CONTAINMENT STRUCTURES

4/19/2011

INTRODUCTION

A misconception about nuclear power plants containment structures is that their massive concrete construction is a protection against the release of radioactive products in the case of a postulated accident. Such a task is achieved by the overall containment system as a collection of the "Engineered Safety Features," not just by the concrete shell alone.

It must be understood that the concrete component is meant as a biological shield against gamma-ray radiation and a protection of the reactor internals against damage from the effects of the outside elements including missiles such as light posts driven by tornado or hurricane 100-miles per hour winds, and even the direct impact by a massive aircraft such as a Boeing-747.

The concrete shell in fact is strong at its exterior curvature, and weak at its interior curvature. This is an inherent characteristic of shell structures. Think about how difficult it is to crush an egg by squeezing it in one's hand, yet it is easy for the weak and helpless chick to peck its way out of the interior of an egg's shell.

The concrete shell is designed to withstand the direct impact of an aircraft on its exterior, but miserably fails a buildup of stress at its interior. An increase of stress by steam release, if unquenched, at its interior will eventually cause it to fail; much like a chain at its weakest link. The weakest links in that case occur at the coolant inlet and outlet pipes and the instrumentation cabling and electrical power penetrations.

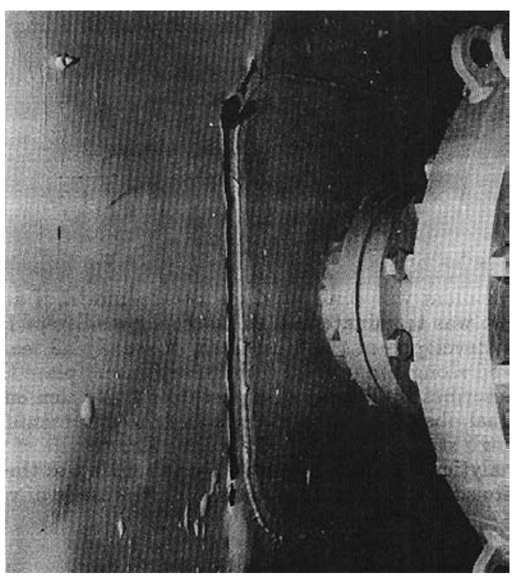


Figure 1. Large 22 in Liner Tear near a containment scale model piping penetration.
Source: Sandia Laboratory.

PRESSURIZED WATER REACTOR, PWR CONTAINMENT SYSTEM

PWR designs are surrounded by a containment system with multiple Engineered Safety Features, ESFs. A dry containment design is shown in Fig. 2, and consists of a steel shell containing multiple safety systems. A concrete biological shield surrounds the steel shell. The biological shield is meant to protect against the outside elements and is not meant as a barrier against the release of radiation. For instance it is designed to withstand a direct hit by a Boeing-747 aircraft, and a 100-miles per hour missile such as a light pole driven by tornado or hurricane winds.

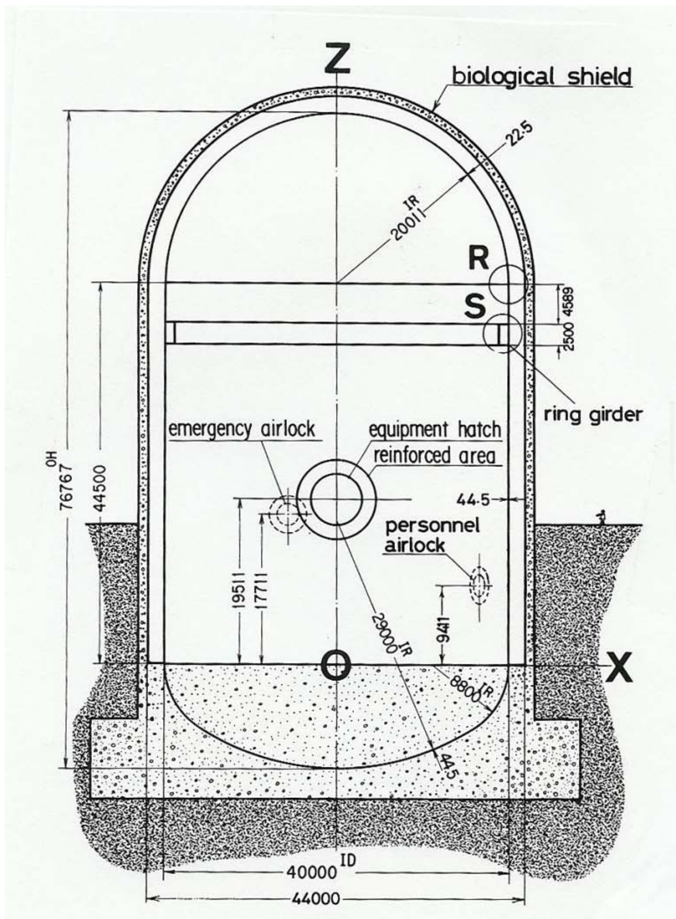


Figure 2. PWR dry steel shell containment surrounded by concrete biological shield.

Another PWR containment design is shown in Fig. 3, where an ice condenser is used to quench any release of radioactivity or steam caused maybe by an earthquake event.

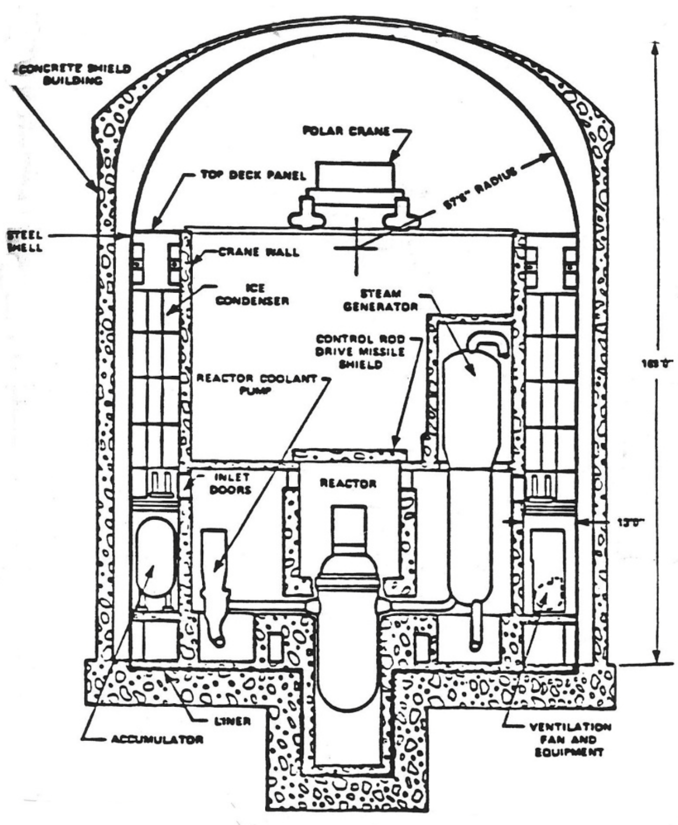


Figure 3. Sequoia Unit 1 PWR ice condenser containment.

The containment contains the various circuits for emergency core cooling water injection into the primary system. These include:

1. *The accumulators* which are large vessels containing water under nitrogen gas pressure. They are connected to the primary system by automatic valves, which open if an accident occurs that reduces the primary system pressure below 40 bars.
2. *The High pressure Injection System (HPIS)* allows pumping of water into the system at a high head or pressure of about 100 bars but at low flow rates.
3. *The Low pressure Injection System (LPIS)* allows water to be pumped at a low head or pressure below 30 bars at high flow rates.
4. *A containment spray system* to quench any released steam in the case of an accident.

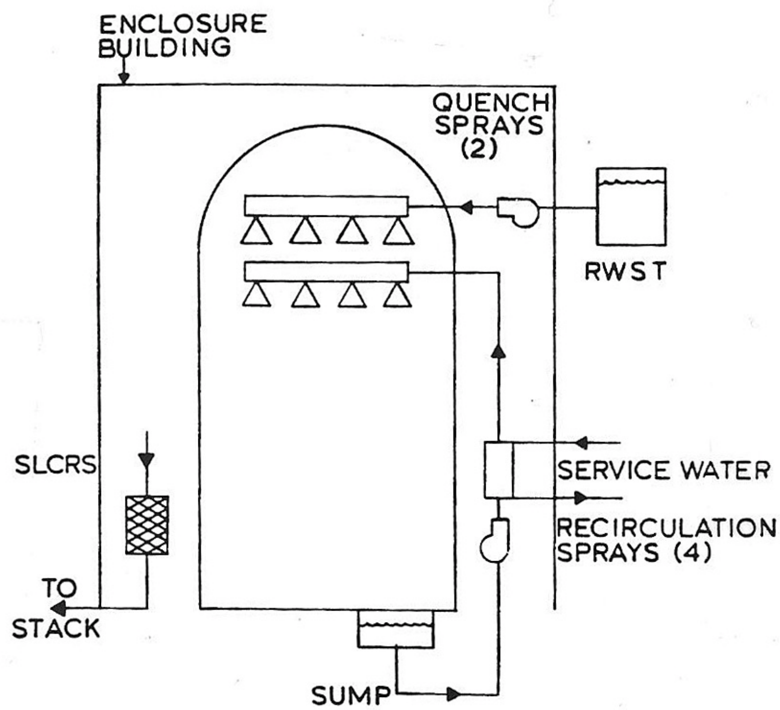


Figure 4. Containment spray and system safeguards components.

Table 1. Functions and types of essential equipment in drywell and the containment structure.

Function	**Type**
Mitigate event consequences	Containment spray isolation valves Hydrogen igniters Hydrogen recombiners Hydrogen mixing fans and compressors Hydrogen mixing valves DW VBK valves MOV
Maintain containment integrity	Low Pressure Coolant Injection, LPCI isolation valve Airlock seals Hatch seals Electrical penetrations
Maintain core in a safe condition	Reactor Pressure Vessel, RPV level / pressure transmitters ADS valves
Post-accident monitoring	Hydrogen sensors Pressure transmitters Temperature transmitters
Supporting equipment	Power cables Instrument cables Electrical terminal box/board

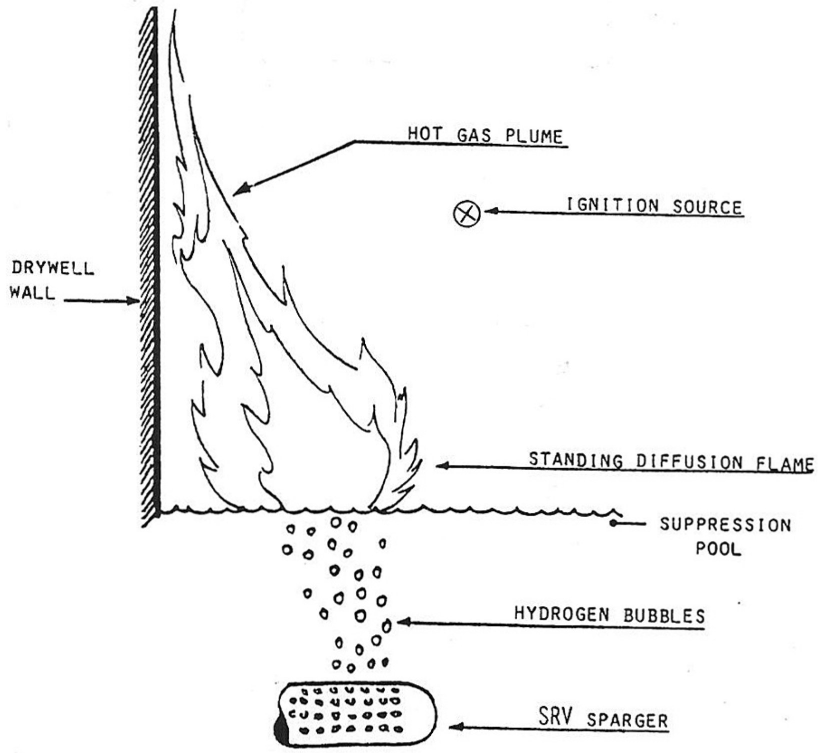


Figure 5. Controlled diffusion flame burning of hydrogen released in a reactor accident.

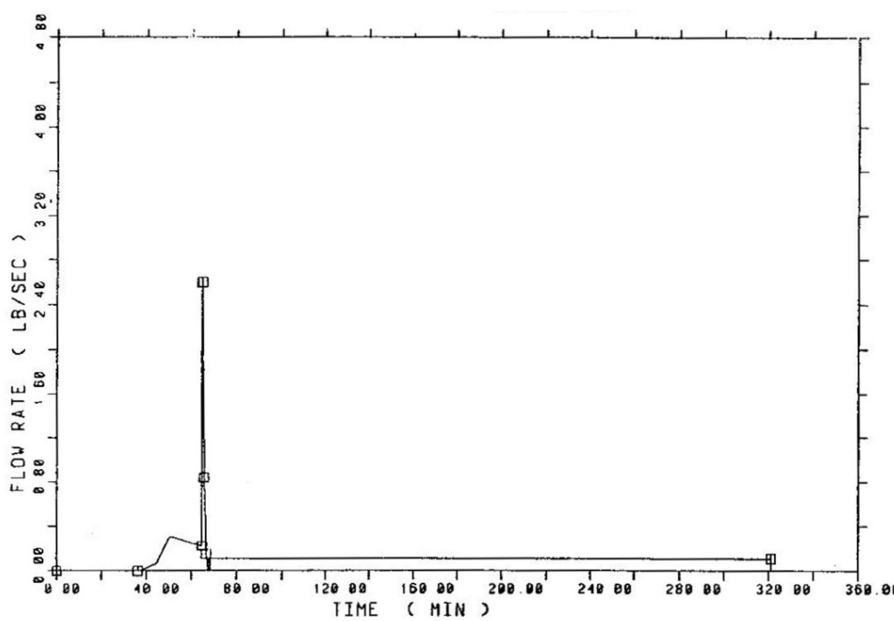


Figure 6. Recorded hydrogen flow rate was associated with a stress spike from suspected hydrogen ignition at the Three Mile Island accident.

DESIGN CHARACTERISTICS OF EXISTING CONTAINMENT SYSTEMS

The concrete structures in the existing power plants designs act as insulators against the controlled release of energy to the environment and would eventually fail, if the ESFs fail to perform their functions (Table 1).

They are being replaced by evolutionary designs that allow heat exchange with the environment, hence avoiding the buildup of pressure in the case of a serious accident and eventual failure to contain the release of radioactivity in a postulated accident.

Table 2. Simulated performance of different containment types [1].

Containment type, plant	Parameter	Technical specification
SP-1, Zion	Containment capability Upper bound spike Early failure physically unreasonable best estimate pressure rise rate, including heat sinks Best estimate failure time, with unlimited water in cavity	149 psia 107 psia 10 psi/hr 16 hrs
SP-2, Surry	Containment capability Upper bound spike Early failure physically unreasonable best estimate failure time, with dry cavity	134 psia 107 psia Several days
SP-3, Sequoyah	Containment capability Upper bound loading Lower bound loading Thermal loads Early failure	65 psia, 330 ^oF 70-100 psia 50-70 psia 500-700 ^oF Quite likely
SP-4, Browns Ferry	Containment capability Upper bound loading Lower bound loading Thermal loads Early failure	132 psia, 330 ^oF 132 psia in 40 min 132 psi in 2 hrs 500-700 ^oF Quite likely
SP-15, Limerick	Containment capability Upper bound loading Lower bound loading Thermal loads Early failure, upper bound too conservative	155 psia, 330 ^oF 145 psia in 2-3 hrs 100 psi in 3 hrs 550-700 ^oF Rather unlikely
SP-6, Grand Gulf	Containment capability Upper bound loading Wall fluxes Penetration seal temperature Pressurization failure from diffusion flames Seal failure	75 psia 30 psia 10^3-10^4 BTU/(hr.ft^2) 345 ^oF Unreasonable Unlikely
SP-A, SP-1 accident comparative results	Containment capability Upper bound loading Thermal loads Early failure (100 percent core dispersal, 100 percent clad oxidation, no seal oxidation, no early depressurization, unobstructed flow)	150 psia 176 psia 1,340 ^oF Quite likely

MODERN CONTAINMENT DESIGN CONCEPTS

ADVANCED PASSIVE AP600 AND AP1000

Toshiba from Japan and its Westinghouse subsidiary that it acquired from British Nuclear Fuel Ltd. (BNFL) in the USA are committed to the design and development of advanced nuclear reactors that are safe, low-cost, reliable, and environmentally acceptable. Their AP1000 design is meant for near term deployment and their 4S and hydrogen production systems are targeted for future technology development.

The AP1000 is the only Generation III+ nuclear power plant to receive design certification from the United States Nuclear Regulatory Commission. It is an advanced plant that further increases safety through the use of naturally occurring forces such as gravity, natural circulation, and condensation. In the unlikely event of a plant emergency, these safety systems, because of their inherent nature, will automatically activate without the need for human intervention.

In addition to the enhanced safety features, the AP1000 is cost-effective. The plant is composed of modules that are constructed in either factories or shipyards, thereby improving quality while reducing the potential for delays that are associated with field construction.

Even though it is an advanced plant, it is a proven design that is based on the same Westinghouse PWR technology that has supported the nuclear industry over the last 50 years. Toshiba brings to the partnership with Westinghouse a highly efficient and reliable turbine generator design, state-of-the-art construction technologies, and knowledgeable construction management.

Toshiba and Westinghouse are also developing the 4S, a Super Safe, Small, and Simple reactor. The 4S is a 10-50 MWe, passive safety fast spectrum plant that has a 30-year operating life before the need to refuel, also known as a battery reactor.

Figure 7. Advanced Passive AP1000 PWR includes a cooling chimney using natural convection in its containment structure. Source: Toshiba-Westinghouse.

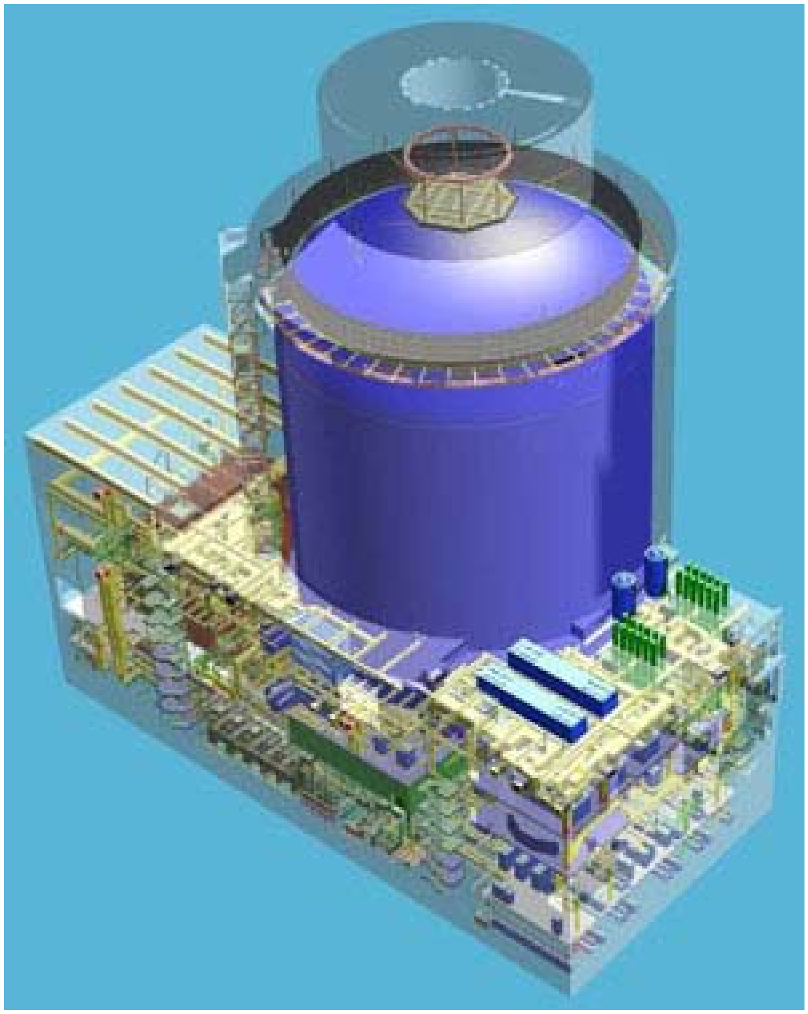


Figure 8. Containment structure of the AP1000 PWR has a gap between the steel shell and the concrete shield allowing natural convection cooling. The cooling is enhanced with a tang on top of it containing a supplemental water coolant supply. Source: Toshiba-Westinghouse.

EVOLUTIONARY PRESSURIZED WATER REACTOR, EPR AREVA DESIGN

The Evolutionary Pressurized Water Reactor, EPR is a Generation 3+ European Pressurized Water Reactor design with a capacity of 1600 MWe. It features advanced technologies, making it a reactor with the advocated following characteristics:

1. A high level of safety:

Extended prevention of the reactor core melt down hypothetical accident and its potential consequences, resistance to external risks such as an aircraft crash or a strong earthquake. The major safety systems comprise four sub-systems or "trains". Each train is capable of performing the entire safety function independently. There is one train in each of the four safeguard buildings, which are separated from each other by the reactor building to prevent simultaneous failure of the trains.

2. Optimized environmental qualities:

A 15 percent reduction in the production of long half-life radioactive waste, and increased performance and thermal efficiency.

3. Simplified operation and maintenance conditions:

Totally computerized control room, with a more user-friendly human-machine interface.

4. Improved economic competitiveness.

Areva is developing two EPR projects in Europe. In Finland construction is underway of an EPR for the Finnish utility TVO (Olkiluoto 3 project). The Finnish EPR will be the first Generation III+ reactor to go into service. In France, Electricité De France (EDF) has reached a decision to build a series of EPR reactors at the Flamanville-3 project site.

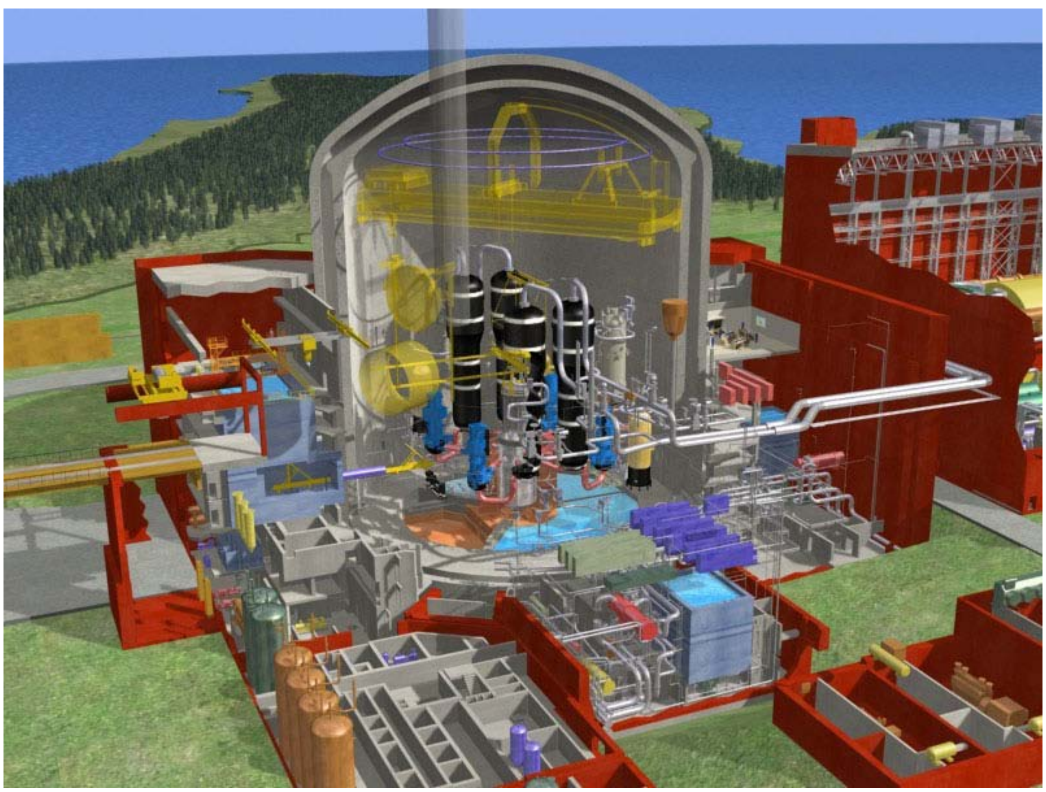


Figure 9. Cutout through the Evolutionary PWR Reactor, EPR pressurized water reactor design showing its double walled containment. Source: Areva.

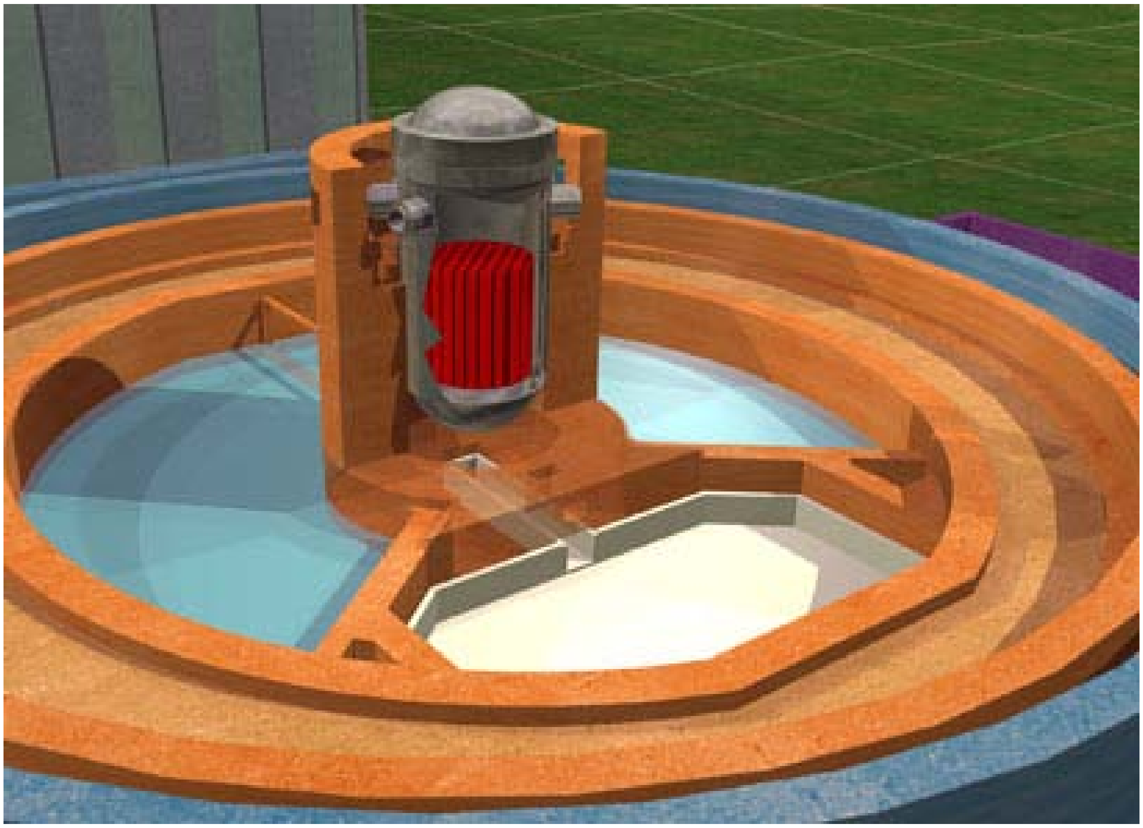


Figure 10. Evolutionary Pressurized Reactor, EPR melted corium retention and auxiliary water storage pools. Source: Areva.

ADVANCED BOILING WATER REACTOR, ABWR CONTAINMENT

The Advanced Boiling Water Reactor, ABWR containment structure has replaced the older light bulb design BWR containment.

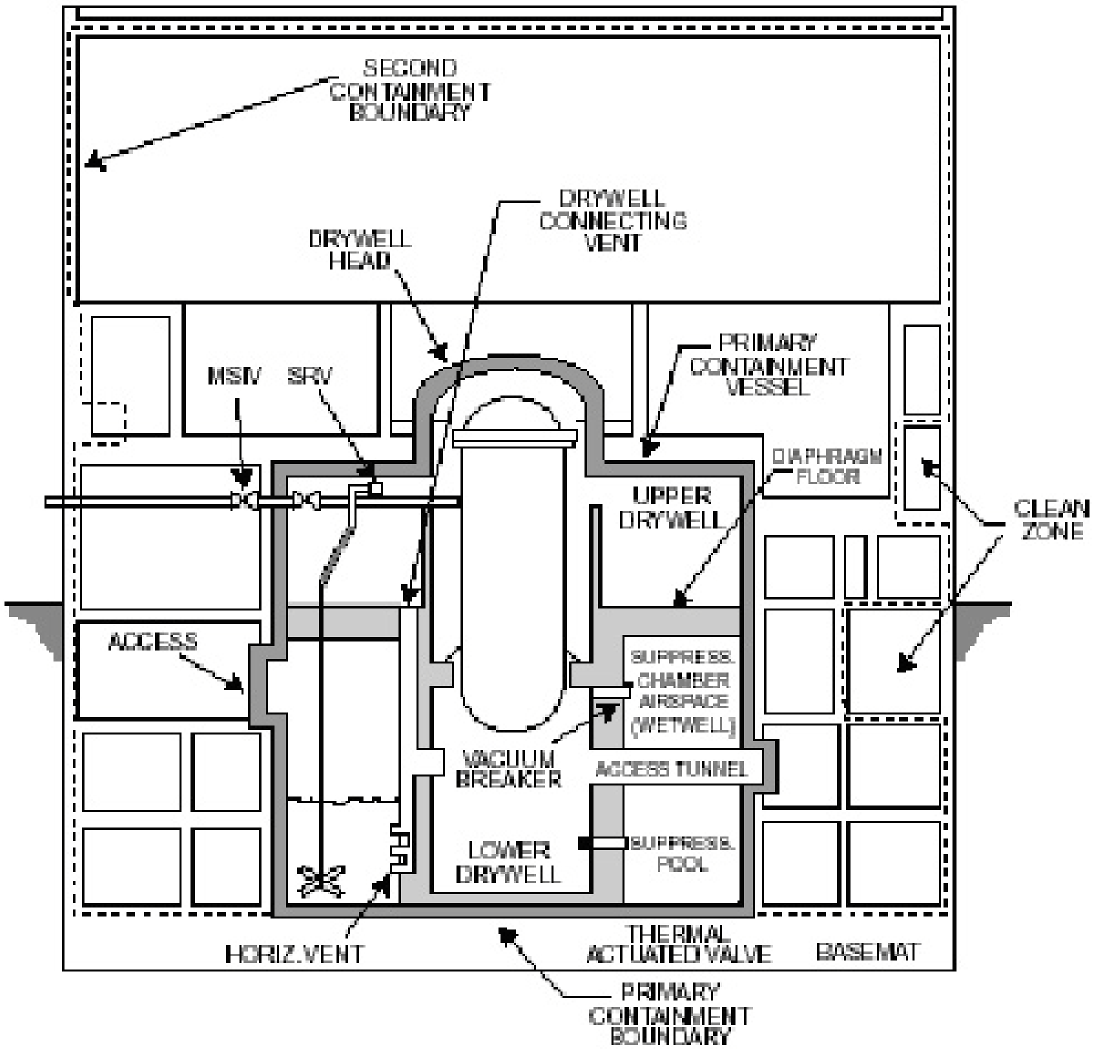


Figure 11. Advanced Boiling Water Reactor, ABWR containment structure. Source: GE.

PWR CONTAINMENT STRUCTURES

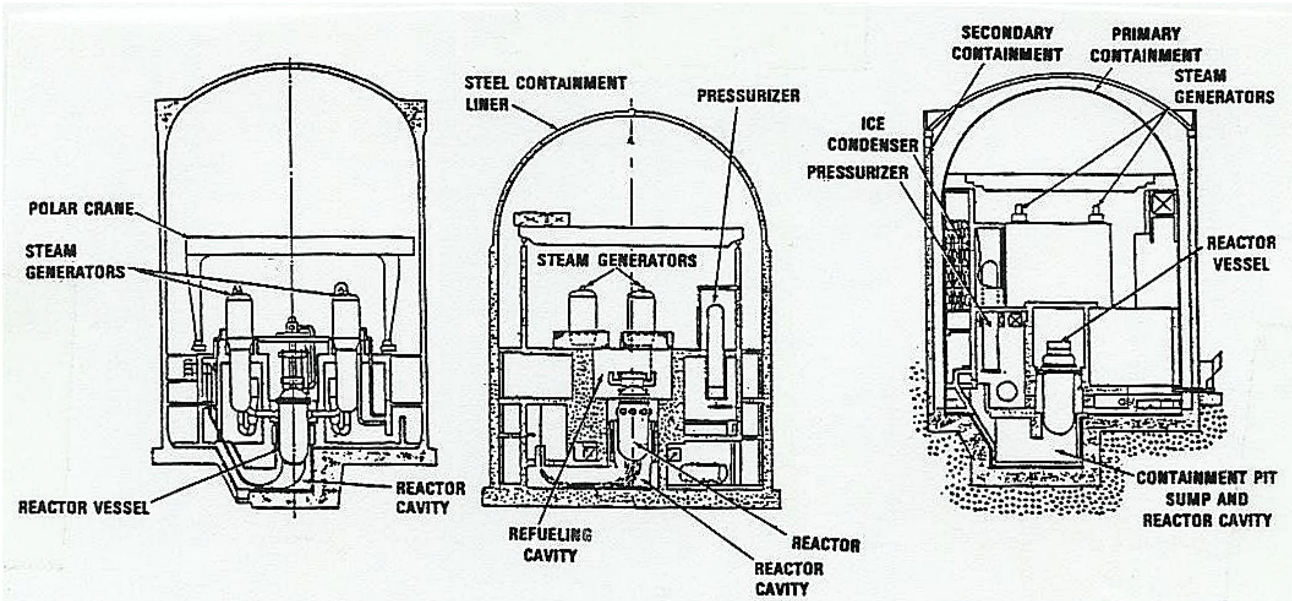


Figure 12. PWR containment systems in the USA: Large dry containment, 78 percent (left), Sub-atmospheric containment, 9 percent (center), ice condenser containment, 13 percent (right).

The PWR containment structures in the USA are predominantly large dry post-tensioned concrete designs.

Table 3. USA containment structures designs, 1986.

Containment type	**Steel**	**Reinforced Concrete**	**Post-tensioned concrete**	**Total**
Large dry	9	8	33	50
Ice condenser	6	2	-	8
Sub atmospheric	-	6	-	6
Total	15	16	33	64

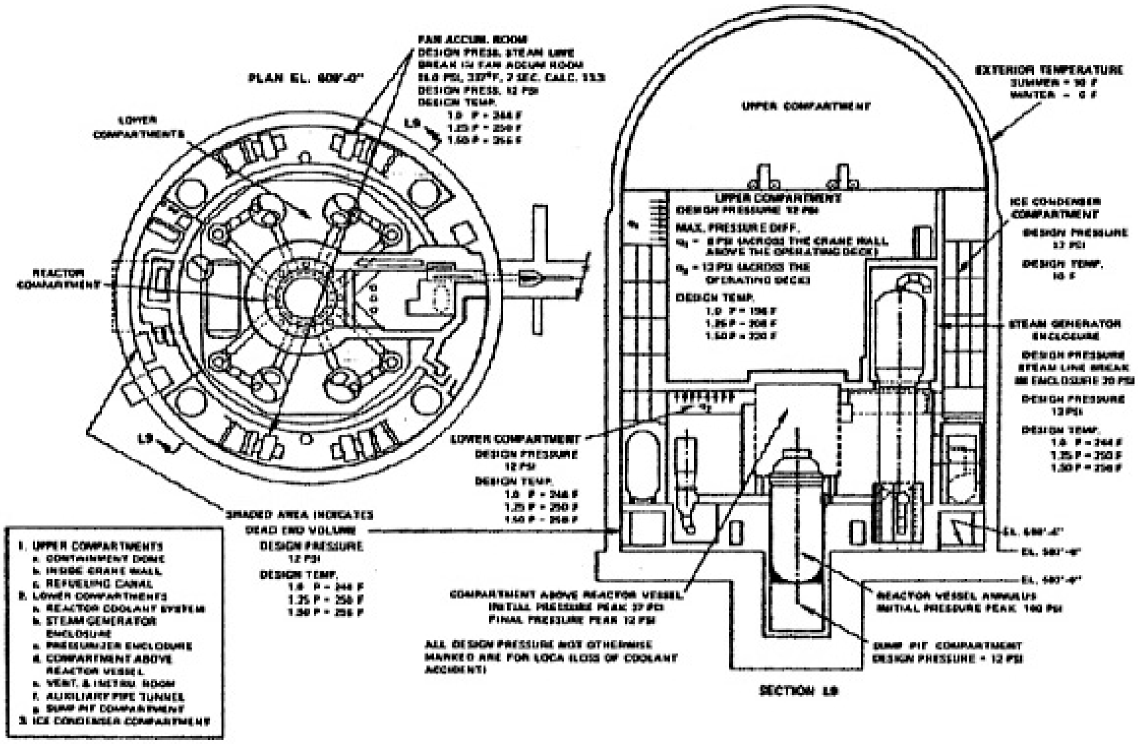


Figure 13. Detail of Ice Containment design. Source: Westinghouse.

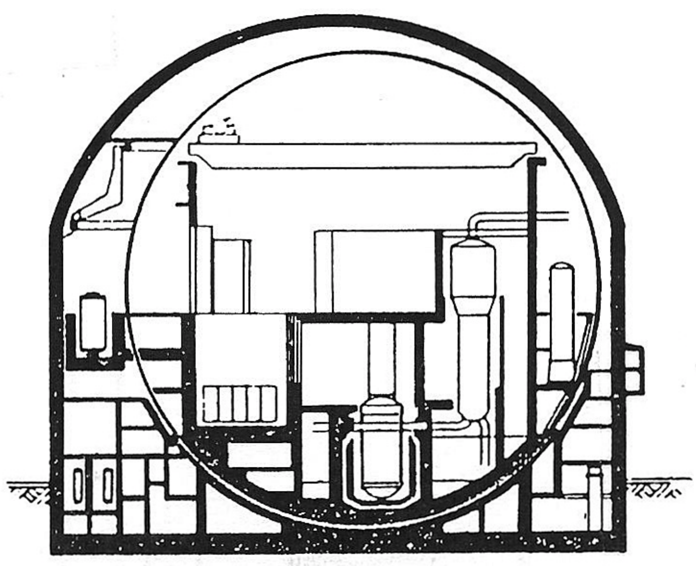


Figure 14. German containment structure for the NPP Goesgen PWR, 920 MWe, design overpressure: 4.9 bar, free volume: 56,000 m^3.

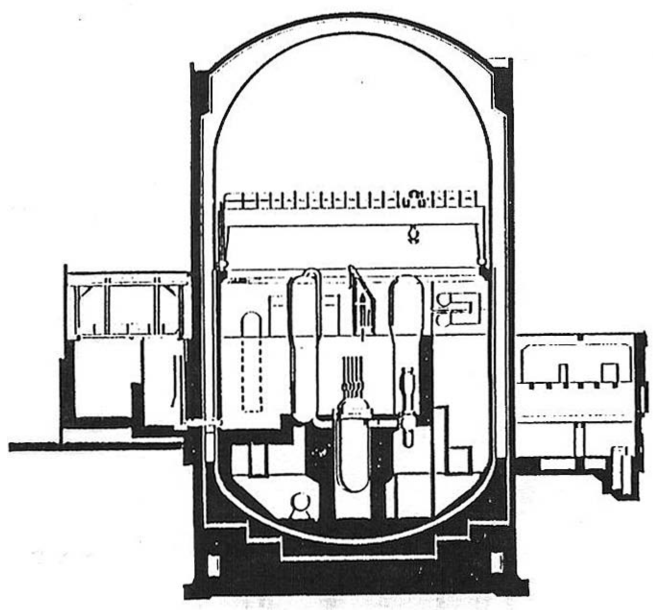


Figure 15. Containment structure of the NPP Beznau PWR, 350 MWe, design overpressure: 2.6 bar, free volume: 37,000 m^3.

BWR CONTAINMENT STRUCTURES

The BWR vessel is surrounded in a containment structure equipped with a pressure suppression pool in a light-bulb containment design, and in steel shell and concrete containment design.

We suggest that the positioning of the pressure suppression pool below the reactor core does not allow for natural circulation convective cooling in the case of a loss of coolant accident (LOCA). More advanced inherently safe designs would position the pressure suppression pool above the core. In case of an accident, the pressure in the core and the pressure suppression pool are equalized automatically or by operator action allowing natural circulation from the core to the pressure suppression pool in this case.

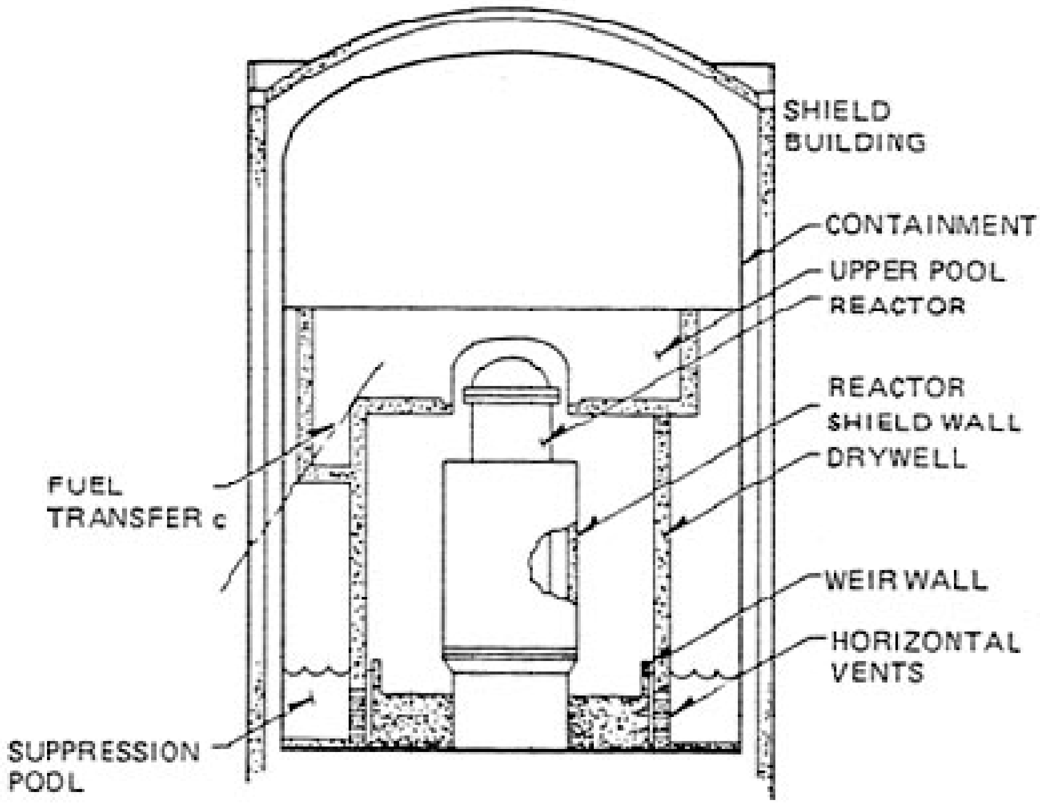


Figure 16. Steel shell and concrete BWR containment structure showing the pressure suppression pool.

Table 4. USA containment structures designs, 1986.

Containment type	**Steel**	**Reinforced Concrete**	**Post-tensioned concrete**	**Total**
Pre Mark I	4	-	-	4
Mark I	22	2	-	24
Mark II	1	3	2	6
Mark III	2	1	-	3
Total	29	6	33	37

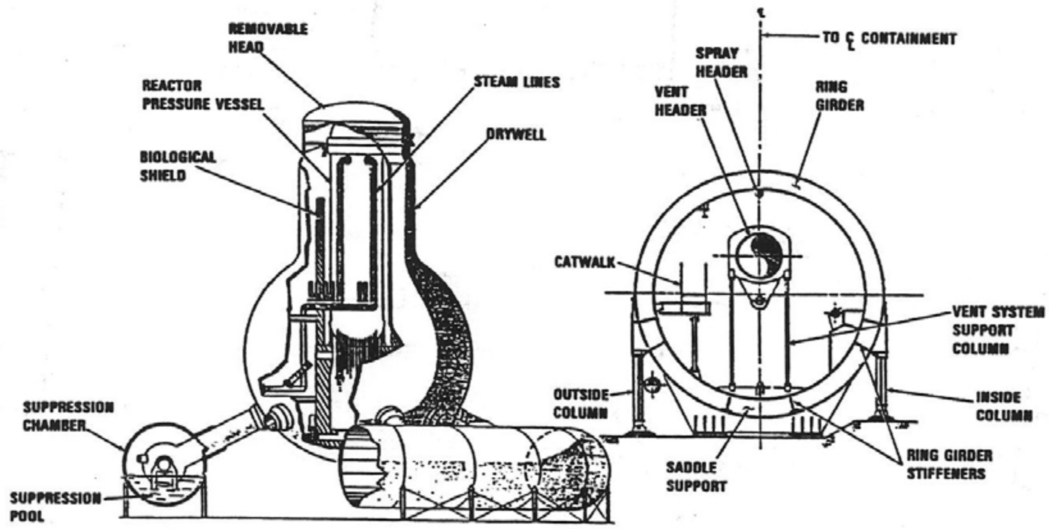


Figure 17. Mark I steel containment design used in 60 percent of USA BWRs.

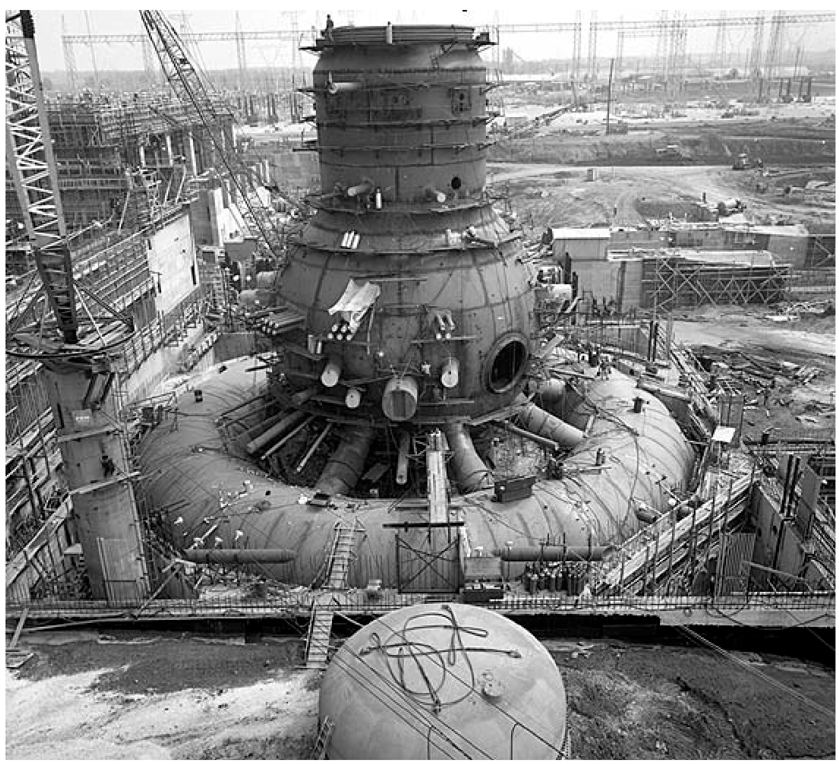


Figure 18. Mark I light bulb BWR containment and toroidal pressure suppression pool design. Source: GE.

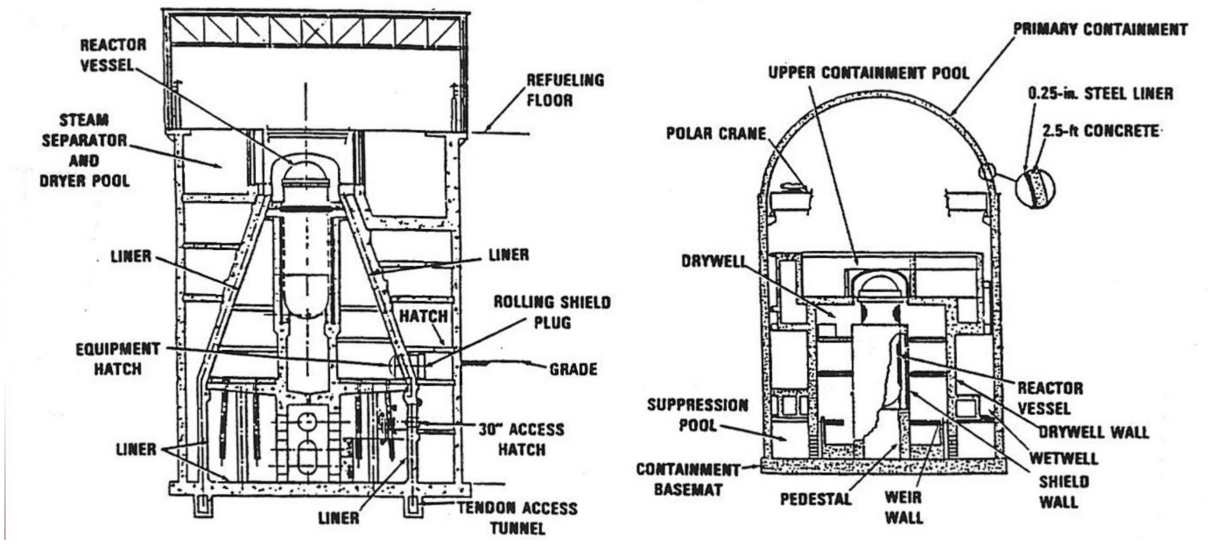


Figure 19. Comparison of Mark II (left), 16 percent and Mark III (right), 8 percent containment systems. Source: GE.

GE MARK I CONTAINMENT SYSTEM

The BWR containment structures in the USA are predominantly Mark I steel designs. The GE Company began making the Mark I, light bulb BWR containment system in the 1960s.

In 1972, concerns were raised that the smaller containment design was more susceptible to explosion and rupture from a buildup in hydrogen in case of fuel damage in the core and steam interaction with the Zircaloy metal cladding of the fuel.

Mark 1 containments were thought susceptible to damage should the fuel rods overheat and melt in an accident and that in an extreme accident, the containment could fail within 40 minutes.

The assessment was disputed given that its failure probability was about 10 percent in the case of a serious accident, and it remained operational with a proven track record of safety and reliability for more than 40 years.

There were 32 BWRs with Mark I containment operating around the globe. There has not been a breach of a Mark I containment system prior to 2011.

Several utilities and plant operators considered suing GE in the late 1980s after the disclosure of internal company documents dating back to 1975 that suggested the containment vessel designs were either insufficiently tested or had flaws that could compromise safety. The key concern was that the containment structure was undersized, and that a potential accident could overwhelm and rupture it.

The BWR Mark I containments in the USA have undergone a variety of modifications since these initial concerns were raised. Among these were changes to the doughnut-shaped torus pressure suppression pool. Steam being quenched from the primary vessel into the torus under high pressure would act as rocket and could cause vessel displacement.

In the late 1980s, all BWRs with Mark I containments in the USA were ordered to be retrofitted with venting systems to help reduce pressure in an overheating situation, rather than allow it to build up in a containment system that regulators were concerned could not take it.

A venting system was in place at the Fukushima plants to help relieve built-up pressure. With electrical power cut off in the aftermath of the earthquake and backup sources of power either failing or exhausted, workers injected seawater mixed with boron into the reactor to maintain control reportedly using fire engines pumps. They had difficulty venting the resulting steam with a report that pressure relief valves were operated manually.

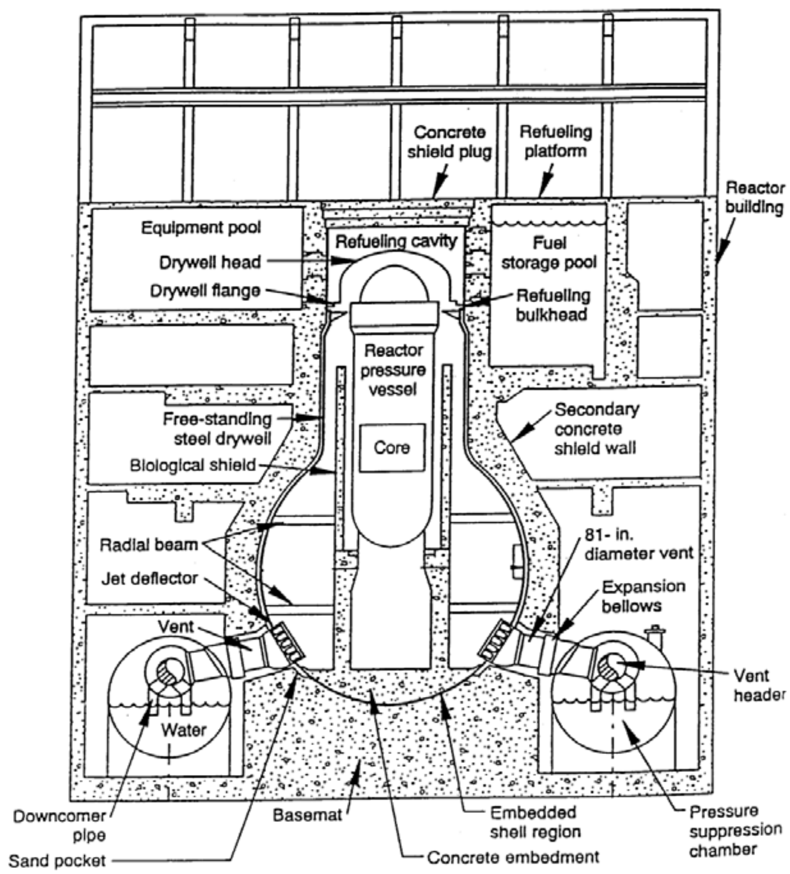


Figure 20. Mark I General Electric,GE BWR Containment. Source: GE.

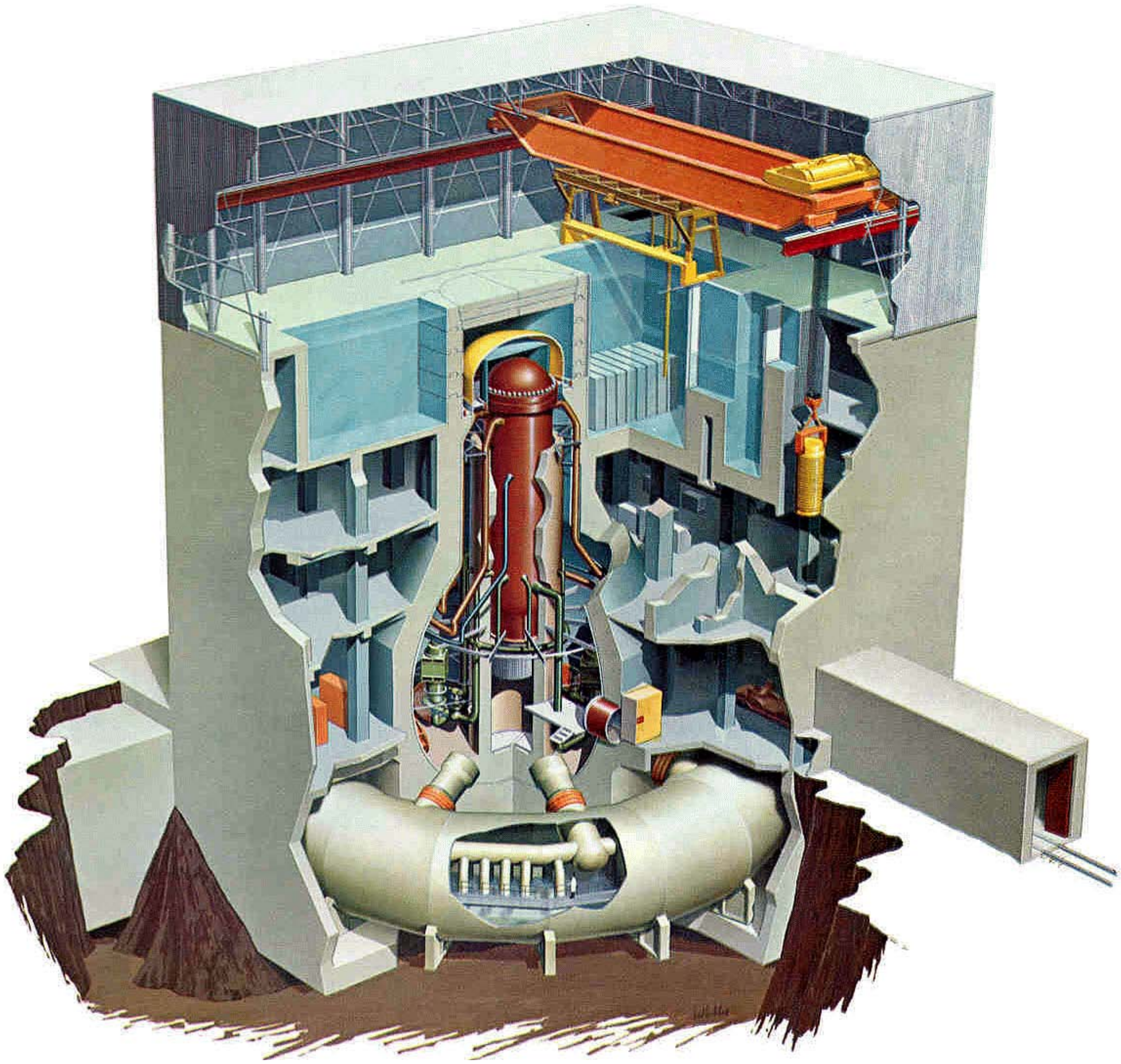


Figure 21. Cutout through concrete Mark I light bulb BWR containment design. Source: GE.

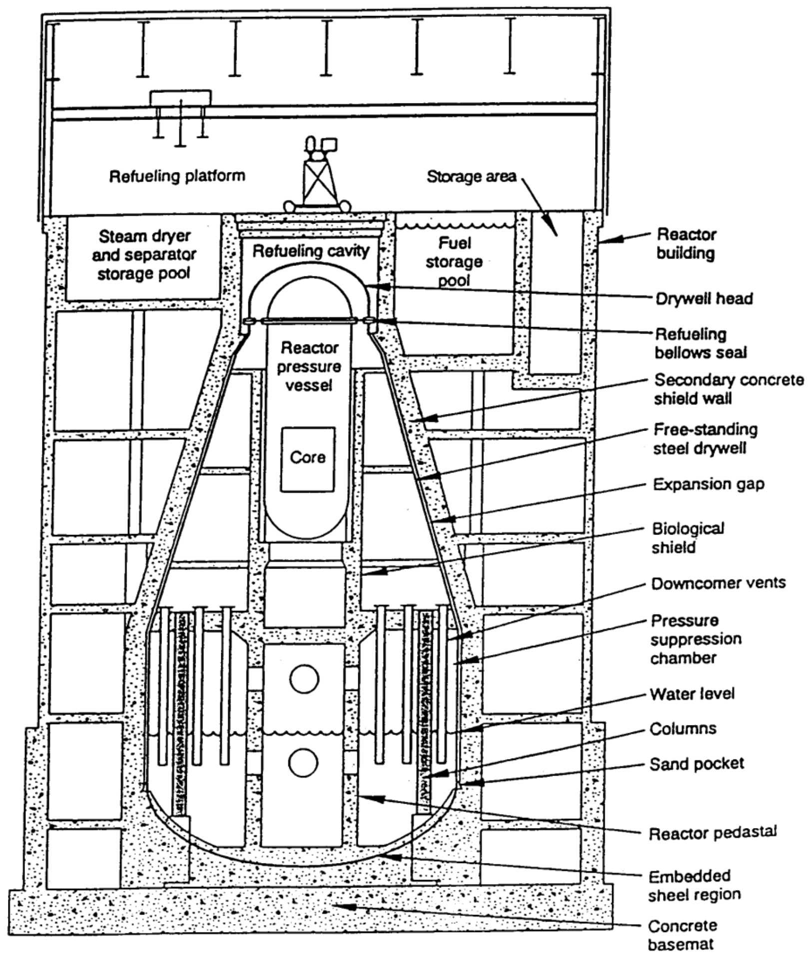


Figure 22. Mark II General Electric, GE BWR Containment. Source: GE.

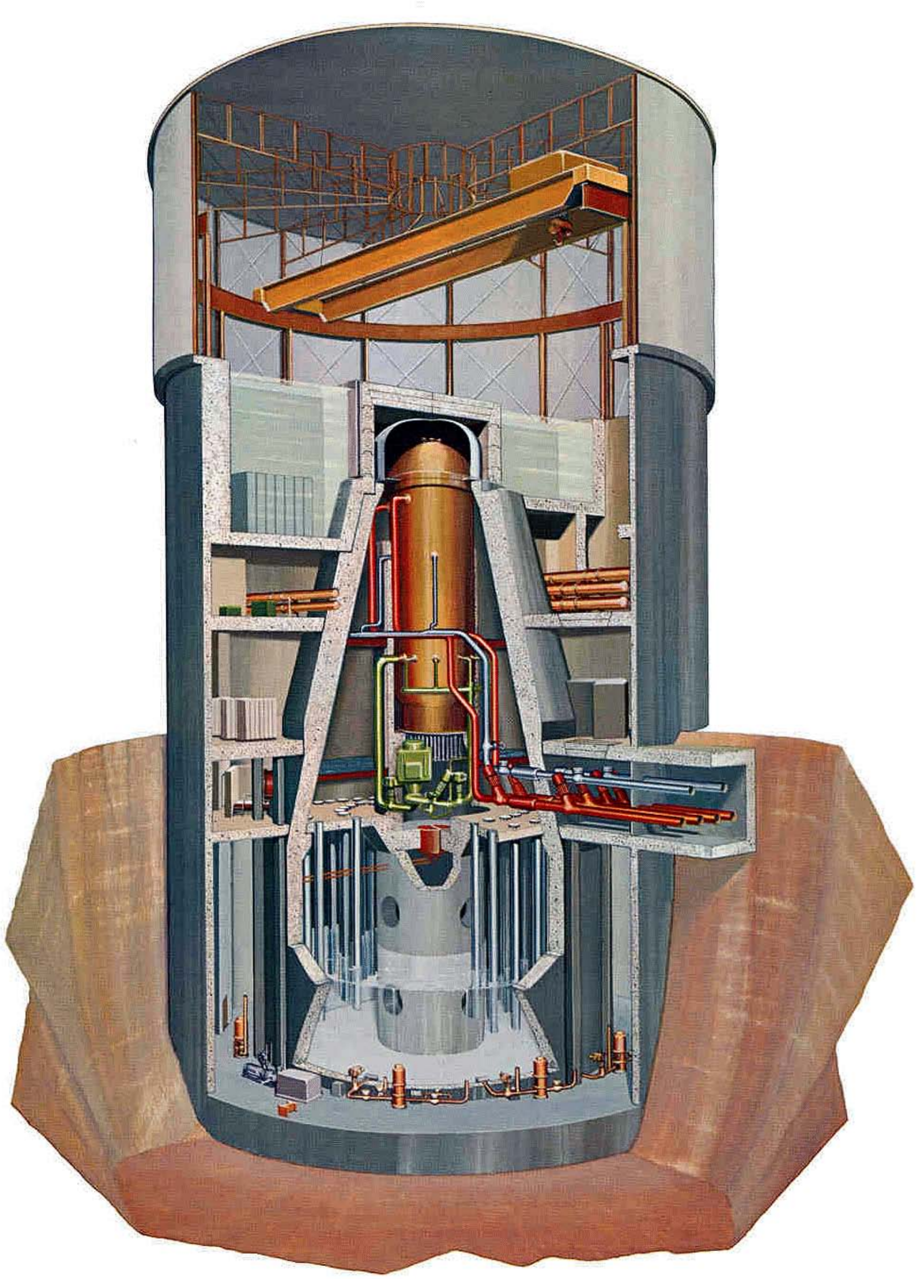


Figure 23. Cutout through Mark II GE BWR containment. Source: GE.

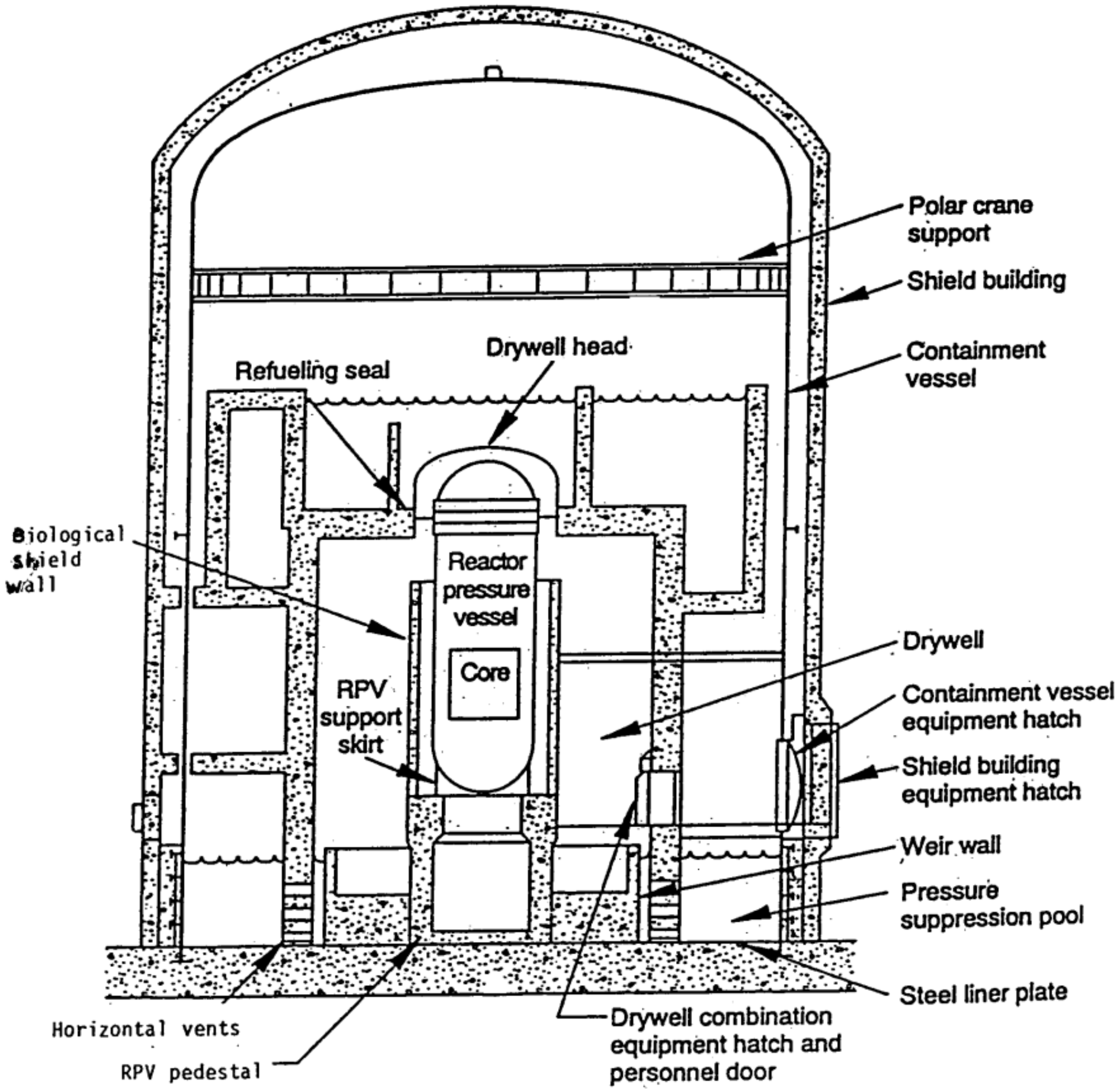


Figure 24. Mark III General Electric, GE BWR Containment. Source: GE.

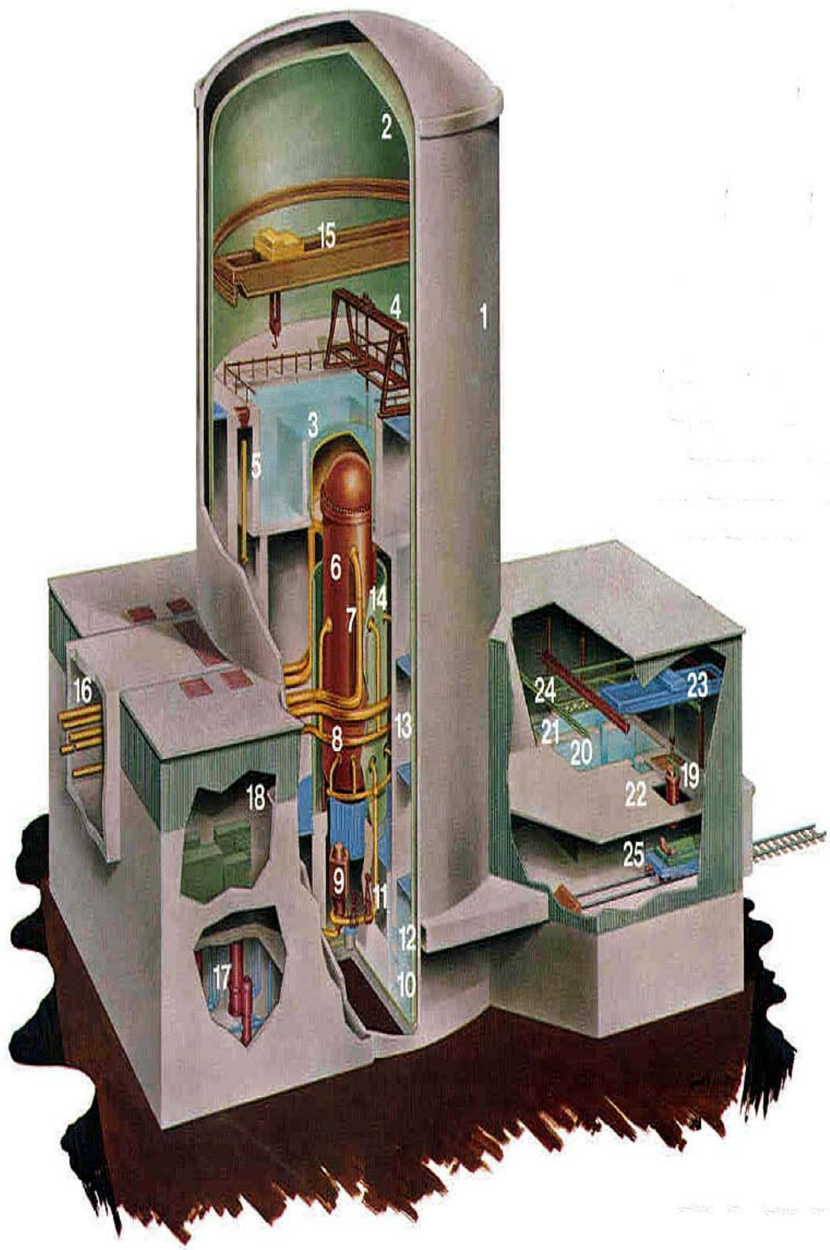


Figure 25. Cutout through Mark III, GE BWR Containment. Source: GE
Reactor Building. 1: Shield building, 2: Freestanding steel containment, 3: Upper pool, 4: Refueling platform, 5: Reactor water cleanup, 6: Reactor vessel, 7: Steam line, 8: Feedwater line, 9: Recirculation loop, 10: Pressure suppression pool, 11: Weir wall.
Auxiliary Building. 16: Steam line tunnel, 17: Reactor Heat Removal, RHR system, 18:Electrical equipment room.
Fuel Handling Building. 19: Spent fuel shipping cask, 20: Fuel storage pool, 21: Fuel transfer pool, 22: Cask loading poll, 23: Cask handling crane, 24: Fuel transfer bridge, 25: Fuel cask skid on railroad car.

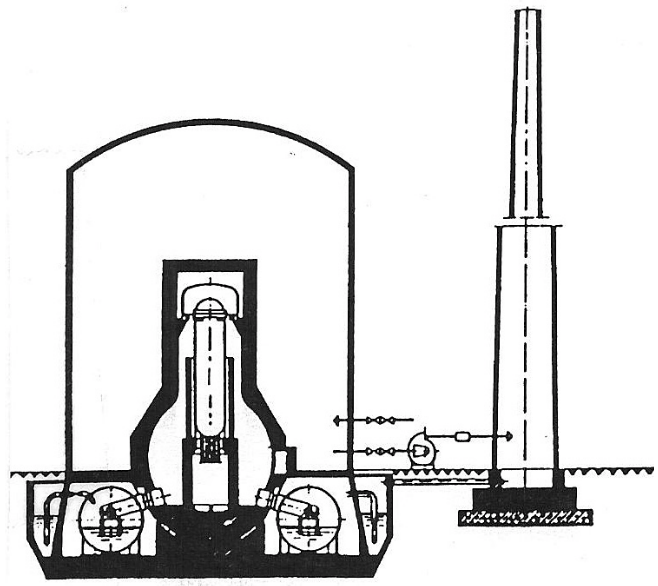


Figure 26. Containment and ventilation system for the NPP Muehleberg BWR, 322 MWe, free volume (dry and wet wells): 5,800 m^3, drywell free volume: 3,700 m^3, water volume in pressure suppression pool: 2,100 m^3, design overpressure: 3.8 bar.

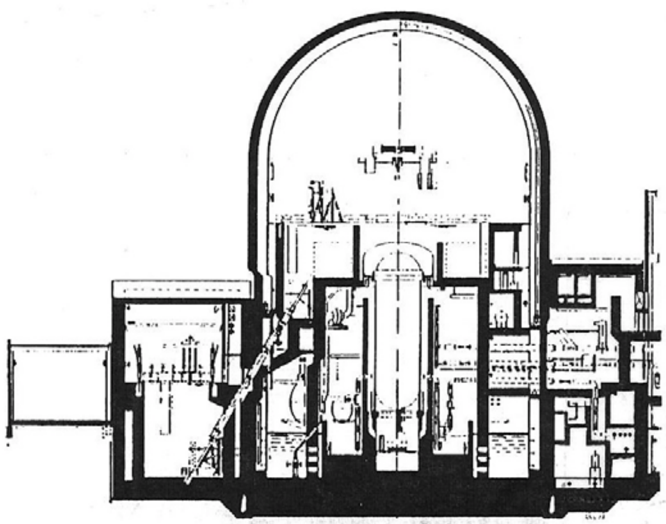


Figure 27. Containment structure of NPP Leibstadt BWR, 990 MWe, free volume (dry and wet wells): 44,000 m^3, drywell free volume: 7,770 m^3, water volume in pressure suppression pool: 3,760 m^3, design overpressure: 1.0 bar.

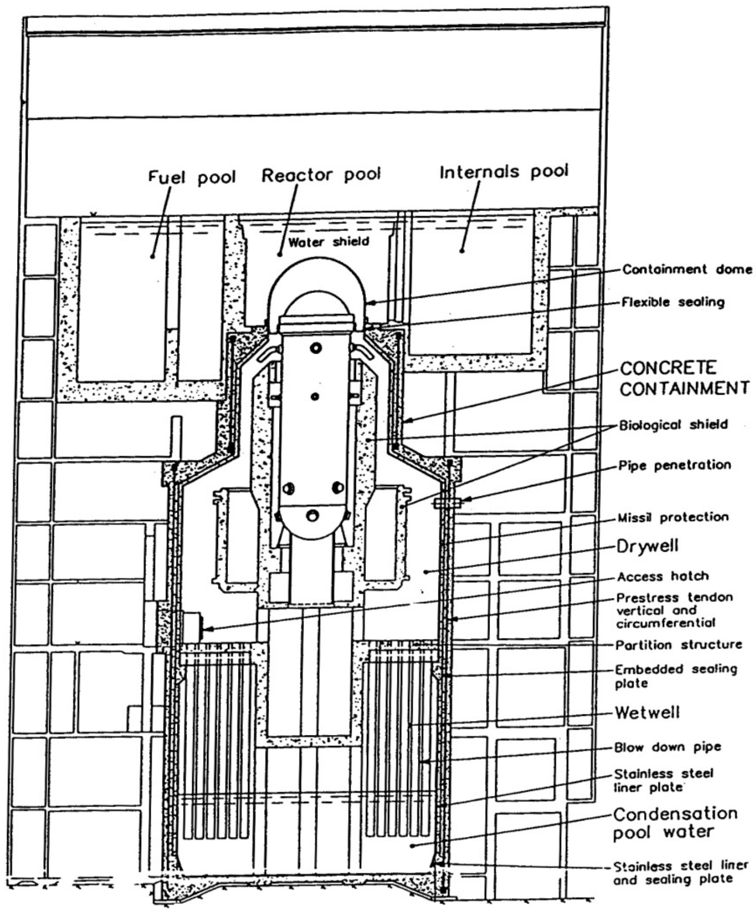


Figure 28. ABB Atom Type I BWR containment design, Sweden.

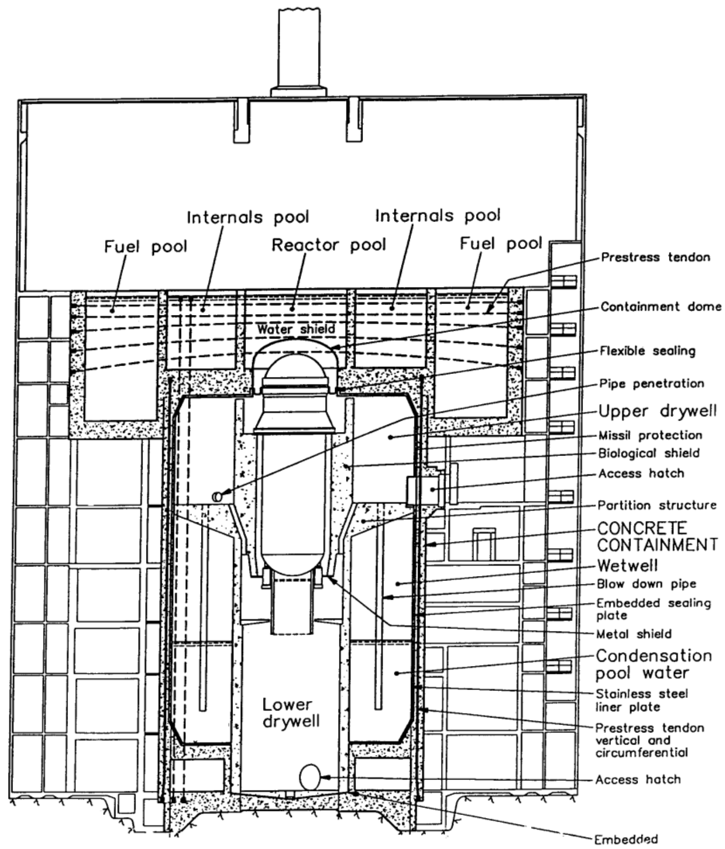
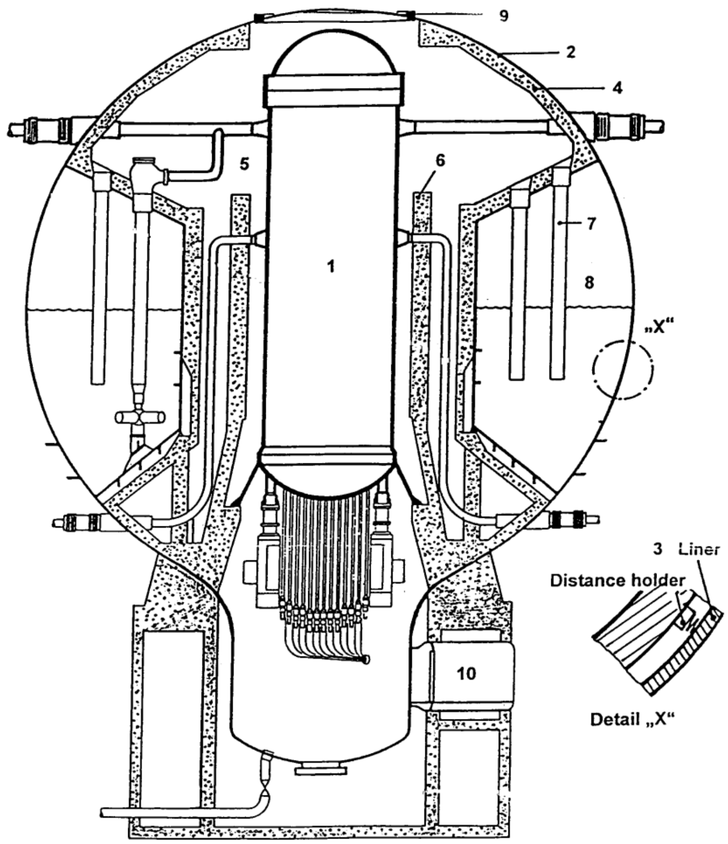


Figure 29. ABB Atom Type II BWR Containment, Sweden.



1 = Reactor Pressure Vessel
2 = Steel Containment
3 = Steel Liner
4 = Protective Concrete Shield
5 = Drywell
6 = Biological Shield Wall
7 = Downcomer Vent Pipes
8 = Pressure Suppression Pool
9 = Containment Vessel Hatch
10 = Personnel Lock

Figure 30. Siemens Kraft Werk Union, KWU Baulinie 69 BWR containment, Germany.

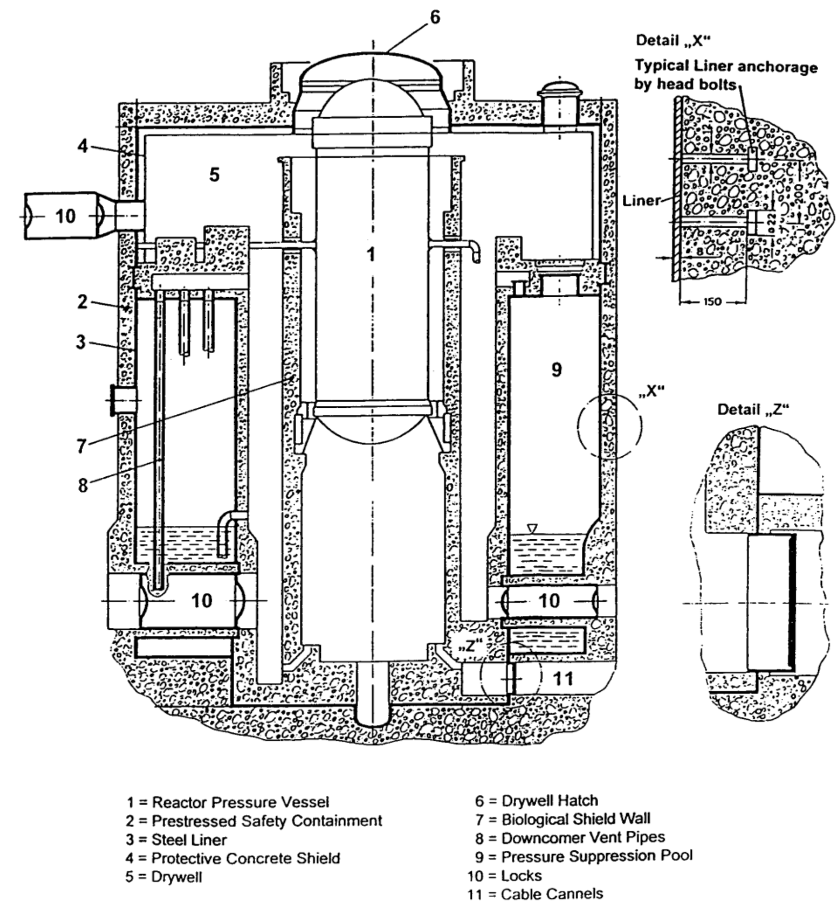


Figure 31. Siemens Kraft Werk Union, KWU Baulinie 72 BWR containment, Germany.

CONTAINMENT ATMOSPHERE FILTERING AND VENTING SYSTEMS

Several containment atmosphere filtering and venting systems have been proposed for containment but were not implemented for economical considerations. These include sand and gravel as barriers to radioactive releases.

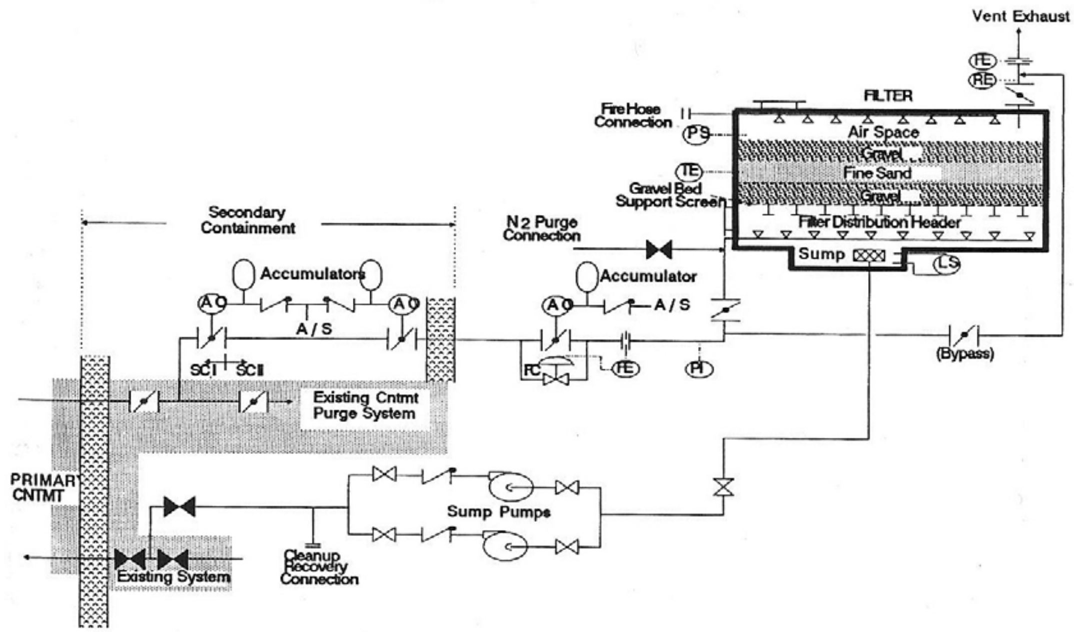


Figure 32. Sand and gravel containment venting system.

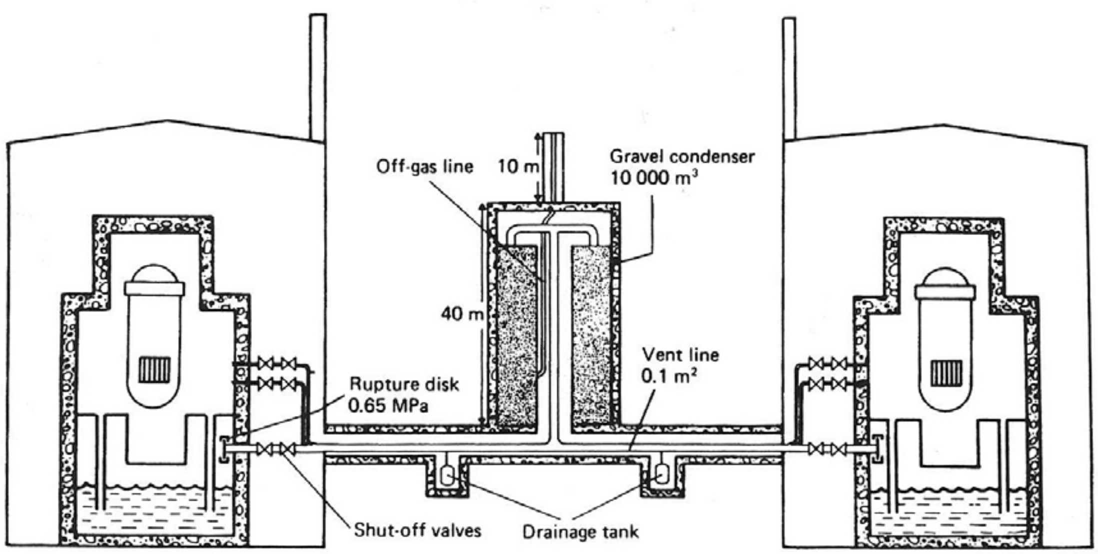


Figure 33. BWR Swedish Filtra venting system.

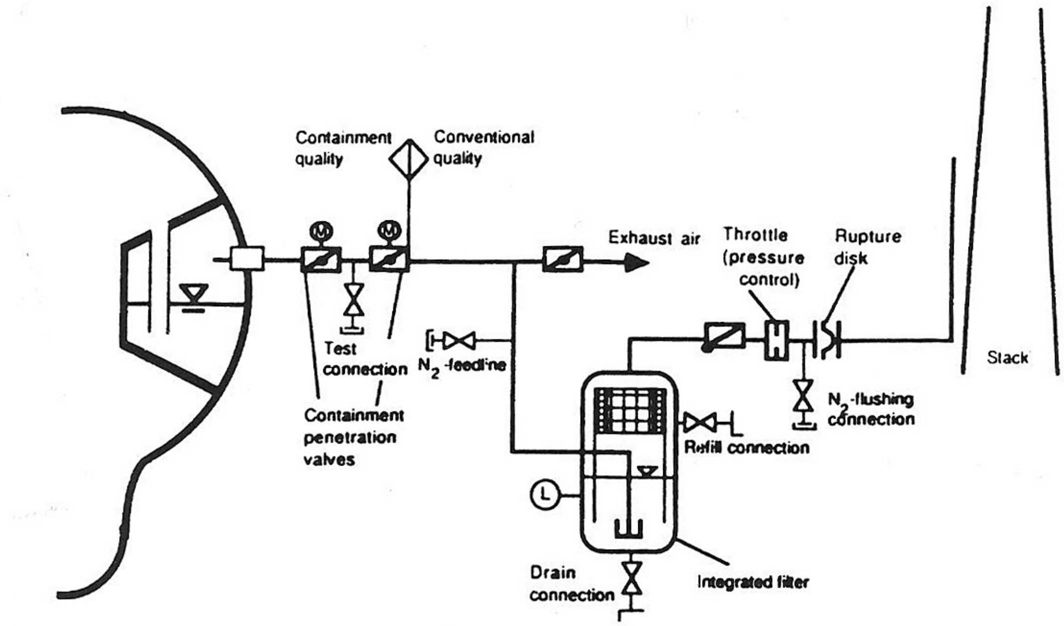


Figure 34. Sliding pressure vent process flow. KWU, Germany.

DISCUSSION

A misconception about nuclear power plants containment structures is that their massive concrete construction is a protection against the release of radioactive products in the case of a postulated accident. Such a task is achieved by the overall containment system as a collection of the "Engineered Safety Features," ESFs not just by the concrete shell alone.

The concrete structures in the existing power plants designs act as insulators against the controlled release of energy to the environment and would eventually fail, if the ESFs fail to perform their functions.

They are being replaced by evolutionary designs that allow heat exchange with the environment, hence avoiding the buildup of pressure in the case of a serious accident and eventual failure to contain the release of radioactivity in a postulated accident.

A suggested more logical location for the pressure suppression pool in BWR reactor designs is above the reactor core. This offers the benefit of providing passive natural circulation convection cooling of the core, upon equalizing the pressure between the core and the pressure suppression pool, without the need for active pumping requiring off-site or on-site power supplies in addition to operator intervention subject to human error. Reactors with the design feature of the water from in the pressure suppression pool below the core should be replaced with more advanced designs providing passive convection cooling using the chimney effect in the core and with a pressure suppression pool positioned above the core.

REFERENCES

1. NUREG-1037, “Containment Performance Working Group Report,” May 1985.
2. John G. Collier and Geoffrey F. Hewitt, “Introduction to Nuclear power,” Hemisphere publishing Corporation, Springer-Verlag, 1987.