This should merit further study from an economic as well as improved safety standpoint. This is particularly true when considering a large aircraft crash as a design basis event. In addition, based on this preliminary study, there does appear to be a containment and nuclear power plant design option at least from a postulated external event hazard or accident standpoint which would permit consideration of metropolitan siting.

REFERENCES

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[3] HSK-AN-4626, "Position of the Swiss Federal Safety Inspectorate Regarding the Safety of the Swiss Nuclear Power Plants in the Event of an Intentional Aircraft Crash," Swiss Federal Nuclear Safety Inspectorate, March 2003.

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[6] ACI-ASME Joint Committee, ASME Boiler and Pressure Vessel Code, Section III – Division 2 and ACI Standard 359, 2001.