

CONTAINMENT STRUCTURES

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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.

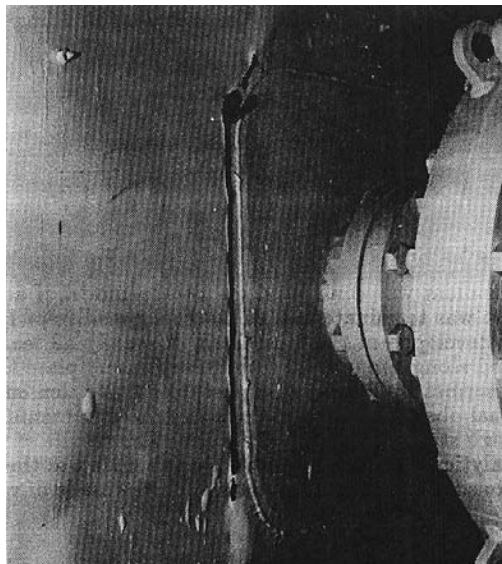


Figure 1. Large 22 in Liner Tear near a containment scale model piping penetration.
Source: Sandia Laboratory.

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.

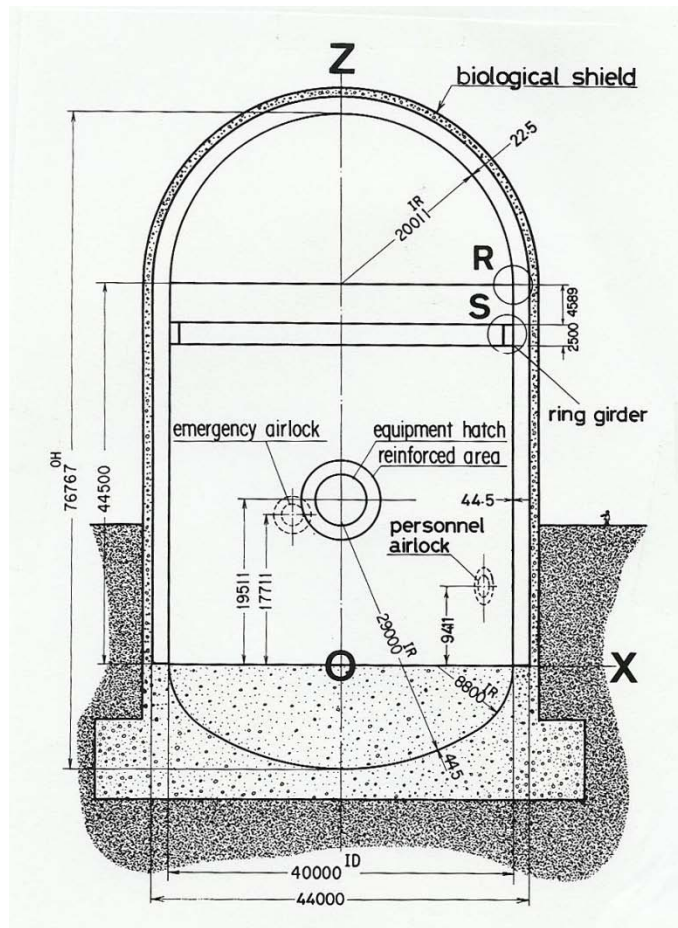


Figure 2. PWR dry steel shell containment surrounded by concrete biological shield.

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.

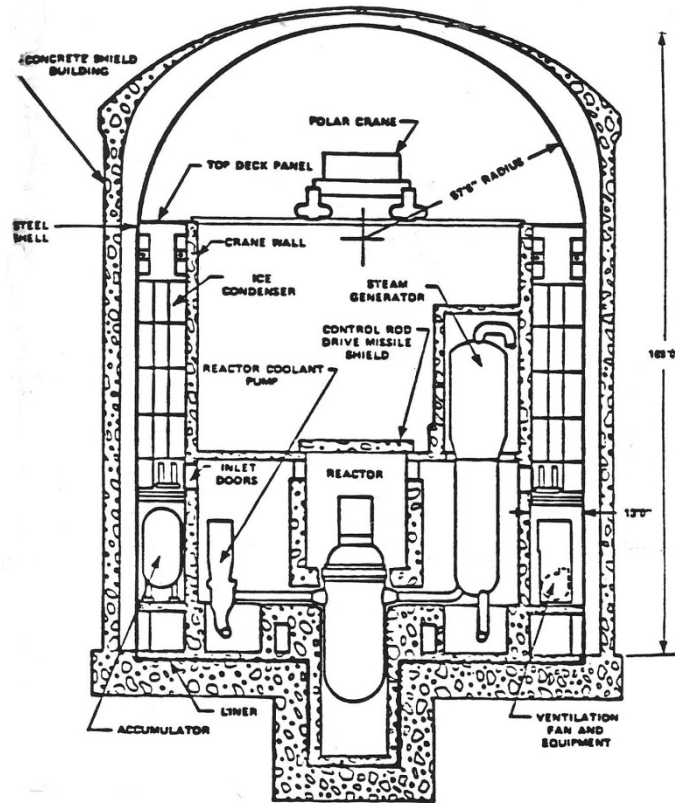


Figure 3. Sequoia Unit 1 PWR ice condenser containment.

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.

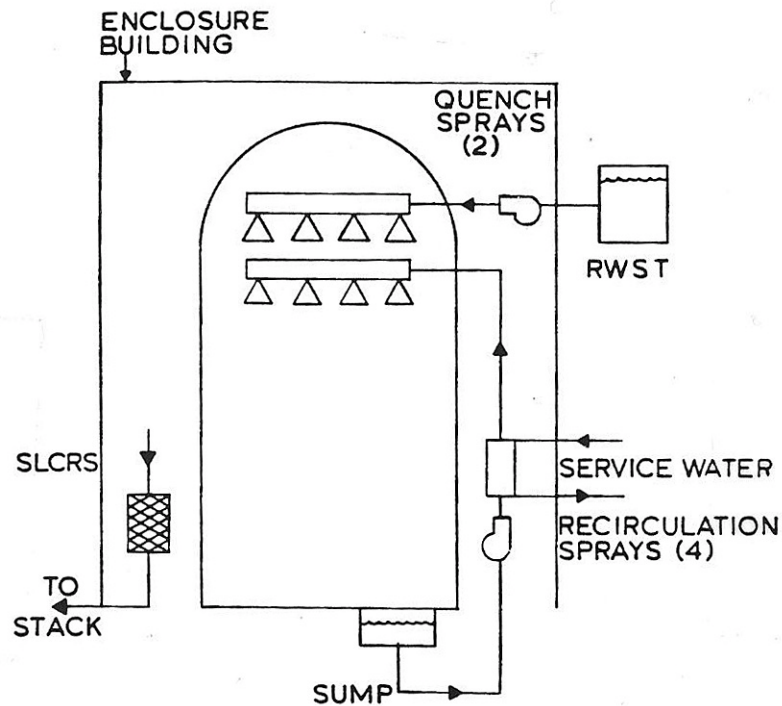


Figure 4. Containment spray and system safeguards components.

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

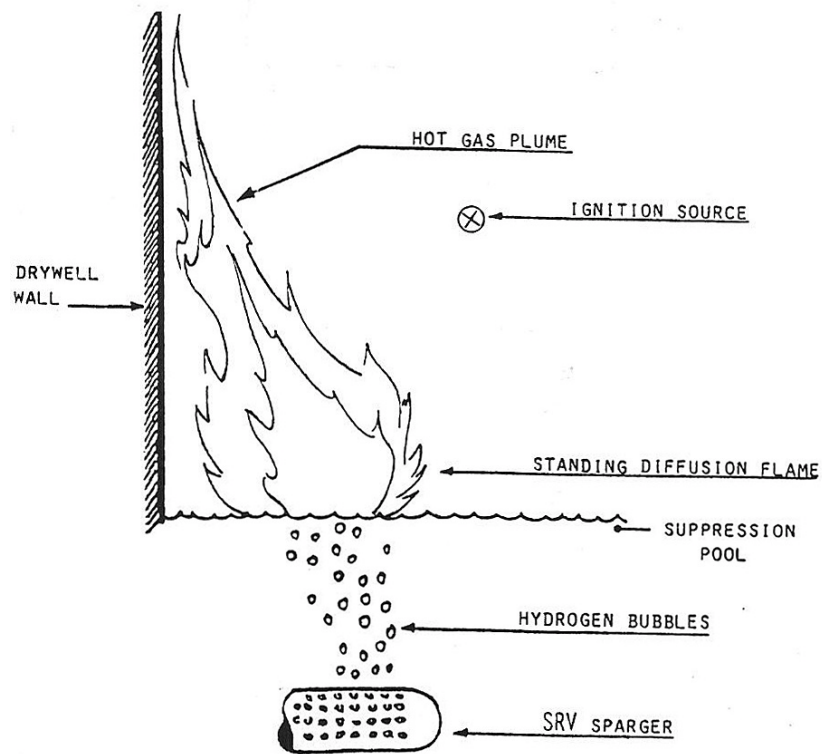


Figure 5. Controlled diffusion flame burning of hydrogen released in a reactor accident.

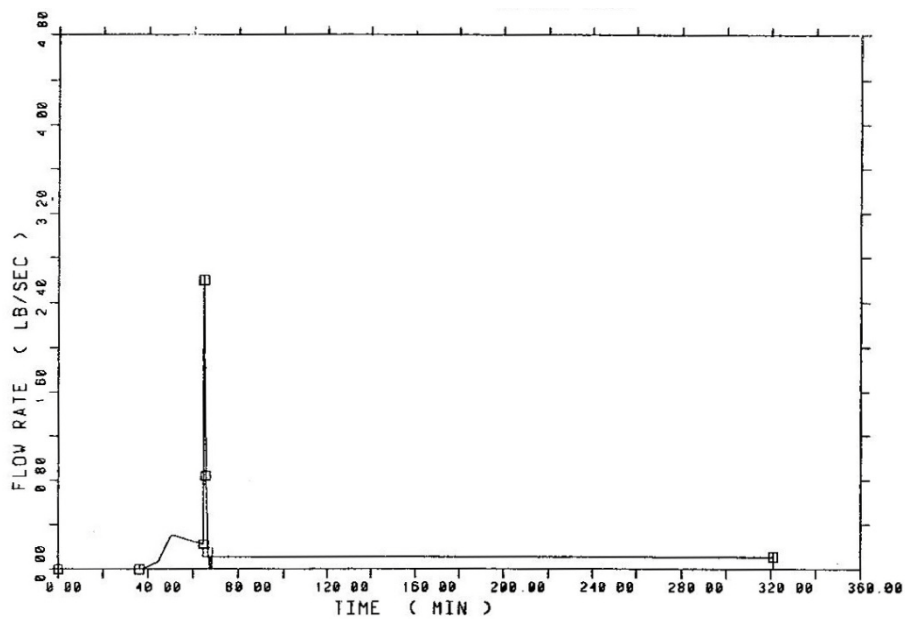


Figure 6. Recorded stress spike from suspected hydrogen ignition at the Three Mile Island accident.

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 °F 70-100 psia 50-70 psia 500-700 °F Quite likely
SP-4, Browns Ferry	Containment capability Upper bound loading Lower bound loading Thermal loads Early failure	132 psia, 330 °F 132 psia in 40 min 132 psi in 2 hrs 500-700 °F Quite likely
SP-15, Limerick	Containment capability Upper bound loading Lower bound loading Thermal loads Early failure, upper bound too conservative	155 psia, 330 °F 145 psia in 2-3 hrs 100 psi in 3 hrs 550-700 °F 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 °F 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 °F Quite likely

NEW 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.

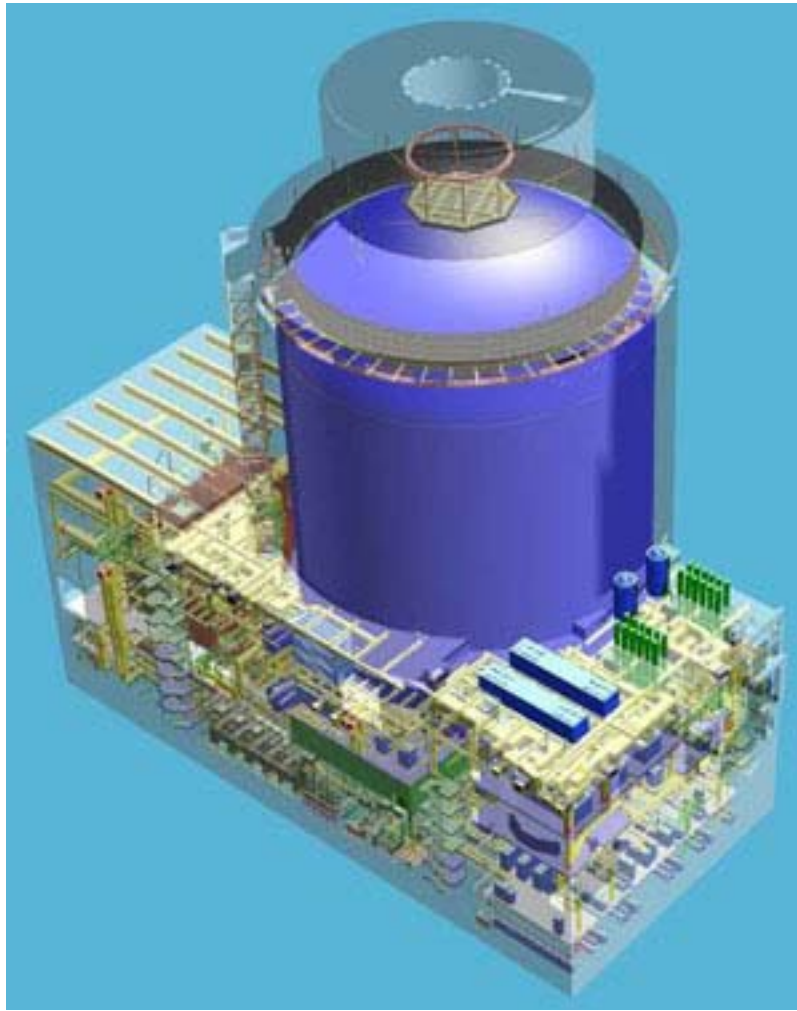


Figure 8. Containment structure of the AP1000 PWR has a gap between the steel shell and the concrete shield allowing natural convection cooling. The cooling is enhanced with a tang on top of it containing a supplemental water coolant supply.

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.

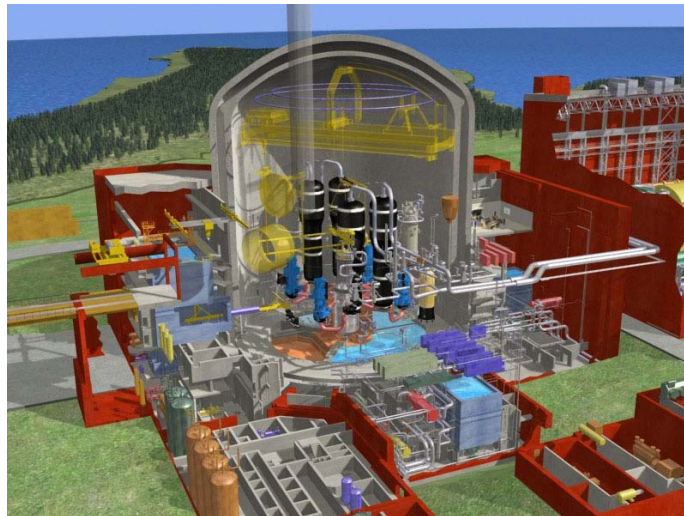


Figure 9. Cutout through the Evolutionary PWR Reactor, EPR pressurized water reactor design showing its double walled containment. Source: Areva.

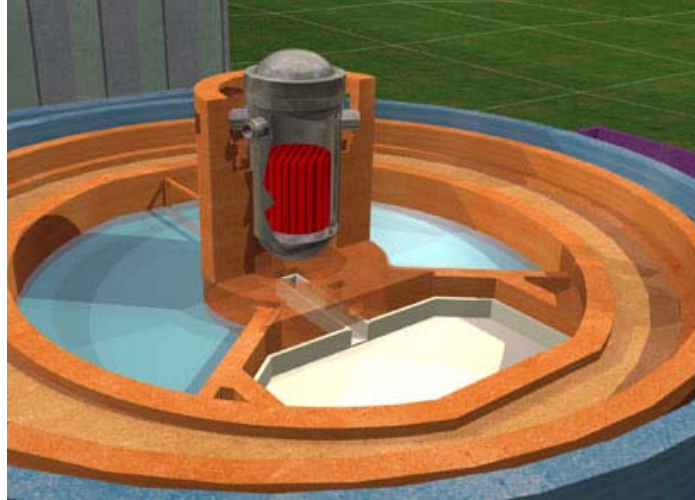


Figure 10. Evolutionary Pressurized Reactor, EPR melted corium retention and auxiliary water storage pools. Source: Areva.

ADVANCED BOILING WATER REACTOR, ABWR CONTAINMENT

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

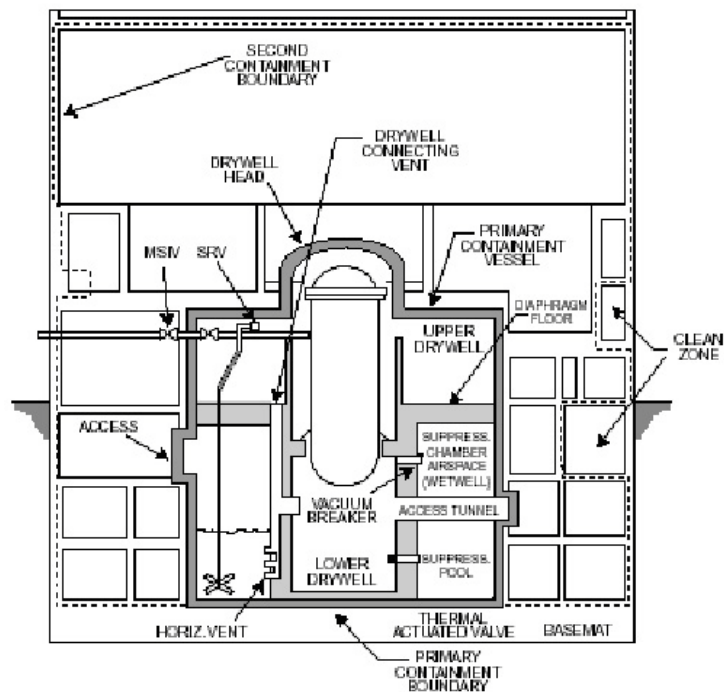


Figure 11. Advanced Boiling Water Reactor, ABWR containment structure. Source: GE.

PWR CONTAINMENT STRUCTURES

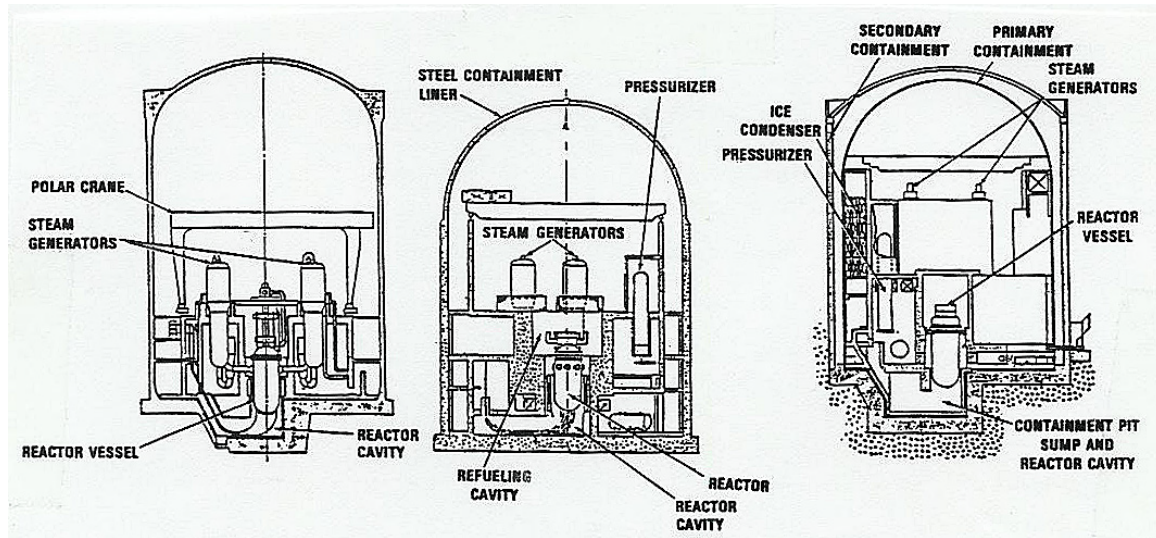


Figure 12. PWR containment systems in the USA: Large dry containment, 78 percent (left), Sub-atmospheric containment, 9 percent (center), ice condenser containment, 13 percent (right).

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

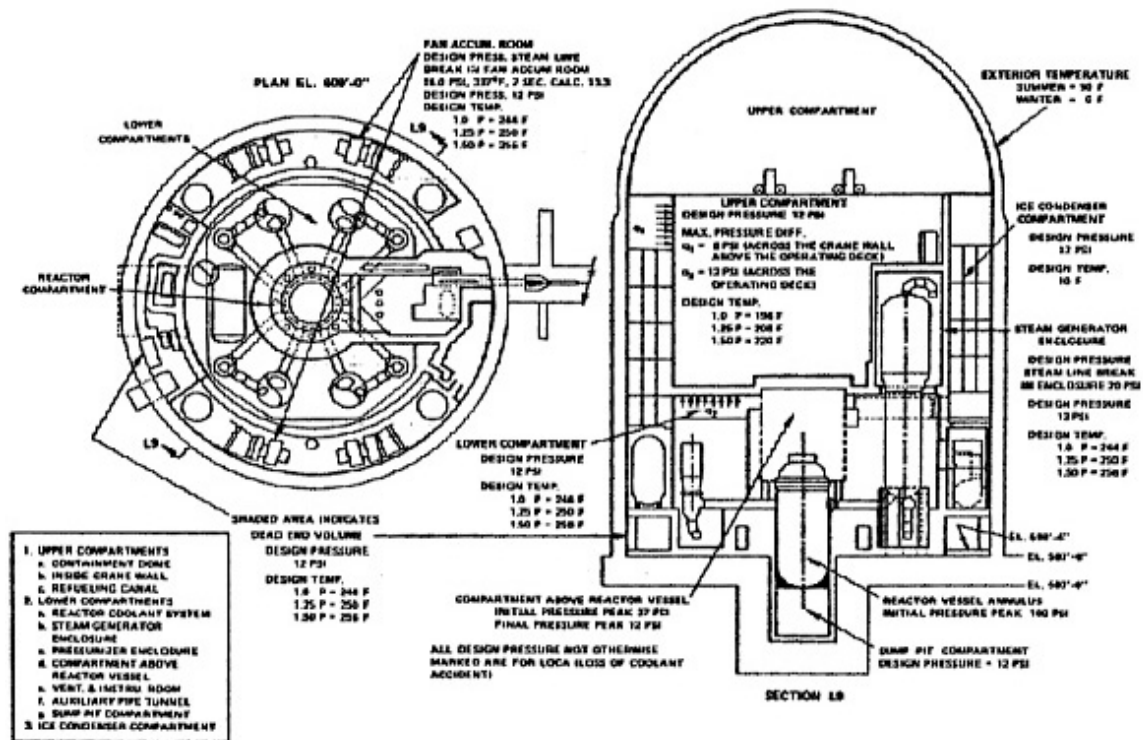


Figure 13. Detail of Ice Containment design. Source: Westinghouse.

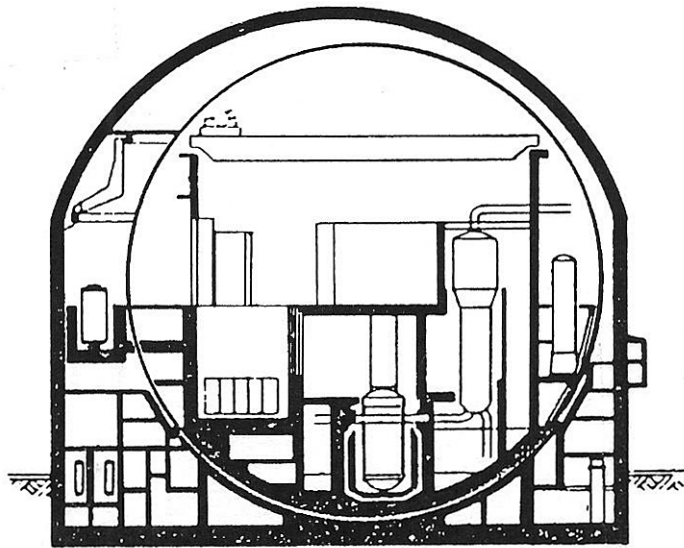


Figure 14. German containment structure for the NPP Goesgen PWR, 920 MWe, design overpressure: 4.9 bar, free volume: 56,000 m³.

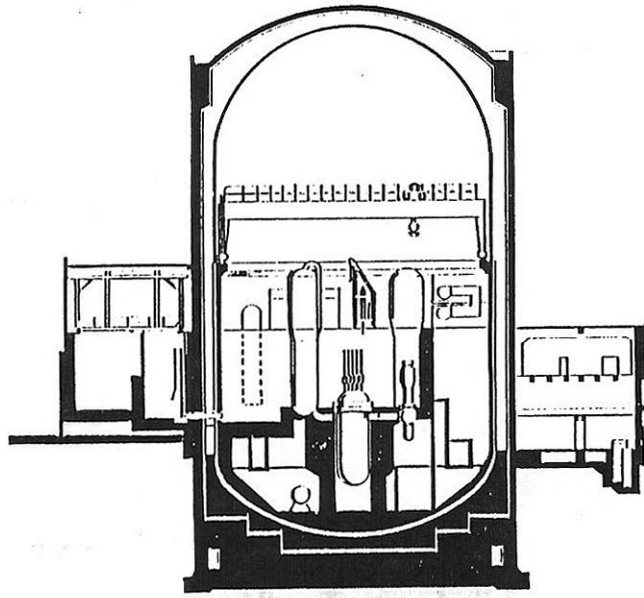


Figure 15. Containment structure of the NPP Beznau PWR, 350 MWe, design overpressure: 2.6 bar, free volume: 37,000 m³.

BWR CONTAINMENT STRUCTURE

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.

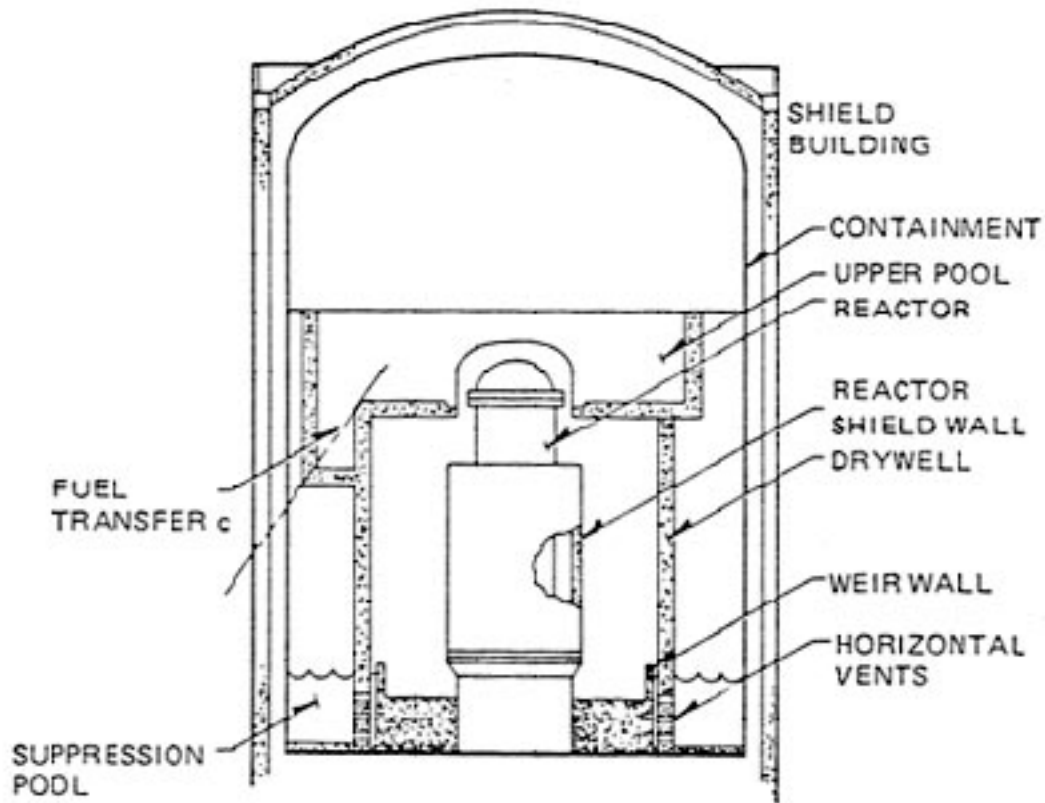


Figure 16. Steel shell and concrete BWR containment structure showing the pressure suppression pool.

The BWR containment structures in the USA are predominantly Mark I steel designs.

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

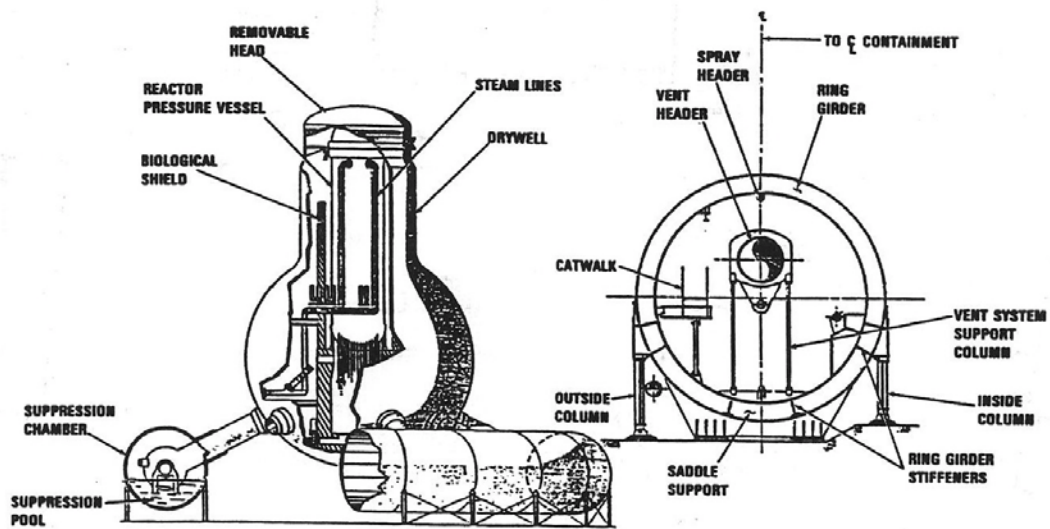


Figure 17. Mark I steel containment design used in 60 percent of USA BWRs.

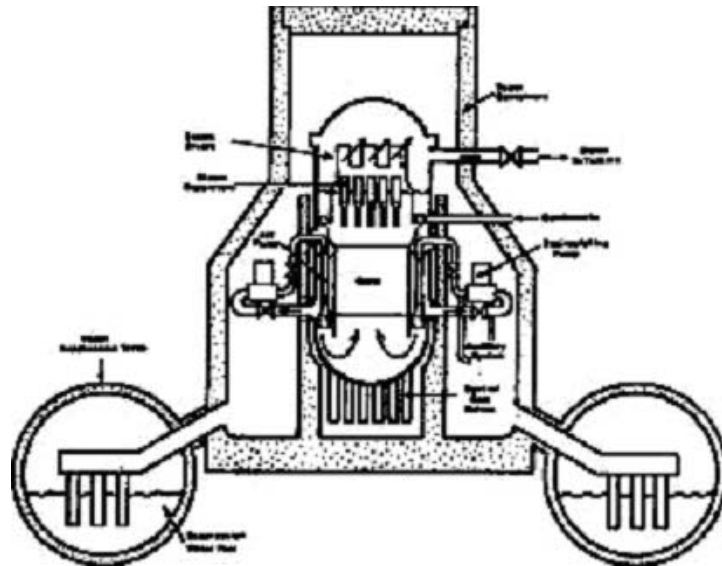


Figure 18. Concrete light bulb BWR containment design.

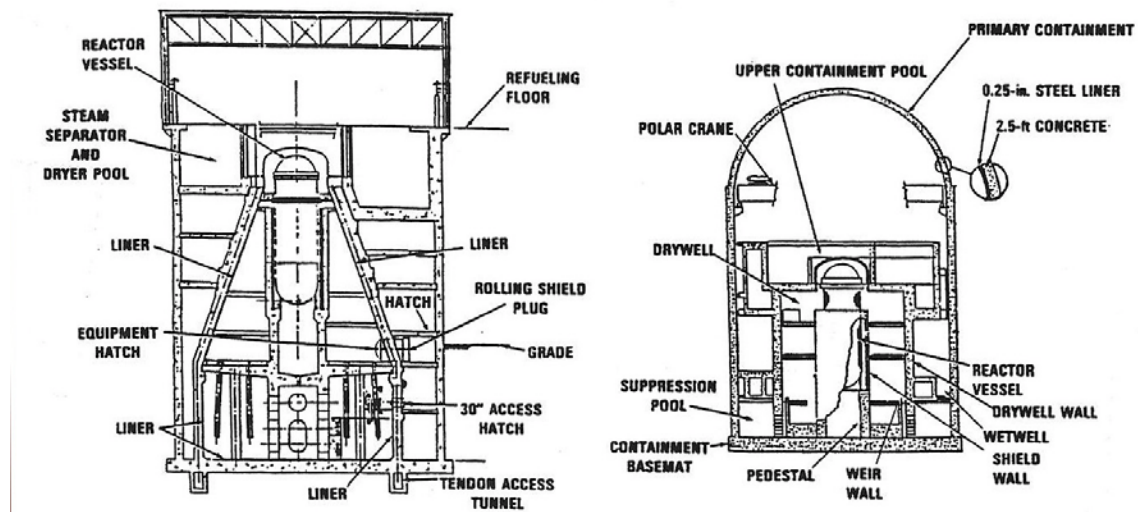


Figure 19. Mark II, left, 16 percent and Mark III, 8 percent containment systems. Source: GE.

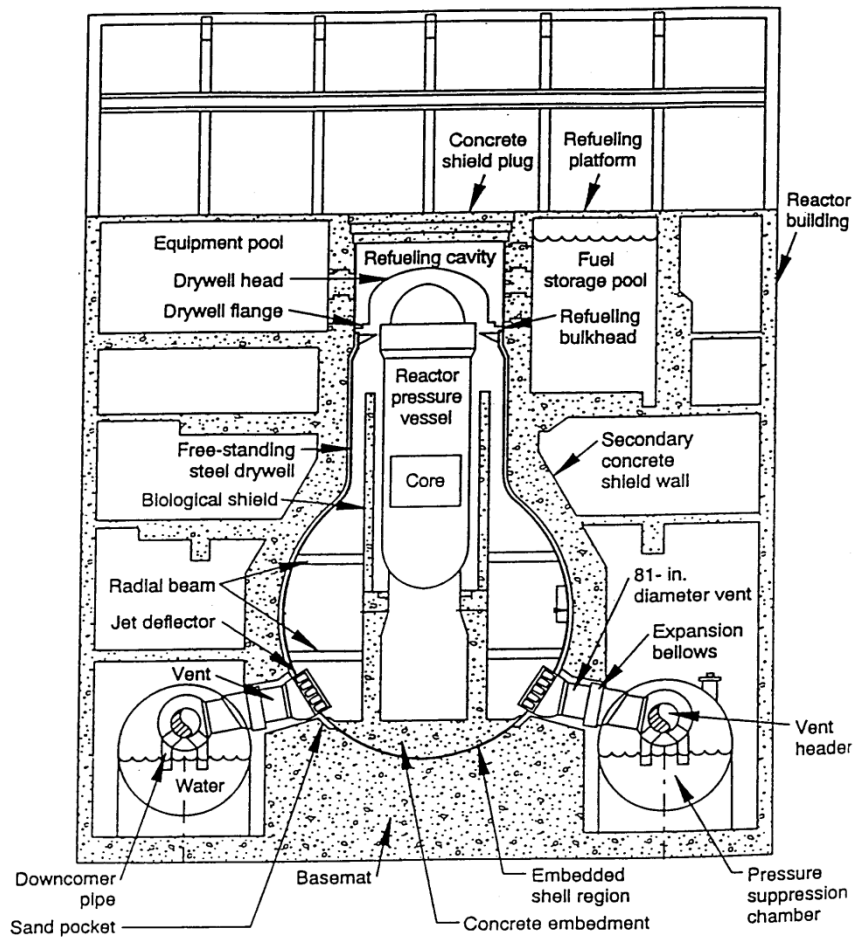


Figure 20. Mark I General Electric, GE BWR Containment. Source: GE.

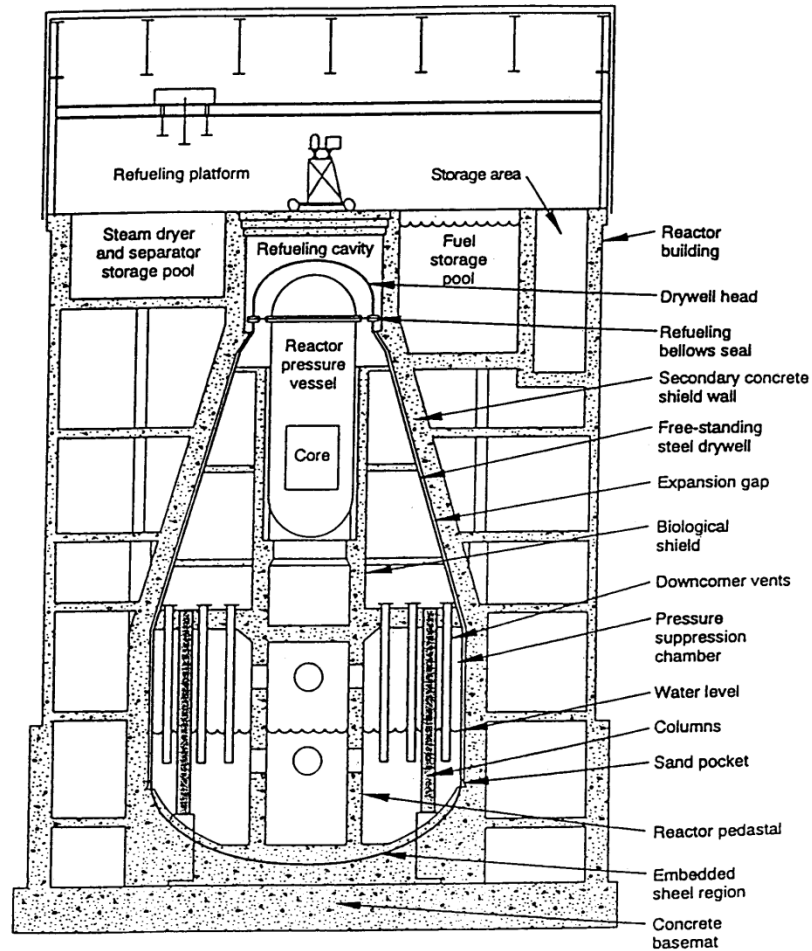


Figure 21. Mark II General Electric, GE BWR Containment. It is suggested that this design is unsupportable through the placement of the pressure suppression below the pressure level. The interaction of molten corium material in the case of a core meltdown would cause a steam explosion event. Source: GE.

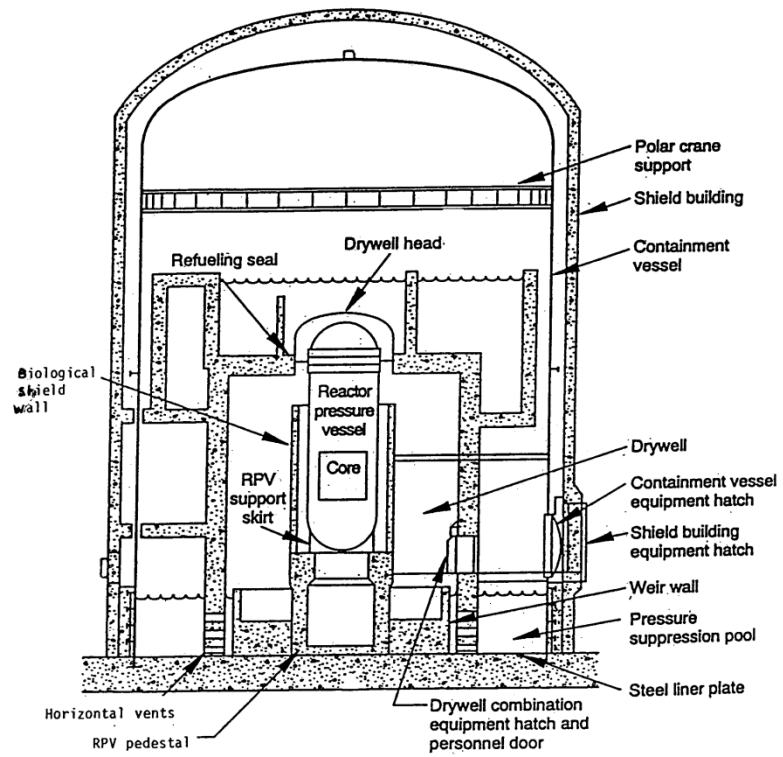


Figure 22. Mark III General Electric, GE BWR Containment. Source: GE.

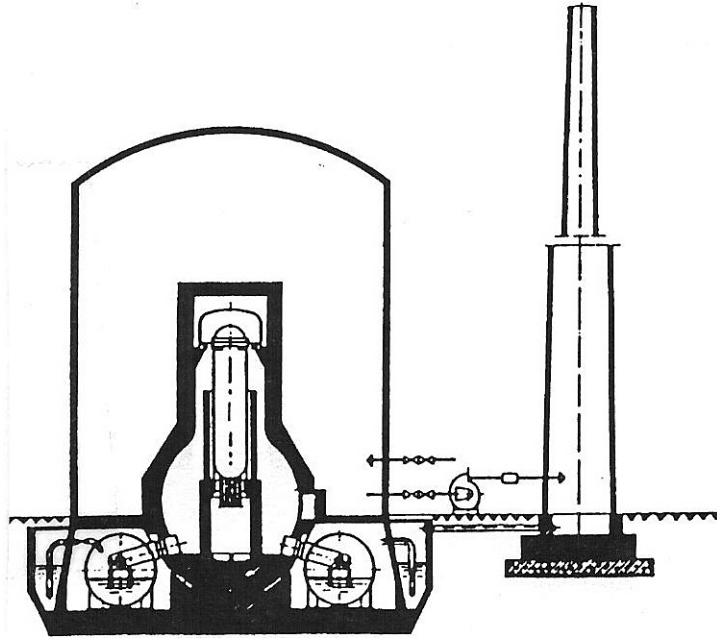


Figure 23. Containment and ventilation system for the NPP Muehleberg BWR, 322 MWe, free volume (dry and wet wells): 5,800 m³, drywell free volume: 3,700 m³, water volume in pressure suppression pool: 2,100 m³, design overpressure: 3.8 bar.

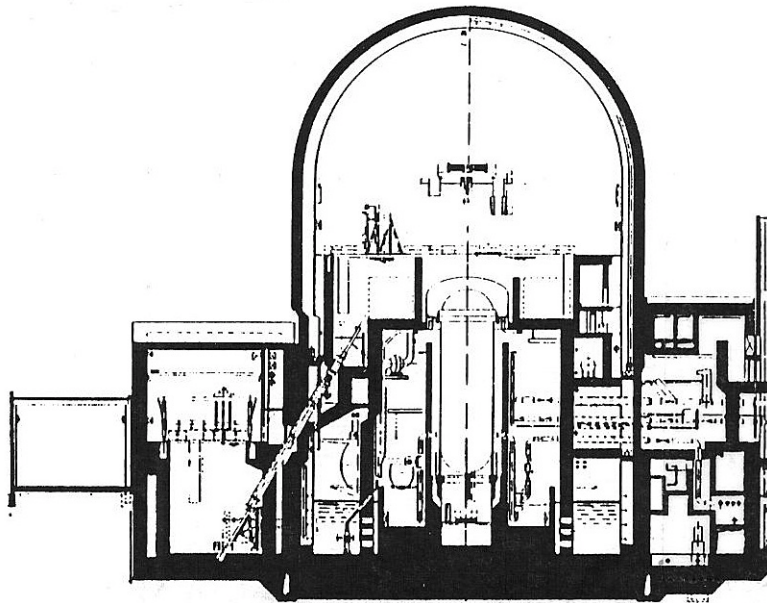


Figure 24. Containment structure of NPP Leibstadt BWR, 990 MWe, free volume (dry and wet wells): 44,000 m³, drywell free volume: 7,770 m³, water volume in pressure suppression pool: 3,760 m³, design overpressure: 1.0 bar.

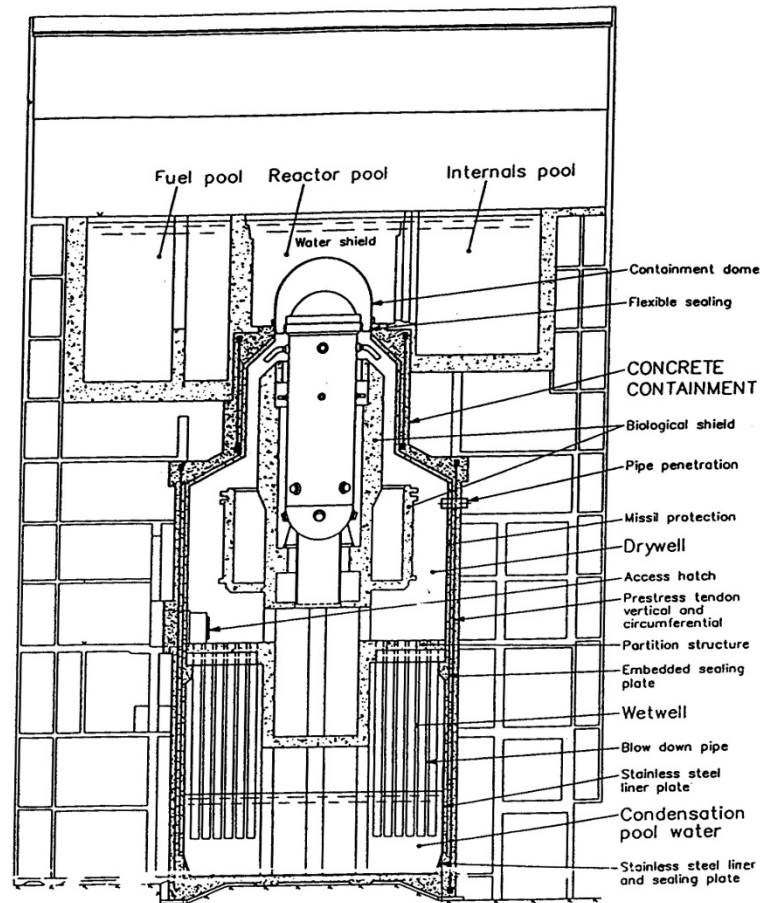


Figure 25. ABB Atom Type I BWR containment design, Sweden.

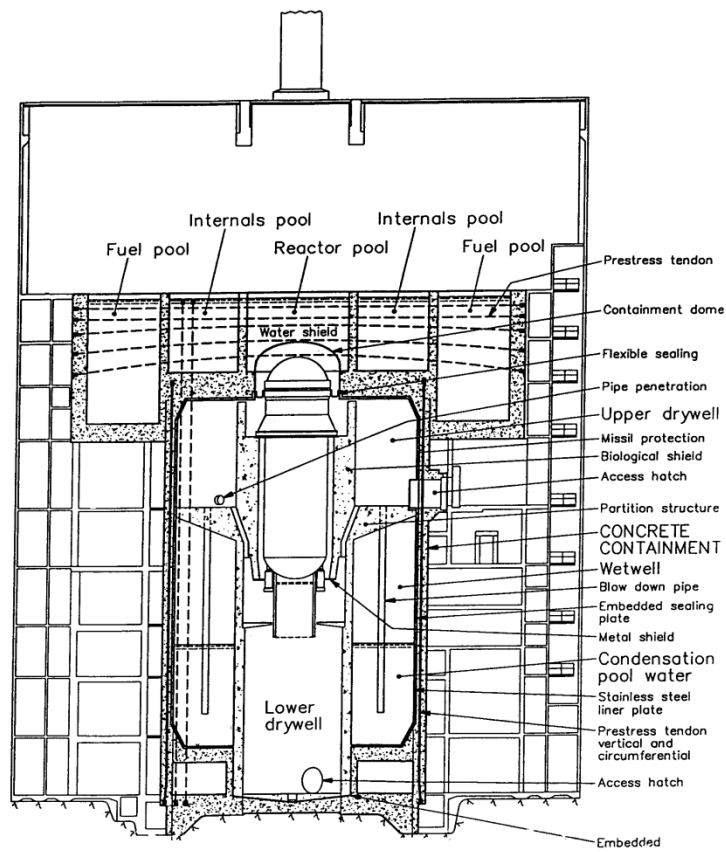
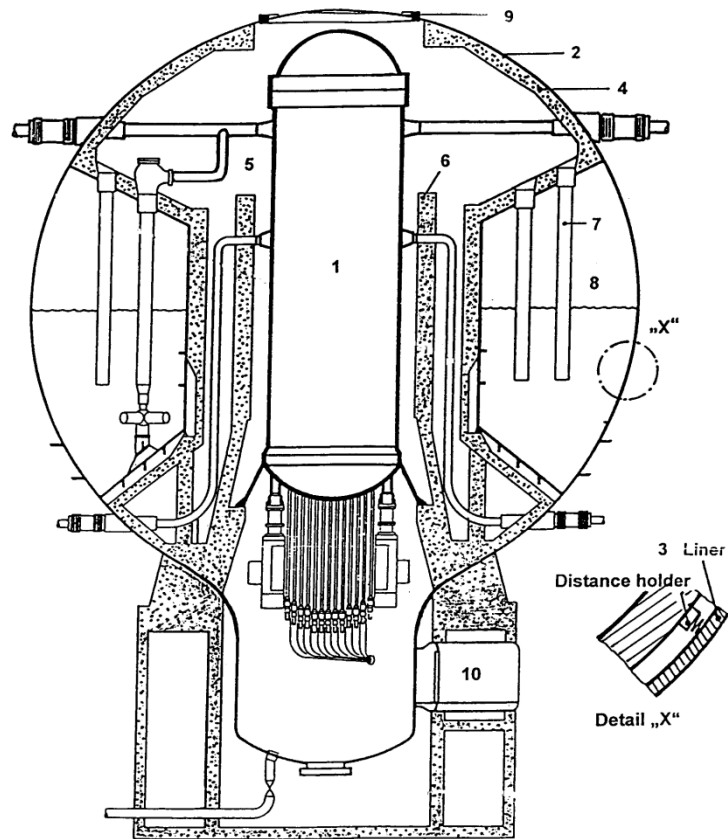


Figure 26. ABB Atom Type II BWR Containment, Sweden.



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

Figure 27. Siemens Kraft Werk Union, KWU Baulinie 69 BWR containment, Germany.

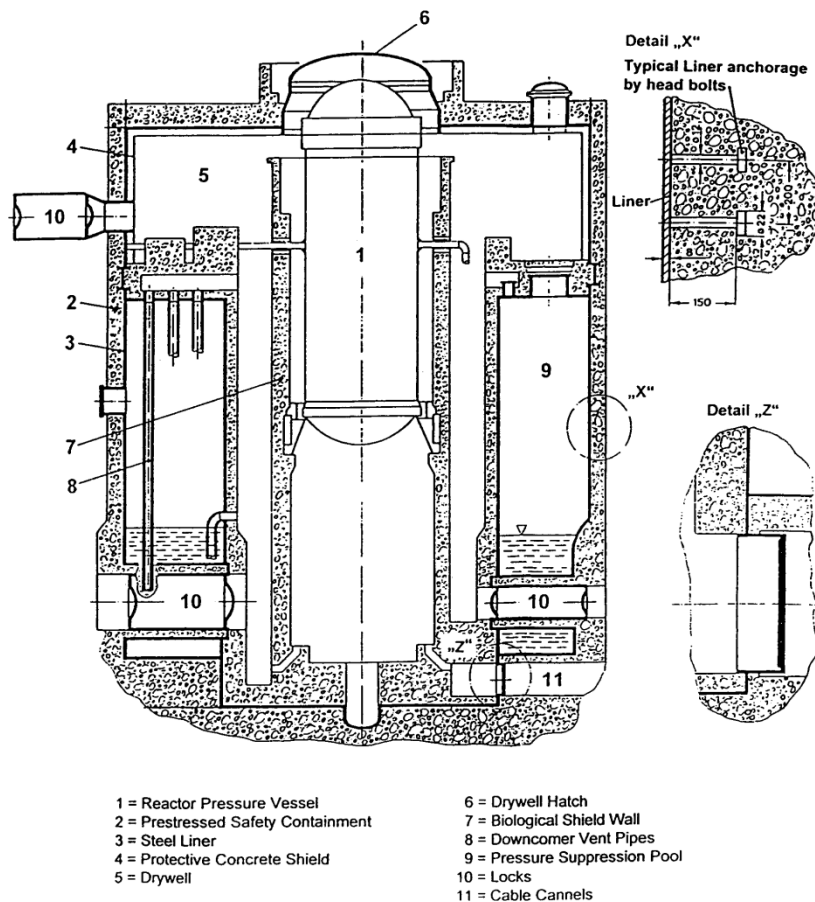


Figure 28. Siemens Kraft Werk Union, KWU Baulinie 72 BWR containment, Germany.

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.

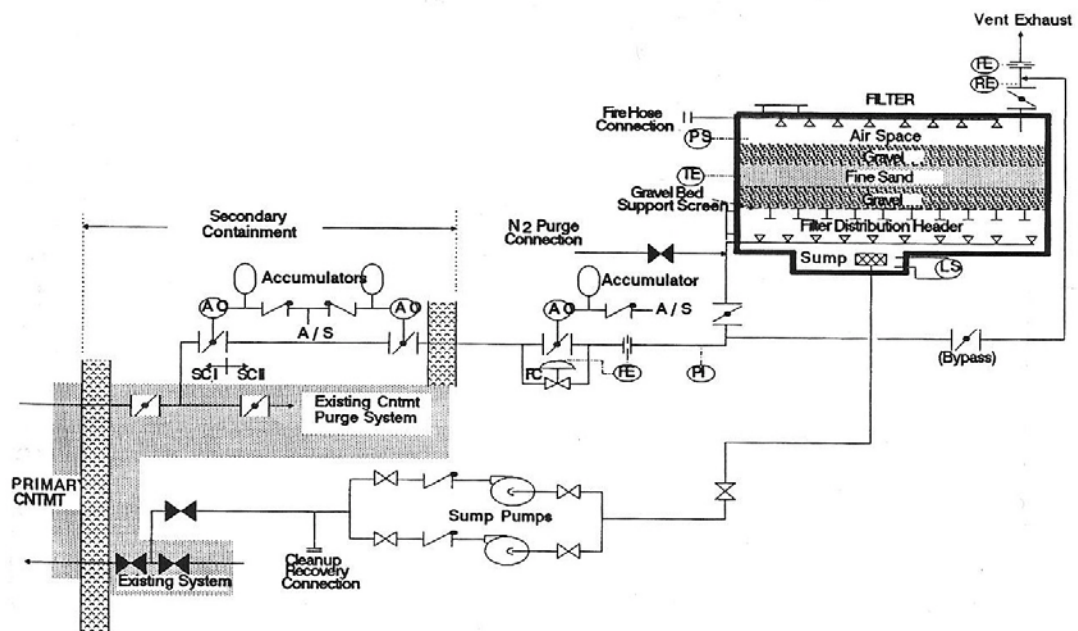


Figure 29. Sand and gravel containment venting system.

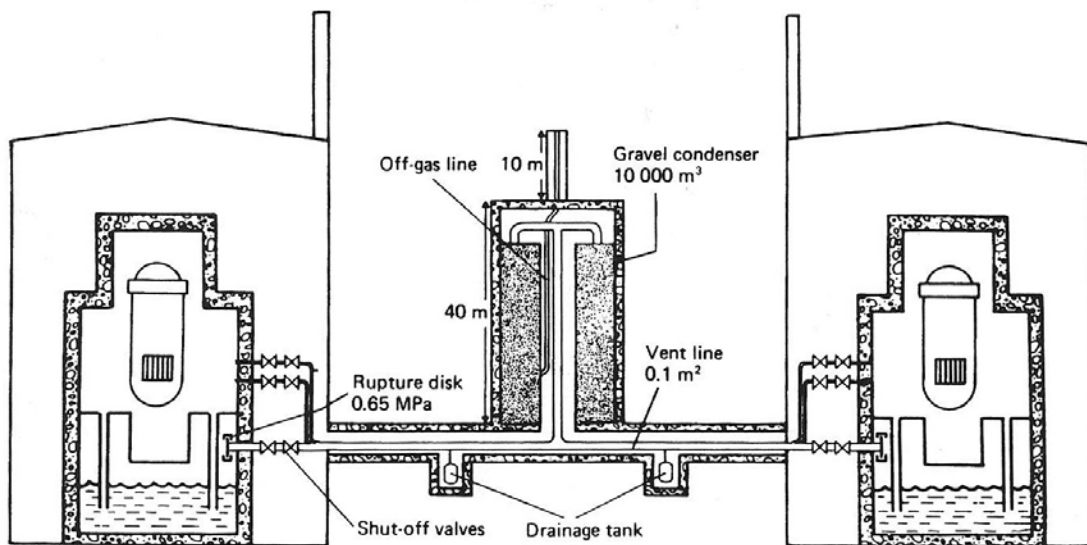


Figure 30. BWR Swedish Filtra venting system.

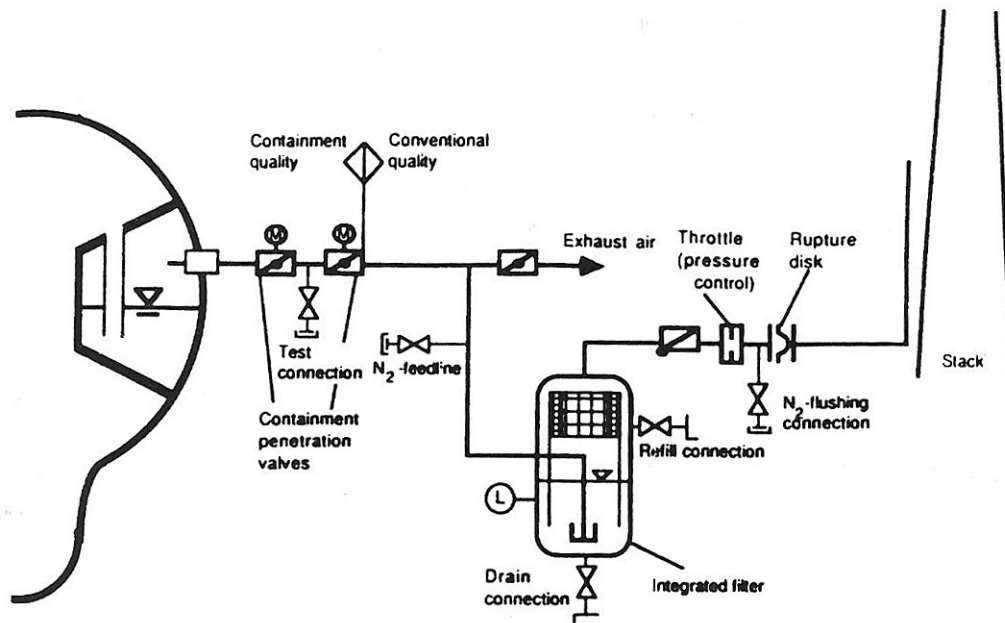


Figure 31. Sliding pressure vent process flow. KWU, Germany.

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.