# CHAPTER 1: DESIGN OVERVIEW

## MODULE A: INTRODUCTION

### MODULE OBJECTIVES:

**At the end of this module, you will be able to describe:**

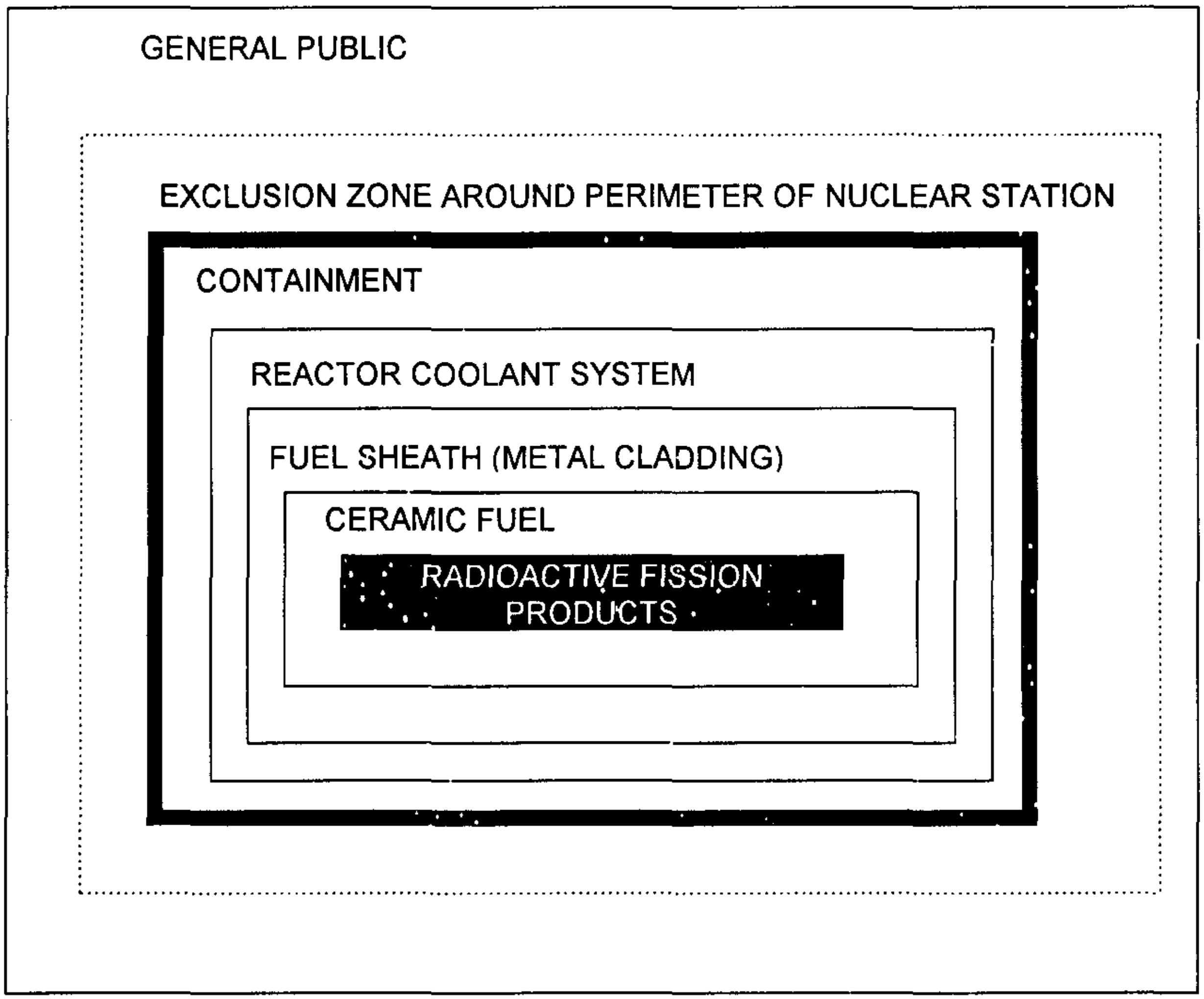
1. **The purpose of containment**
2. **The concept of defence in depth**
3. **The main types of commercial power reactors**
4. **The safety systems that operate during accidents**
5. **Accidents when safety systems operate normally**
6. **Severe accidents when safety systems fail**

# 1.0 PURPOSE OF CONTAINMENT

- **Primary objective:**
- **The IAEA Code of Practice on Design for Safety of Nuclear Power Plants, section 8.1, states:**
- **"To keep the release of radioactivity to the environment within acceptable limits in accident conditions, a system of confinement shall be provided unless it can be demonstrated that the release of such quantities of radioactivity can be limited by other means. This system may include hermetically sealed[leaktight] buildings or boundaries, pressure suppression subsystems, and cleanup installations. Such a system is usually called a 'containment system' and can have different engineering solutions, depending on its design requirements."**
- **Translation: containment keeps radioactivity inside the reactor building during an accident**
- **Secondary objectives:**
- **Radioactive shielding during normal and accident conditions for personnel working just outside containment in adjacent buildings.**
- **Minimize releases of radioactivity during normal operations**
- **Protect reactor against external events, e.g. severe weather, airplane crash**

## 2.0 DEFENCE IN DEPTH

- **Containment is the last of the multiple barriers between radioactivity and the public**



# 3.0 NUCLEAR POWER STATION TYPES

## 3.1 BWR Boiling Water Reactor

- Light water coolant flows directly from the fuel in a pressure vessel to the boilers (steam generators), turbine-generator, condenser and back to the fuel.
- Operates at 7 Mpa
- coolant also acts as moderator
- Slighly enriched uranium fuel

## 3.2 PWR Pressurized Water Reactor

- Coolant flows from the fuel in a pressure vessel to the tube-side of the boilers and back to the fuel.
- A separate circuit carries steam from the boilers to the turbine-generator, condenser and back to the shell side of the boilers.
- If light water coolant: slightly enriched fuel in a pressure vessel at 15 MPa, and coolant also acts as moderator
- If heavy water coolant: unenriched fuel in pressure tubes at 10 MPa, and a cool low pressure heavy water moderator in a vessel enclosing the pressure tubes.
- A heavy water PWR is called a PHWR.
- A BWR or a light-water PWR is called a LWR.
- BWR and PWR are the commonest reactor types.
- A VVER is a Russian PWR

## 3.3 HTR or AHTR High Temperature Reactor

- Slightly enriched fuel is cooled by low pressure gas (Helium, $CO_2$)
- No metallic sheath for ceramic fuel
- Gas then transfers heat to boilers
- Graphite moderator
- Operates at higher temperature than water-cooled reactors
- Considered excellent design, but very few actually have been built

## 3.4 Advanced passive designs (presently under development)

- Further development of PWR, PHWR, BWR designs
- Simpler, larger margin of safety, higher reliability, longer lifetime (60 yrs)
- Easier operation, less need for human intervention, less chance of human error
- Large volumes of water with gravity replacing pumps, and natural convection cooling

## 3.5 Other

- Liquid sodium cooled (fast breeder)
- Water cooled, graphite moderated (RBMK, Russian) has many vertical fuel channels through a graphite moderator. Reactor coolant goes to boilers as in a BWR.
- Focus of this course will be on water-cooled reactors

## 4.0 SAFETY SYSTEMS

**Containment is one of three special safety systems:**

### 4.1 Reactor shutdown (scram)

- **Inserts neutron absorbing rods into core upon detection of potential loss of heat sink**
- **Initiated by:**
  - **High reactor power, high rate of increase of power**
  - **High/Low pressure in main coolant loop**
  - **High pressure inside containment**
  - **Low boiler level, boiler feedwater problems**
- **CANDU has a backup shutdown system as well, injects gadolinium solution into moderator.**

### 4.2 Emergency core cooling system, emergency coolant injection system (ECC, ECCS, ECI)

- **Flushes cold water through the main coolant system in the event of a break to cool the fuel.**
- **Consists of large cold storage tank usually at some height above the RCS, pumps, valves connecting system to main coolant loop, plus instrumentation to detect LOCA.**
- **When tank is empty, water from the sump is recirculated through heat exchangers and pumped back into the RCS.**

**4.3 In addition, the station electrical system may switch to diesel generators if power not availabale from outside nuclear station during an accident**

## 5.0 ACCIDENT SCENARIOS

- Four basic types challenge the containment designer : large break in reactor coolant system, large break in steam piping, very small break in coolant system, severe accident
- Large break in coolant system could release the most radioactivity
- Large steam pipe break could cause the highest pressure, but little radioactivity released
- Very small break could release radioactivity without activating safety systems
- For the moment, assume all safety systems respond as designed to the break.

### 5.1 Large Loss of Coolant Accident (LOCA) (involves large break in an RCS header)

- A pipe break in the reactor coolant system causes sudden depressurization of the coolant loop and rising gas pressure in the reactor building, which trigger three safety systems: reactor shutdown, emergency core injection, and containment isolation.
- Reactor shutdown (scram, trip) in seconds by dropping shutoff rods. Reactor thermal power drops immediately to 7-8% full power, then decays within hours to ~1-2%FP
- Cooling and further depressurization of the reactor coolant system (RCS) in about ten minutes by venting boiler steam, which causes boiler pressure and temperature drop, thus increasing heat transfer from reactor coolant to boilers.
- Emergency coolant injection (or emergency core cooling, ECC) system injects water at ambient temperature from a very large storage tank into the RCS.
- While RCS cools to ~100C, break outflow changes from superheated liquid to subcooled liquid and steam flow into containment from break reduces rapidly

- **Automatic containment isolation on detection of elevated pressure or radioactivity immediately closes off containment penetrations (openings through walls) and stops the normal ventilation system which draws in air from outside and exhausts it through the stack.**

- **Containment pressure rises, atmosphere becomes steamy and hot**

- **Hot water accumulates on the floor.**

- **When the emergency coolant storage tank is empty, hot water from the floor is passed through heat exchangers and pumped back into the RCS.**

- **After sufficient decay of reactor thermal power, boilers are no longer used as heat sink. Residual heat removal system is valved in (connected by opening valves), with heat exchangers cooled by service water.**

- **Containment atmosphere is slowly cooled by condensation on the walls, air coolers, and possibly spray from a containment spray system. Steam condenses.**
- 
- **Water on floor (sump water ) is cooled by ECC heat exchangers.**

- **Eventually (many hours, days) air must be discharged from containment through to maintain unit at or below atmospheric pressure**

- **Only minor release of radioactive fission products from fuel into the coolant if ECC operates normally. ECC is designed to ensure adequate fuel cooling, which means the fission products remain inside the fuel cladding.**

- **No hydrogen bubble will form because the cladding does not get hot enough to react with water.**

## 5.2 Large steam pipe break (involves a large pipe between boilers and turbine)

- For PWRs, no radioactivity in the boiler steam unless there is a leak between the boiler tubes and the RCS.
- Problem is that break outflow is very high energy (superheated initially, later saturated) and very flow high rate, will cause large rapid pressure increase in containment.
- Boiler steam outflow stops within minutes as boiler pressure becomes atmospheric and cold water is injected into boilers.
- Immediate reactor shutdown, containment isolation.
- Only minor accumulation of liquid on floor.
- Containment is cooled and depressurized as with large LOCA.

## 5.3 Smaller breaks in steam or RCS piping

- Longer timescale, multiple indications should betray the leak before safety system activate automatically
- Operator diagnoses problem and manually activates the safety systems.
- Only potential problem is unnoticed release of radioactivity before containment isolation.

## 5.4 Severe accidents - human error, or safety systems fail

- Operations staff may move to seismically-qualified (survives earthquake) secondary control area, a smaller control room with limited control/instrumentation only for safe unit shutdown.
- If reactor cannot be shut down (Chernobyl) and power increases, containment cannot withstand the explosion.
- A brief small overpower before the reactor shutdown systems respond is taken into account in the design and will not cause failure.
- Inadequate fuel cooling causes fuel sheath (cladding) failure.
- Radioactive fission products escape from fuel pellets into coolant and thus into containment through the break
- High concentration of fission products in containment atmosphere, which is at high pressure due to vapour.
- Inadequate fuel cooling overheats metallic sheath enough to make it react with water and generate hydrogen inside containment, which raises pressure further.
- If hydrogen removal systems are inadequate, hydrogen reaches critical concentration and explodes, possibly destroying reactor building
- If fuel cooling problems continue, fuel and reactor vessel internal structures melt and collapse onto floor of reactor building. This is what happened at Three Mile Island.
- Molten fuel and debris react with concrete, releasing noncondensible gases (another pressure rise), fuel melts through concrete and contaminates groundwater.

These situations are what containment must prevent or contend with. They determine the design.

# CHAPTER 1: DESIGN OVERVIEW

# MODULE B: COMPONENTS AND FUNCTIONS

## MODULE OBJECTIVES:

**At the end of this module, you will be able to describe:**

1. **The five major components of a containment system**
2. **How functional requirements are derived**
3. **The major functions that a containment design must perform**
4. **Examples of different ways of carrying out these functions**

# 1.0 COMPONENTS OF A CONTAINMENT SYSTEM

**Accident scenarios require that containment have all the following components:**

**(1) Containment structure and extensions**

- **together with external passive fluid-retaining boundaries form the envelope around the reactor coolant system**
- **Example: the concrete and/or steel outer wall of reactor building**

**(2) Active features**
- **cause the openings in the containment envelope to close when required.**
- **Example: Automatic closure of dampers on detection of high radiation**

**(3) Energy management features**

- **limit pressures, temperatures and mechanical loadings within the containment envelope.**
- **Example: Heat removal by air conditioners**

**(4) Radionuclide (radioactive isotope) management features**

- **reduce the release of radioactivity to the external environment**
- **Example: Charcoal filters that absorb iodine**

**(5) Combustible gas control features**

- **limit the accumulation of combustible gases (oxygen, hydrogen) within containment and prevent uncontrolled combustion**
- **Example: Fans to circulate air and prevent buildup of local hydrogen concentrations.**

# 2.0 FUNCTIONAL REQUIREMENTS

- Further specification of the basic containment design requirement calls for:
    - a numerical value fot the acceptable dose to the public
    - analysis of postulated initiating events (PIEs), i.e. accidents, to see how much radioactivity will be absorbed by the public during the worst possible accident
- Analysis of radionuclide dispersal outside containment (the many paths from containment to the population) sets upper limit on allowed release of radioactivity from containment.
- Accident analysis determines maximum expected rates of energy release within containment. This in turn gives the maximum pressure and the pressure as a function of time.
- The concentration of radionuclides inside the containment atmosphere is also known from analysis as a function of time
- Knowing the allowed maximum release, calculate

  (1) the maximum allowed leakage rate at the design pressure (which will be the maxumum predicted pressure + a safety margin ). This leakage rate will be expressed as a percentage of containment volume per day.

  (2) how quickly, and at what setpoint, containment isolation must occur.

# 3.0 GENERAL FEATURES OF CONTAINMENT DESIGNS

## Structural portion

- Steel or concrete shell that withstands pressure, thermal and mechanical loads
- Interconnected rooms, with barriers that open during an accident to equalize pressure
- Flowpaths for liquid from breaks to sumps on reactor building floor.
- Basemat under the core, possibly with corecatcher, to prevent groundwater contamination if core collapses

## Containment isolation (boxup, buttonup)

- Valves, dampers, seals to close off penetrations through the containment envelope
- Control system(s) to ensure automatic closing when required
- Actuators, electrical, pneumatic systems to move the valves, dampers, etc.

## Monitoring

- **Instrumentation as required to inform the operator about containment status:**
- **Temperature, humidity, pressure, sump levels, moisture, radioactivity, etc.**
- **Status of containment penetrations**

## Energy Management

- **Limit pressures (high and low), temperatures, mechanical loadings < design values on equipment using:**
  - **Pressure suppression pools, ice condensers, vacuum chambers**
  - **Heat sinks in structures, air coolers, sprays, sump cooling systems**
  - **Air extraction system for the annulus (dual containment designs)**
  - **Free volume inside the reactor building (that's why the big empty dome)**
  - **Pressure venting (through filters or scrubbers)**

## Hydrogen management

- Prevent explosion by limiting hydrogen concentrations using:
    - Free volume for dilution
    - Natural or forced convection
    - Smothering hydrogen with inert gases (this is called inerting)
    - Controlled burning
    - Catalytic recombiners

## Radionuclide management

- Limits radiological consequences of an accident:
- Dual containment systems that trap leaks between inner and outer envelopes
- Containment structures on which radionuclides (radioactive fission products) are deposited (plate out)
- Suppression pools which dissolve or entrain airborne particulates or molecular radionuclides during bubbling
- Spray systems that dissolve iodine or particulates ( may be chemically treated for this purpose)

Filters/scrubbers on the system that discharges containment air to outside.

# CHAPTER 1: DESIGN OVERVIEW

# MODULE C: GENERAL DESIGN REQUIREMENTS

## MODULE OBJECTIVES:

**At the end of this module, you will be able to describe:**

1. **Qualification, reliability, maintainability**
2. **Considerations and requirements for containment components**

# GENERAL DESIGN REQUIREMENTS

## 1.0 Performance requires qualification

- **Once the containment design is fully specified, then ask again: can it carry out its functions?**
- **Will it keep design parameters within the required limits during the most severe accidents?**
- **Do the safety systems activate soon enough? Setpoints OK?**
- **Do the safety systems activate during every possible combination of circumstances (adequate trip coverage)?**
- **Will that heat exchanger still have the required capacity after 15 years of operation?**
- **Formal qualification answers these questions systematically.**

## 2.0 Qualification

- **Proves formally that containment will function as intended.**

- **Overall containment function is verified by accident analysis, which calculates temperature, pressure, humidity, forces on walls and floors, etc.**

- **But this analysis may assume that individual pieces of equipment, e.g. valves, function as required despite environment.**

- **Require formal test or analysis of every structure and equipment to prove it can perform as required:**

  **- during accident conditions**

  **- after experiencing the normal operating environment for the lifetime of the plant**

  **- after experiencing the estimated number of operational cycles.**

- **For containment individual equipment, qualification is typically seismic or environmental.**

- **Testing should be done on the actual installed equipment (rather than a duplicate) - if later performance not degraded by testing.**

- **The elaborate computer programs that perform safety analysis must also be formally qualified.**

## 3.0 Reliability

- Will containment function as required all the time?
- Will all the redundant components be available all the time?
- In Canada, probabilistic reliability assessments are permitted by regulatory agency
- 
- Reliability requirements for containment are that unavailability (not function as required) should be < .001 years / year
- Fault tree analysis based on probability of component failure
- Must account for equipment shared between several units

## 4.0 Maintainability

- Are components standard and easily accessible?
- Can personnel work safely on containment equipment?

## 5.0 Containment integrity and penetration requirements

- Requirements for containment structure (outer shell and internal walls)
    - Withstand absolute and differential pressures generated during accidents
    - Withstand temperature gradients and absolute temperatures for the required length of time
    - Withstand dynamic loads: earthquake, pressure from high-speed jet of water from break
    - Will not say anything more about earthquakes (I'm not a civil engineer), see handout for Canadian seismic design requirements if interested.
    - Withstand missiles (in the context of containment analysis, this means anything that is thrown at high speed) e.g. turbine blades that fly loose when the turbine overspeeds.
    - Acceptable leakage rates during accident conditions
    - Leakage through microscopic cracks in concrete will occur (steel or epoxy liner should prevent this)

- Penetration definition:

"an opening in a containment structure, or the device that penetrates the containment wall and seals the opening"

- Extensions of the containment envelope are defined as:

"structural components which extend from the containment structure and are attached to the device penetrating containment"

- Considerations:

  - There may be hundreds of containment penetrations - ducts, pipes, personnel airlocks, electrical cables, hatches, equipment airlocks, closed-off spare penetrations, instrumentation..

  - Some opened only for maintenance or construction

  - Some normally open for cooling water flows (service water) and must stay open during accident conditions

  - Some open only for infrequent operations, e.g. sampling, and must close during buttonup.

  - Some very large, e.g. the main steam lines from boilers to turbine

  - Some essential safety systems, e.g. emergency power supply, possibly ECC must not be isolated

  - Real danger of an unnoticed open penetration - happens too often!

General requirements for penetrations and extensions

- Penetrations must withstand same dynamic loads, temperatures, pressures, radioactivity as containment structure itself

## Specific requirements for different penetration types

- At least two barriers for each penetration (some exceptions permitted for small instrumentation lines), one barrier inside containment envelope, the other outside
- Usually seismically qualified barriers
- Valves/dampers must be remotely and automatically operated, if they are not normally closed, and they communicate with RCS or containment atmosphere
- For pipes/ducts, this means two valves/dampers in series, as close to containment boundary as possible, except for very small instrument lines.
- Independent reliable actuators for each member of the pair of valves/dampers
- A check valve that depends only on system pressure for closing is NOT considered an acceptable automatic isolation device
- For personnel/equipment airlocks that are usable when plant is running, this means an interlocking double-door system
- At least two personnel escape routes must be available

**Examples of implementation:**

- **Note that containment buttonup logic is not the only logic that closes penetrations. Some penetrations may be closed by ECC logic. Or there may be instruments/logic independent of containment and ECI logic for a particular penetration.**
- **ECC logic automatically closes lines penetrating the envelope when LOCA detected**
- **High atmospheric radioactivity levels automatically closes lines communicating with containment atmosphere**
- **High sump activity automatically closes penetrations communicating with the sump**
- **Penetration lines directly connected to the RCS (e.g. main steam lines in a BWR) are automatically closed upon high radiation in those lines.**

6.0 Automatic containment isolation system (boxup, buttonup)

- Manual remote activation of containment isolation system by operator
- Automatic activation of containment isolation system when instrumentation detects accident condition
- Indication of containment isolation system status in control room
- Instrumentation independent of other systems that measure the same parameters, e.g. ECC, reactor trip (scram) logic also measure reactor building pressure. Do not try to save money by sharing equipment between safety systems!
- Channelized logic - at least two independent sets of identical instruments, relays, alarm contacts, actuators etc. Require 1/2 or 2/3 channels detecting a problem to initiate isolation.
- Signals to trigger isolation
  - High containment pressure, (a few kPa above normal)
  - High radioactivity in atmosphere or sump water
  - High containment temperature

## 7.0 Leak test requirements

- **Entire unit**
  - **Test required during construction, as soon as all penetrations are complete**
    - **Measure leak rate at design over- and underpressures, including peak expected pressure.**
  - **Required periodically while unit is in service (during maintenance outage)**
    - **Measure leak rate at a value of pressure that permits extrapolation to the design basis pressure.**
- **Individual isolation devices and penetrations**
  - **Must be possible to do periodic in service tests**
- **Functional tests of containment isolation**
  - **Must be able to confirm operation of containment isolation devices, e.g. adequate damper closing times, by periodic tests**
  - **Must be able to test control logic and instrumentation for buttonup system using methods similar to those used to test other channelized safety systems**

## 8.0 Hydrogen and oxygen control requirements

**Considerations:**

- **$H_2$ and $D_2$ (deuterium) and $O_2$ are created by radiolysis of water by gamma rays**
- **Normal production rate proportional to reactor thermal power**
  - **Always present in main coolant loop, outgas (emerge from solution) in cover gas above pressurizer or in boilers of a BWR**
  - **Always present in cover gas of CANDU moderator (more intense irradiation)**
  - **Usually a removal/recombination subsystem in main coolant loop and moderator**
  - **May also be outgassed in sump after LOCA**
  - **Not the major expected source**
- **H2/ D2 from interaction between very hot steam and metal**
  - **Major expected source of hydrogen**
  - **Only if inadequate fuel cooling, not expected if ECC functions normally during LOCA**

**Requirements for hydrogen and oxygen:**

- **Monitoring or sampling system within containment**
- **Must have active or passive methods of control - except for rooms that can withstand explosion**
  - **Passive methods**
    - **Dilution in free volume**
    - **Pre-inerting (inert gas always fills closed containment volume around core)**
    - **Natural convection, unimpeded by barriers between rooms, through floor grates**
    - **Catalytic recombiners (no power supply needed)**
  - **Active methods**
    - **Forced convection by fans**
    - **Post-inerting (inert gas is injected into containment during accidents**
    - **Igniters**

## 9. Instrumentation requirements

**Considerations:**

- **Must allow monitoring of situations that could lead to release of radioactivity or possible containment impairment. This leads to requirements for instrumentation, must detect:**
    - **Rapid release of high-energy fluid**
    - **Slow leakage of high-energy fluid**
    - **Radioactive gas, particulate or liquids**
    - **Component failure, e.g. airlock deflation**
    - **Containment penetration status**
    - **Buttonup system status**
    - **Fire**

**Required sensors for containment monitoring:**

- Temperature - atmosphere and sumps
- Pressure
- Humidity (dewpoint)
- Water levels in sumps
- Water accumulation in normally dry places - e.g. air cooler drain lines
- Gas flows and pressure differences between rooms (indicate leak into containment)
- Analysis (on-line by microprocessor) of flow/pressure/temperature in containment volumes to detect unsuspected opening in containment envelope.
- Radioactivity in atmosphere - or deuterium or tritium in unexpected places
- Chemical analysis of drains
- Noise and vibrations - sensors attached to large pumps
- Fire
- Visible problems - camera may show steam from break

## 10. Radionuclide management system requirements

- Require conservative estimate of release within containment, with conservative assumptions about plateout (deposition on surfaces) and desorption (detachment from surface after plateout) on containment internal surfaces.

- Containment spray

    - Adequate spray duration, coverage, drop size, drop residence time for dissolving or entraining radionuclides

    - Adequate chemical additives (hydrazine, NaOH, sodium thiosulfate) in spray
        - initial radionuclide removal from atmosphere
        - subsequent retention in the sump liquid over the very long term
        - Particular attention to iodine (high biological activity)
        - Must consider sump and radionuclide chemistry

    - Inadvertent spray
        - Low probability
        - Not damage equipment
        - Chemical additives may be corrosive to electrical equipment

- **Containment ventilation and venting**
  - **Post-accident venting may be through the normal stack filter, or through a qualified emergency filtered discharge system.**
  - **If the venting is through the usual stack filter, this filter must be designed so that it is not loaded with pollutants before it is needed in an accident.**
  - **During an accident, filters could be clogged by water droplets, or by condensation inside the filter pores. Must therefore have demisters (moisture separators) or preheaters.**
  - **Must prove the efficiency of the iodine adsorption material in the filters by in situ tests**

- **Leakage from recirculation systems**
  - **Recirculation heat exchangers for the ECC or containment sprays may be outside containment**
  - **May be leakage from valves, pumps, heat exchangers, etc. Require provision to prevent release, e.g. collection lines from valves.**

## 11. Energy management systems

- Passive systems as far as possible
- Base design on conservative estimates of energy release
- Will discuss detailed requirements after describing containment designs

## 12. Miscellaneous considerations/requirements

- Recovery after accidents
  - Facilitate cleaning of surfaces, disposal of contaminated liquid and vapour
- Decommissioning
  - Avoid easily activated materials in construction
- Power supplies
  - Suitable reliability and redundancy as for any safety system
- Coating of reactor building interior wall/liner surface
  - Epoxy should not peel or flake and block filters/strainers
- Design to prevent accumulation of debris that could block of intake of recovery/recirculation pumps

# CHAPTER 1: DESIGN OVERVIEW

## MODULE D: SPECIFIC CONTAINMENT DESIGNS

### MODULE OBJECTIVES:

**At the end of this module, you will be able to describe:**

1. **Describe the major types of containment design**
2. **Describe trends in containment design**
3. **Describe design requirements specific to these types**
4. **Magnitudes of typical containment parameters**

# 1.0 OVERVIEW OF CONTAINMENT DESIGNS

## General types:

- RBMK non-containment
- PWR dry containment
- PWR subatmospheric containment
- PWR full-pressure double-walled containment
- PWR ice condenser containment
- PWR bubbling condenser containment
- BWR pressure suppression containment
- Pressurized containment
- Negative pressure containment
- Advanced passive containment (future)

## 1.1 AGR, HTGR, AHTR Gas-cooled reactors

- **Totally different containment requirements**
    - **No high-energy coolant fluid escape although operates at high temperature**
    - **gas is low pressure and leaks out slowly**
    - **No Zircaloy fuel cladding to generate hydrogen**
- **Problem is keeping air out to prevent graphite burning**
- **Can't use water spray on graphite (explodes), spray must be on external walls**
- **Current designs have thick prestressed concrete vessels to prevent air ingress (inflow)**

## 1.2 RBMK

- **No outer shell, just multiple compartments, <u>no containment</u> of the type required by IAEA**
- **Inert gas circulated in sealed compartment around graphite-moderated core**
- **Bubble condensers for pressure suppression.**

## 1.3 PWR dry containment

- Cylindrical or spherical steel structure, or concrete shell with steel liner
- Energy management by
  - air coolers and/or sprays,
  - large free volume
  - heat absorption by structures
- Spray system shares large tank (outside containment) with ECC
  - Recirculation of ECC and spray from sump during LOCA after tank empty
  - Recirculated flow to coolant system may be cooled by heat exchanger
  - Recirculated flow to spray headers usually cooled by heat exchanger
- HEPA (high efficiency particulate) filtered discharge system

## 1.4 PWR subatmospheric containment

- **Similar to PWR dry containment**
- **Maintained at slightly subatmospheric pressure during normal operation by ventilation system**
- **Larger capacity spray system, larger capacity HX in recirculation spray circuit**
- **Containment pressure soon returns to subatmospheric after accident**

## 1.5 PWR full-pressure dual containment

- Many current nuclear stations
- Steel or concrete inner shell (the containment boundary)
  - Encloses reactor coolant
  - Withstands any accident without pressure suppression
  - Designed as air-tight, pressure resistant
- Sump water cooling with ECCS heat exchangers
- Outer concrete shell (secondary confinement) surrounding the inner shell
  - Encloses ECCS, safety systems
  - Radiation shielding for personnel during normal and accident situations
  - Protects equipment in secondary confinement from external accidents (weather, airplane crash, etc.)
  - Prevents leakage from inner shell from reaching environment
- Air extraction system for region between shells (annulus)
- Discharges filtered air through stack

## 1.6 PWR ice condenser containment

- Cylindrical, with three <u>normally isolated</u> compartments
- Lower compartment:
  - reactor coolant system
  - spray system using tank, later, when tank empty, recirculation through heat exchanger
- Middle compartment:
  - chambers containing borated ice in baskets. Boron absorbs neutrons and halts reaction
- Upper compartment
  - main free volume
- High pressure in lower compartment is vented through doors to the ice rooms into the upper chamber.
- Steam is condensed on ice, which eventually melts, and other cooling methods must be used in long term.
- Underpressure is possible in any containment system with isolated compartments. Steam pushes the air out of the compartment where the break occurs, later the steam condenses and pressure falls.

## 1.7 PWR bubbling condenser containment

- Cylindrical, with <u>three normally isolated</u> compartments
- Lower compartment:
  - Reactor coolant system
  - Passive spray system using tank in upper compartment
  - Active spray system with pump and tank outside containment
  - Recirculation through HX back into active spray headers
- Middle compartment:
  - Multiple small suppression pools (bubbling condensers)
- Upper compartment:
  - main containment free volume
- High pressure in lower compartment is vented through the bubbling condensers into upper chamber.
- Sprays in lower chamber very quickly reduce pressure to subatmospheric
- Gas in upper chamber cannot flow back to lower chamber through water seals in condenser tubes

## 1.8 BWR pressure suppression containment

- **BWRs must have pressure suppression because steam from boilers must stay inside containment during an accident.**
- **Confinement encloses inner containment shell**
- **Subatmospheric normally and during most of accident scenario**
- **Two compartments inside containment, normally isolated: dry and wet wells**
- **Dry well**
    - **Reactor coolant system**
    - **Possibly a spray system**
    - **Free volume of reactor building**
- **Wet well**
    - **Annular (ring-shaped) pool of water surrounding bottom of dry well**
    - **Pipes from dry well lead to bottom of pool**
    - **Possibly a spray system**
- **High pressure steam from dry well is forced through water in wet well, where it condenses**
- **Wet well also used for normal operation: automatic pressure relief from main coolant loop when steam must bypass turbine.**

## 1.9 BWR weir-wall pressure suppression containment

- Confinement (reactor building) encloses inner steel containment envelope
    - Protection from external missiles
    - Shielding from radiation
    - Secondary barrier against releases
- Two compartments inside containment, normally isolated: dry well and reactor building
- Dry well
    - Encloses reactor pressure vessel
- Containment envelope
    - Pressure suppression pool
    - Active spray system for long term
    - Free volume of reactor building
- High pressure in dry well forces water level down on inside of weir-wall until openings in wall are uncovered.
- Gas is vented through weir wall openings into pressure suppression pool.
- Spray system recirculates pool water through heat exchanger

## 1.10 Pressurized containment

- Containment envelope
  - prestressed, post-tensioned concrete reactor building
- Containment isolation system
- Passive spray system
  - no recirculation, only controls peak pressure
  - internal dousing tank
- Long-term energy management by
  - air coolers
  - ECCS heat exchangers
- Subatmospheric in long term using filtered discharge system

## 1.11 Negative pressure containment

- Economical only in multi-unit nuclear stations
- Three normally isolated compartments: reactor buildings (slightly subatmospheric), vacuum building (<1/10 atmospheric pressure), connecting relief duct (ambient pressure).
- High pressure in reactor building bursts panels into the relief duct
- Flow from relief duct into vacuum building through special relief valves
- Passive spray cooling in vacuum building (no recirculation)
- Pressure in reactor building returns to subatmospheric soon after accident
- Large underpressure in accident unit due to steam condensation requires venting of non-accident units into relief duct
- Reactor building also cooled by air coolers, structures, no spray
- Sump cooled by ECC recirculation heat exchanger
- Filtered discharge system for long-term subatmospheric pressure

## 1.12 Advanced passive containment

- None yet built, design well advanced
- Example: Westinghouse AP600 proposed design
- Entire unit is designed with passive components relying on gravity, large volumes of water, natural convection
- Double-walled containment
    - Steel containment shell
    - Concrete shield building
    - Natural air circulation in interspace cools by convection
- Annular tank sprays water onto the steel containment shell for LOCA cooling
    - No recirculation, sufficient spray for 3 days
- ECC storage tank injected by gravity into RCS
    - ECC tank floods reactor building above core level
- No ECC recirculation pumps or heat exchangers, natural convection cooling of sumps
- Other examples are the General Electric SBWR (Simplified BWR) and the passive CANDU

## 2.0 Trends in containment design

- Post-TMI focus on hydrogen management
- Post-TMI recognition that most fission products are absorbed by water. Previous estimates of radionuclide escape from reactor building were far too high
- Post-TMI interest designing for severe accidents
- Focus on reliability of containment closures, monitoring closures
- General trend in nuclear design
  - Simpler designs
  - Passive features, requiring neither motors/pumps/operator action

## 3.0 Energy management design requirements

- List of energy management systems:
  - Containment structure
  - Spray systems
  - Air coolers
  - Pool-bubbling suppression systems
  - Ice condenser systems
  - Full-pressure dual containment
  - Vacuum pressure reduction

- Containment structure
  - Sufficient free volume for reducing pressure
  - Heat absorption by condensation on structures (walls) is a major (or the major) way of reducing pressure within containment.
  - Must facilitate condensation of steam on exposed surfaces
  - Thermal conductivity of wall surface should not be reduced by any protective coatings applied to walls to prevent leakage
  - Connections between rooms must be sized to allow sufficient flow so that overpressure cannot occur when there is a sudden mass/energy inflow to a room

- **Spray systems and sumps**
  - **Must minimize peak pressure and duration of pressure transient**
  - **Ensure most of the containment volume is accessible to sprays**
  - **Spray headers and nozzles must provide even distribution of water droplets, small enough to reach containment temperature before they reach the sump, for maximum heat transfer between spray and atmosphere**
  - **Conflicting requirement: must have adequate spray duration, but equipment such as residual heat removal pumps must not be flooded. Must consider capacity of spray tank in locating equipment, or make equipment submersible.**
  - **Problems with suction intake for recirculation pumps must be considered:**
    - **Must be adequate depth of water in sump, when the spray tank and/or ECC tanks are empty, for the net positive suction head of the recirculation pumps.**
    - **Sump liquid must also be cold enough by then for the pumps**
    - **Sump liquid must be colder than the RCS, since it is reinjected.**
    - **Suction intake points for ECC and spray recirculation should be spatially separated**
    - **Suction intake should be designed to minimize air vortex formation and ingestion of foreign materials, which could damage the pumps, clog the spray nozzles or heat exchangers.**
  - **For reducing peak pressure in large breaks, require very fast activation of spray system. Detailed analysis of time to fill headers and activation setpoint is required.**
  - **Analysis must also consider possibility that sump may boil and vapour will <u>increase</u> containment pressure.**

- Air coolers
  - Most important operation mode of coolers is as condensers, not dry air coolers. Use appropriate condensing heat transfer correlation in design; air greatly reduces heat transfer coefficient for condensing heat transfer
  - Must consider also operation of air cooler in superheated steam conditions

- Pool-bubbling suppression systems
  - Pools receive discharge of steam from dry well, maybe also from steam relief valves from steam system
  - Very complex hydraulic and pressure transients will occur. System must be designed so that dynamic loads and pressure transients can be predicted in all likely combinations of normal and accident events.
  - Must be designed so that the path taken by steam from the dry well is through the submerged vents into the pools - not through some other path.
  - Should be minimal leakage between dry and wet wells that bypasses the submerged vent lines.
  - No interference with safety function of pools by normal operational functions (recall BWR uses pressure suppression pool when turbine is bypassed).

- Ice condenser systems
    - Sufficient heat transfer to ice in all postulated accident conditions
    - Ice condenser structures maintain geometry (don't collapse) in all accident loadings
    - Vent door opening is reliable
    - Bypass flows (around condensers) between upper and lower compartments must not exceed design assumptions
    - Heat transfer correlations for ice must be based on representative tests
    - Must be able to maintain ice temperature, total inventory, distribution, adequate flow passages between ice.
    - Spray in upper compartment will be ineffective if air accumulates there
    - Spray in lower compartment may cause underpressure, requires vacuum relief

- Full-pressure dual containment
    - Annulus design calculations require consideration of
        - expansion of inner shell due to heating or pressure
        - heat load from inner shell
        - waste heat loads within annulus

- **Vacuum pressure reduction containment**
  - **Requirements for pressure relief valves between reactor building and vacuum building**
    - **Isolation during normal operation**
    - **Sufficient flow capacity to prevent reactor building overpressure above design**
    - **Open fast enough to keep radionuclide release below limits**
    - **Control to return reactor building to subatmospheric pressure.**
  - **Underpressure relief: reactor building will be purged of air by large steam line break, subsequent condensation causes serious underpressure.**

# 4.0 REPRESENTATIVE VALUES OF CONTAINMENT PARAMETERS

**These numbers are for PWR, BWR, CANDU containments (very approximate)**

- **Free volumes: 50,000-150,000 $m^3$;**
  **BWR Mark I, II $9x10^3$; Mark III $4x10^4$**
  **PWR ice condenser $4x10^4$**
  **PWR dry containments $6x10^4$**
  **older CANDU $6x10^4$; CANDU 6 $5x10^4$; CANDU9 $1.2x10^5$**
- **Concrete thickness: 1-2 m for external and internal walls, dome .5 m, basemat 2-3 m**
- **Design pressures: 2-4 bar (most types); much higher for some of the newest**
- **Design leakage rates: ~< one percent per day of containment volume at the design pressure**
- **Expected peak pressures: 3 bar for CANDU9 steam break, 1.7 for PNGSA steam break, 7 bar for hydrogen explosion**
- **Expected temperatures: ~35C normally, peak ~130C, long-term ~80 c after accident**
- **Air cooler capacities: 2 MW (dry), 40 MW (condensing) for CANDU**
- **ECC heat exchangers: 80 MW (CANDU)**
- **Pressure suppression pool inventory: some are about 4000 $m^3$**
- **Ice mass for ice condensers: $1x10^6$ kg**
- **Spray inventory: 1300 $m^3$ for AP600; 1600 $m^3$ for CANDU 6; 10,000 $m^3$ for CANDU vacuum building**

- **Spray rate: 30 $m^3$ /s for CANDU vacuum building; 4.5 $m^3$ /s for CANDU6; far less in older LWR designs**
- **RCS inventory: 125 Mg (CANDU), 60 Mg (some PWR)**
    - **Energy release from PWR coolant: $4 \times 10^8$ kJ initially**
    - **$2 \times 10^8$ kJ/hr subsequently from decay heat**
- **Reactor thermal power: 1500-4000 MW at full power (about 3 x rated electrical power)**
    - **drops to 7% immediately on shutdown, <2% in 20 min, <1% in 3 hours, .1% in a day**
    - **integrated thermal power as a function of time:**

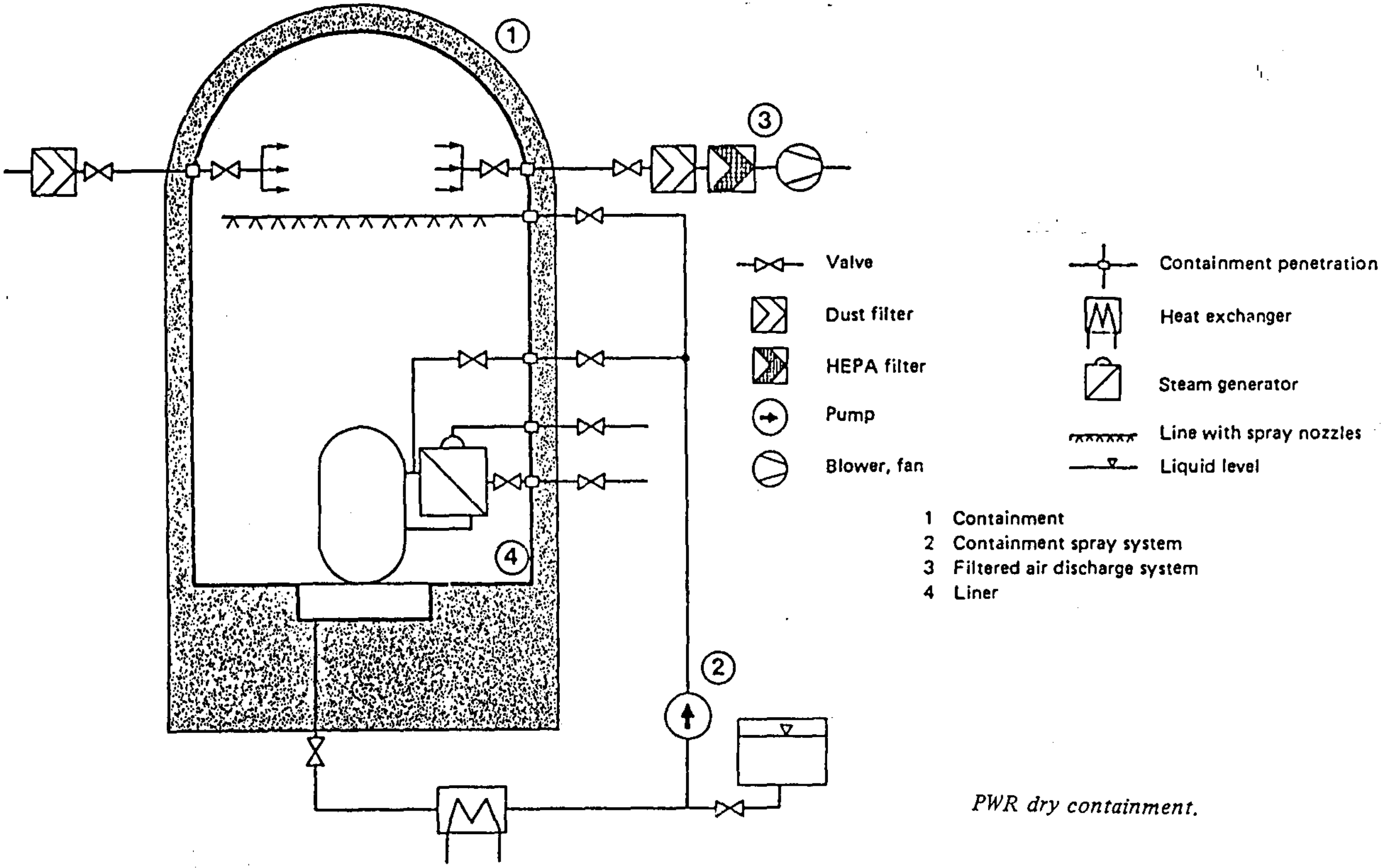
      **.5 full power-seconds after 10s,**

      **4. FP-s in 100 s,**

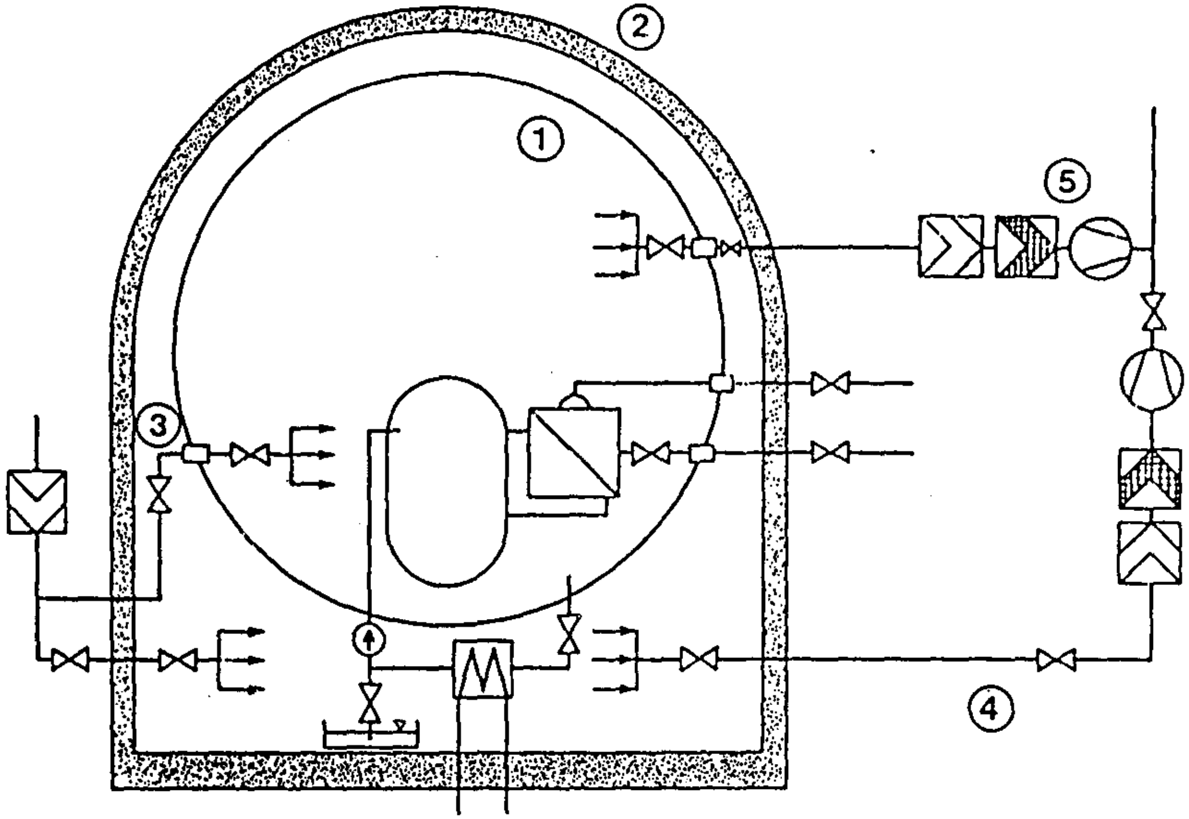
      **25 FP-s after 20 min,**

      **140 FP-s after 3 hrs,**

      **2000 FP-s after first day**



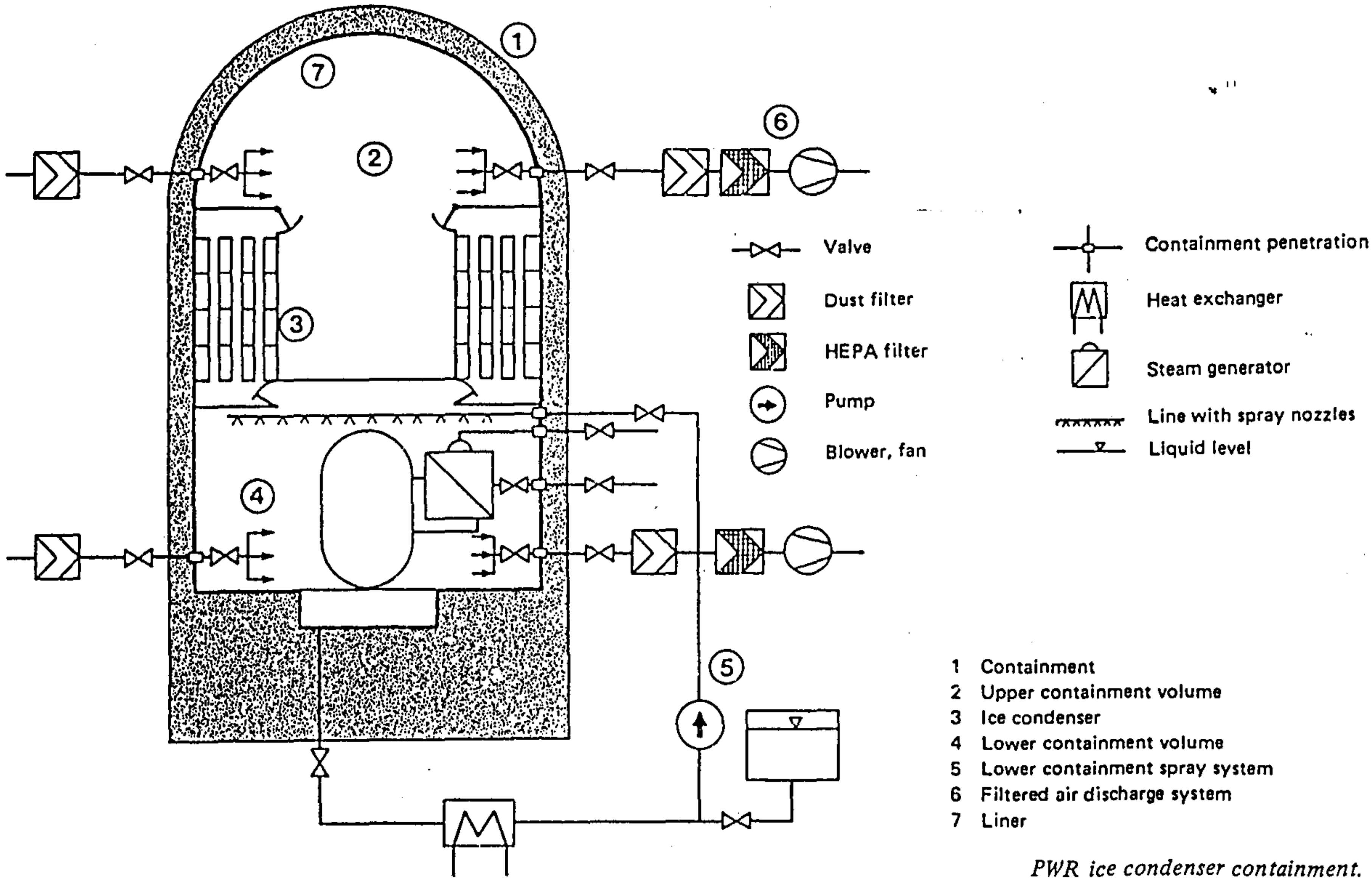

*PWR dry containment.*




Valve
Dust filter
HEPA filter
Pump
Blower, fan
Containment penetration
Heat exchanger
Steam generator
Line with spray nozzles
Liquid level

1 Full-pressure containment
2 Secondary confinement
3 Annulus
4 Annulus evacuation system
5 Filtered air discharge system

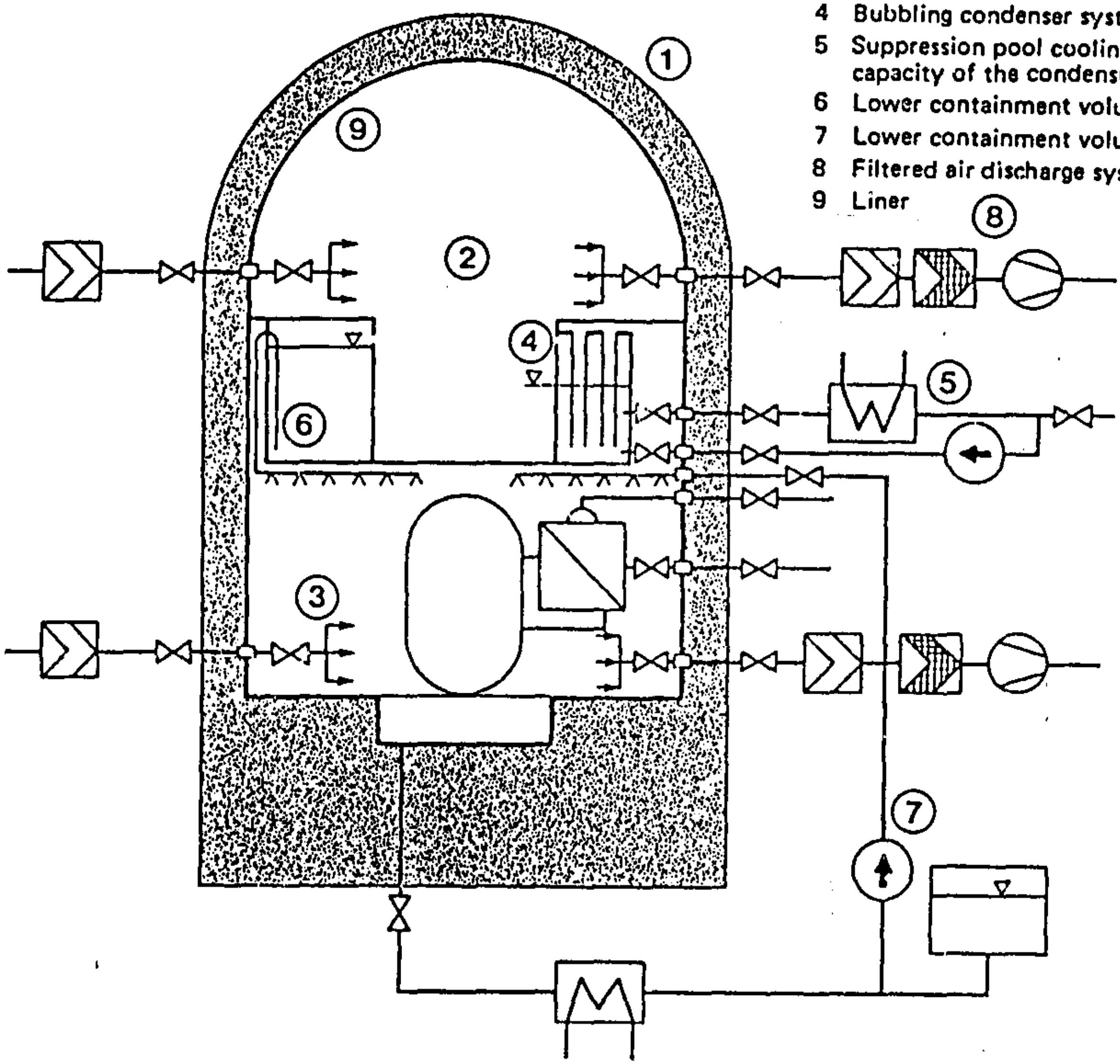
*PWR full-pressure dual containment.*

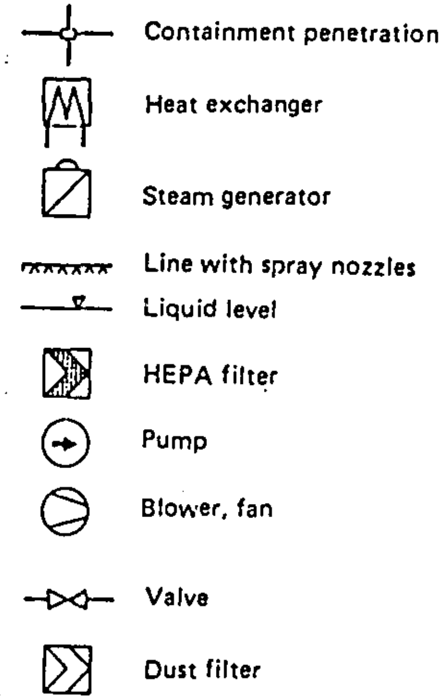



1 Containment
2 Upper containment volume
3 Ice condenser
4 Lower containment volume
5 Lower containment spray system
6 Filtered air discharge system
7 Liner

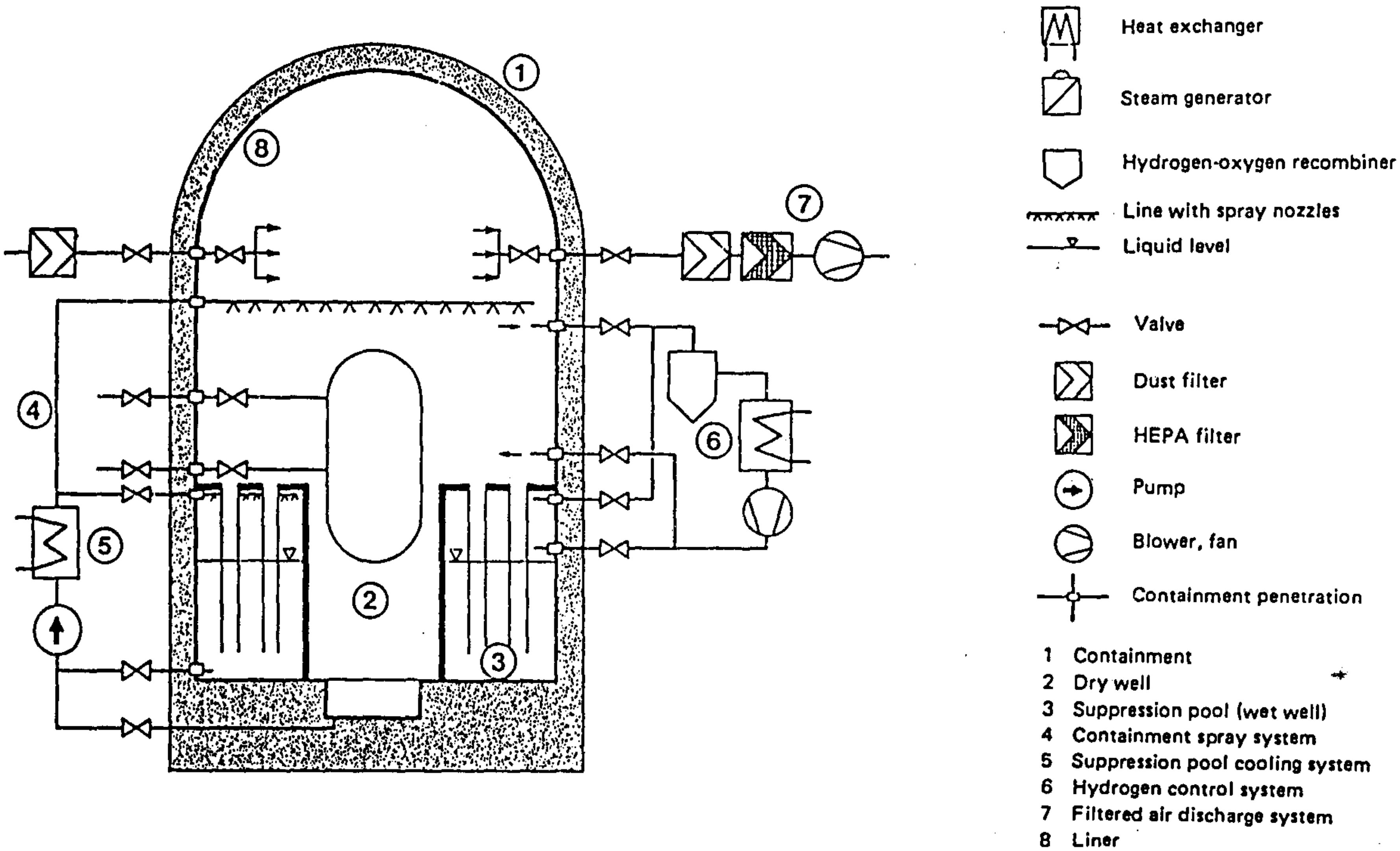
*PWR ice condenser containment.*

1 Containment
2 Upper containment volume (wet well)
3 Lower containment volume (dry well)
4 Bubbling condenser system (suppression pool)
5 Suppression pool cooling system (not required if the heat capacity of the condenser system (4) is sufficiently large)
6 Lower containment volume passive spray system
7 Lower containment volume active spray system
8 Filtered air discharge system
9 Liner

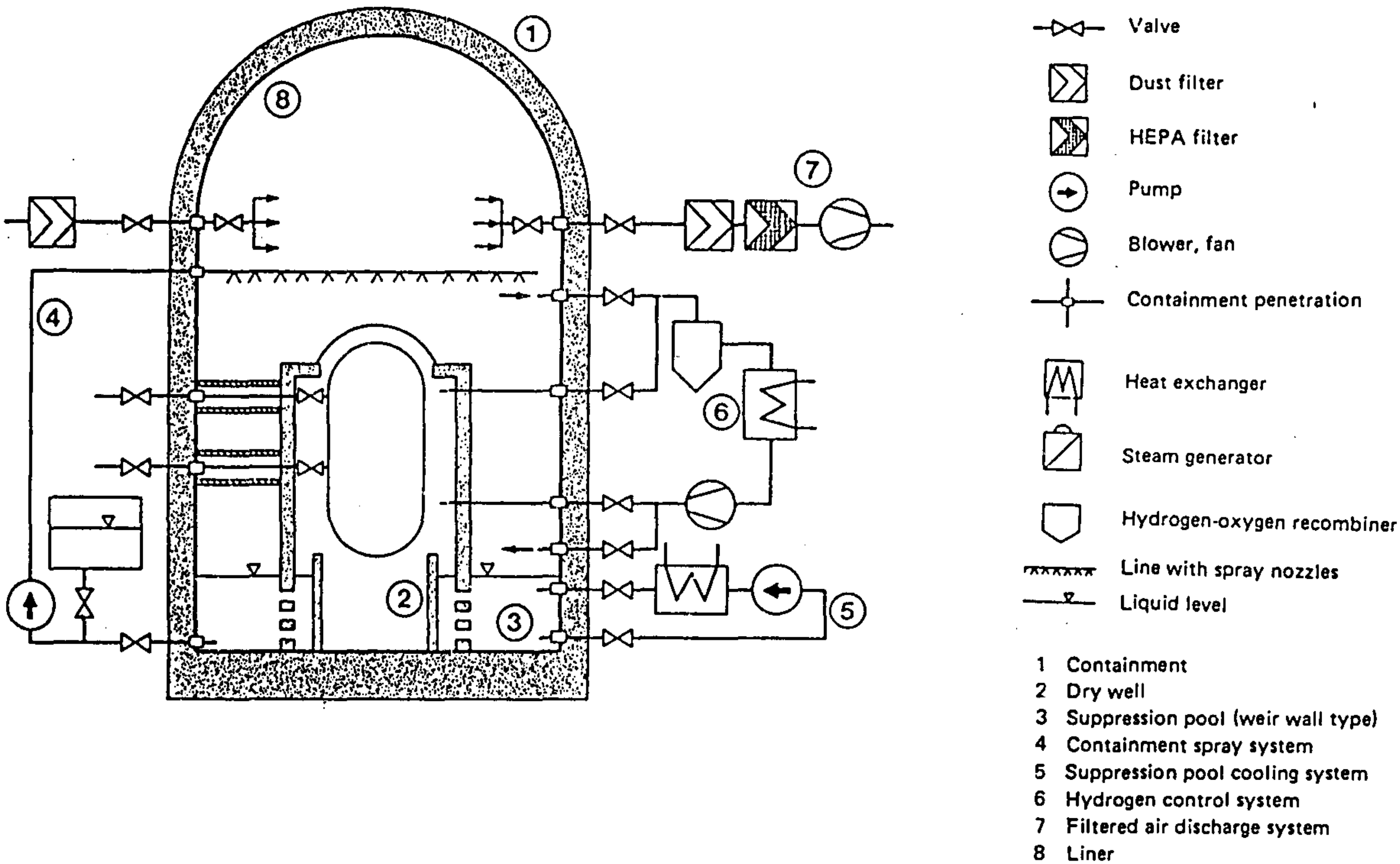


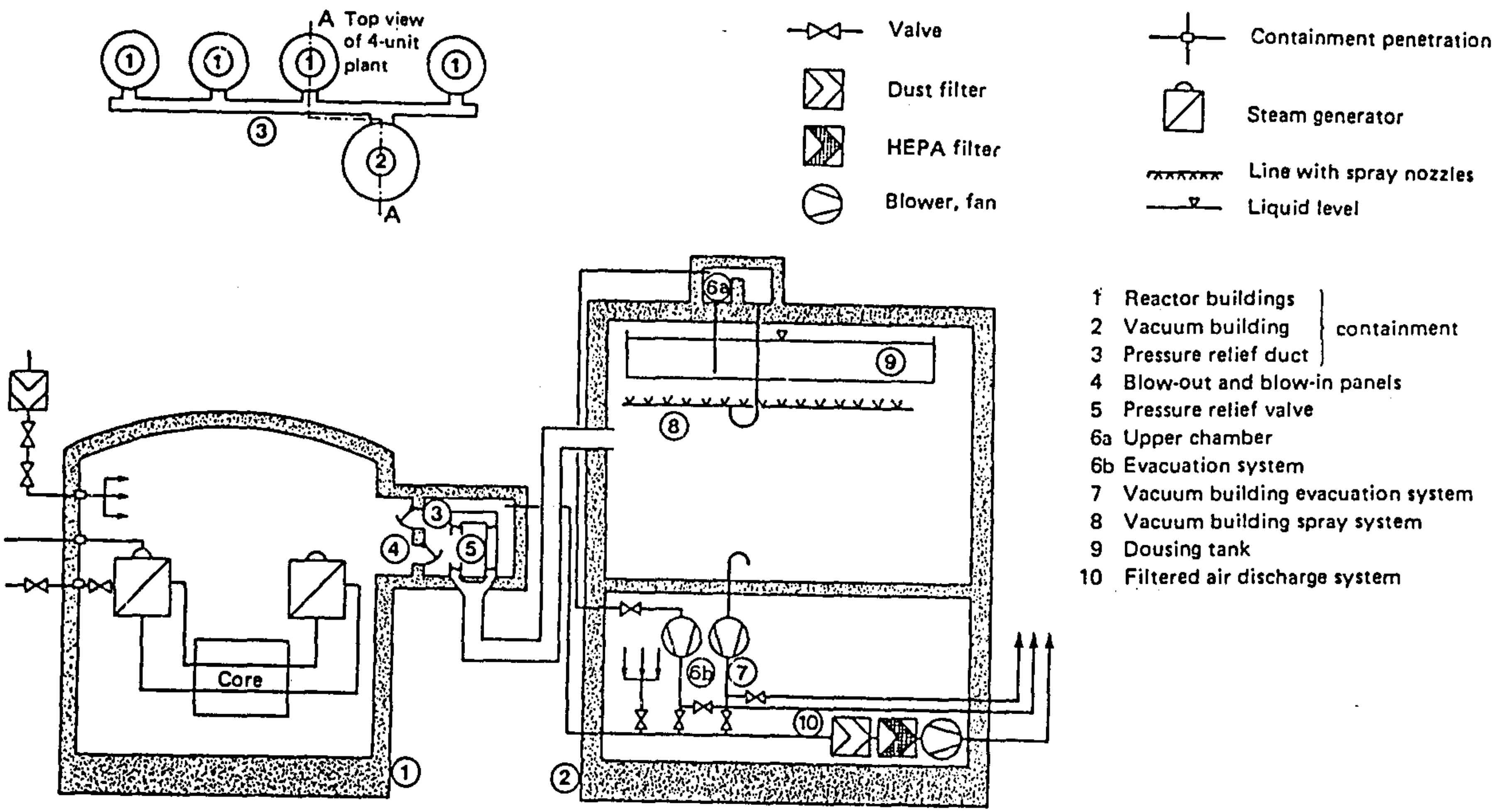

*PWR bubbling condenser containment.*




*BWR pressure suppression containment (the reactor building with its confinement is not shown).*

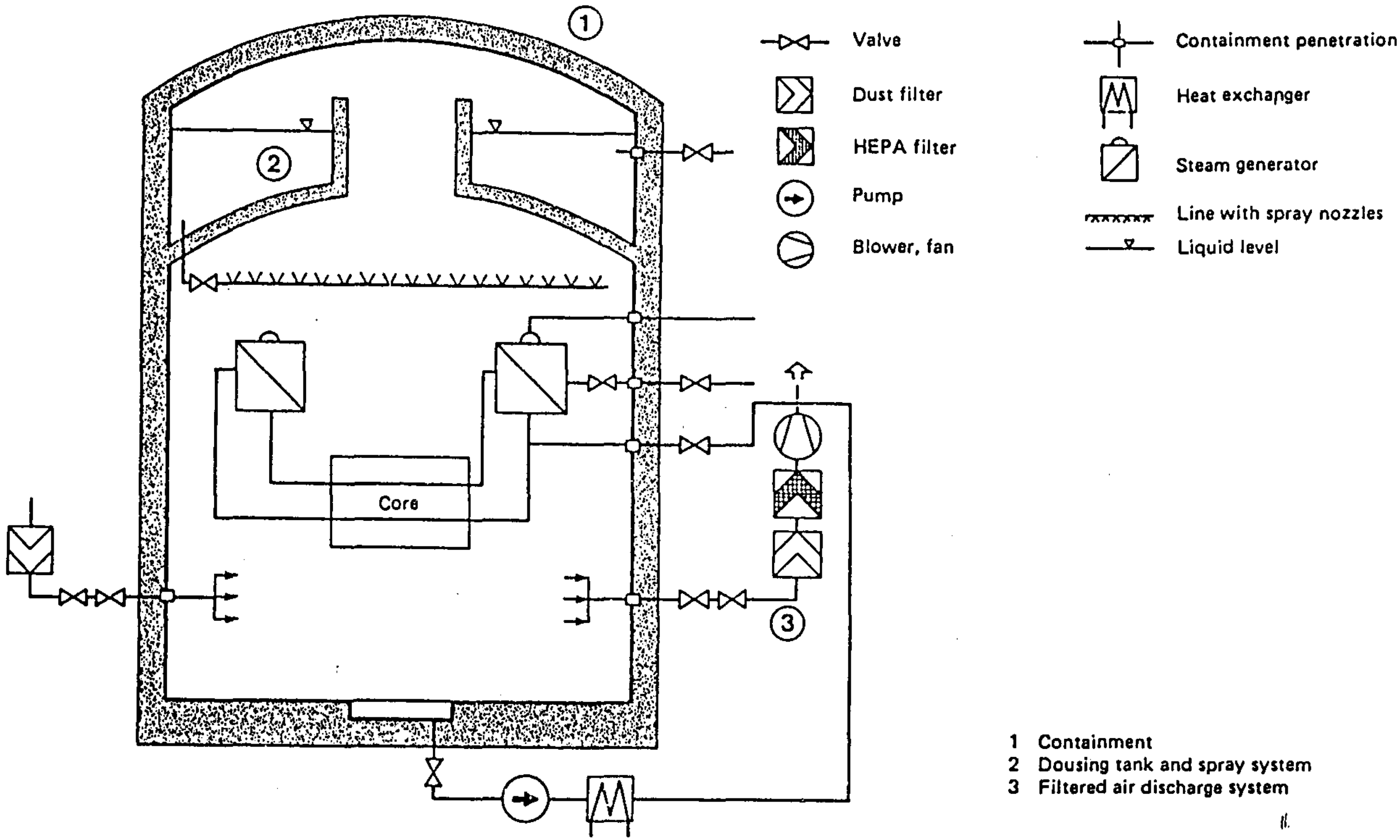



*BWR weir-wall pressure suppression containment (the reactor building with its confinement function is not shown).*




Cross-section
A-A

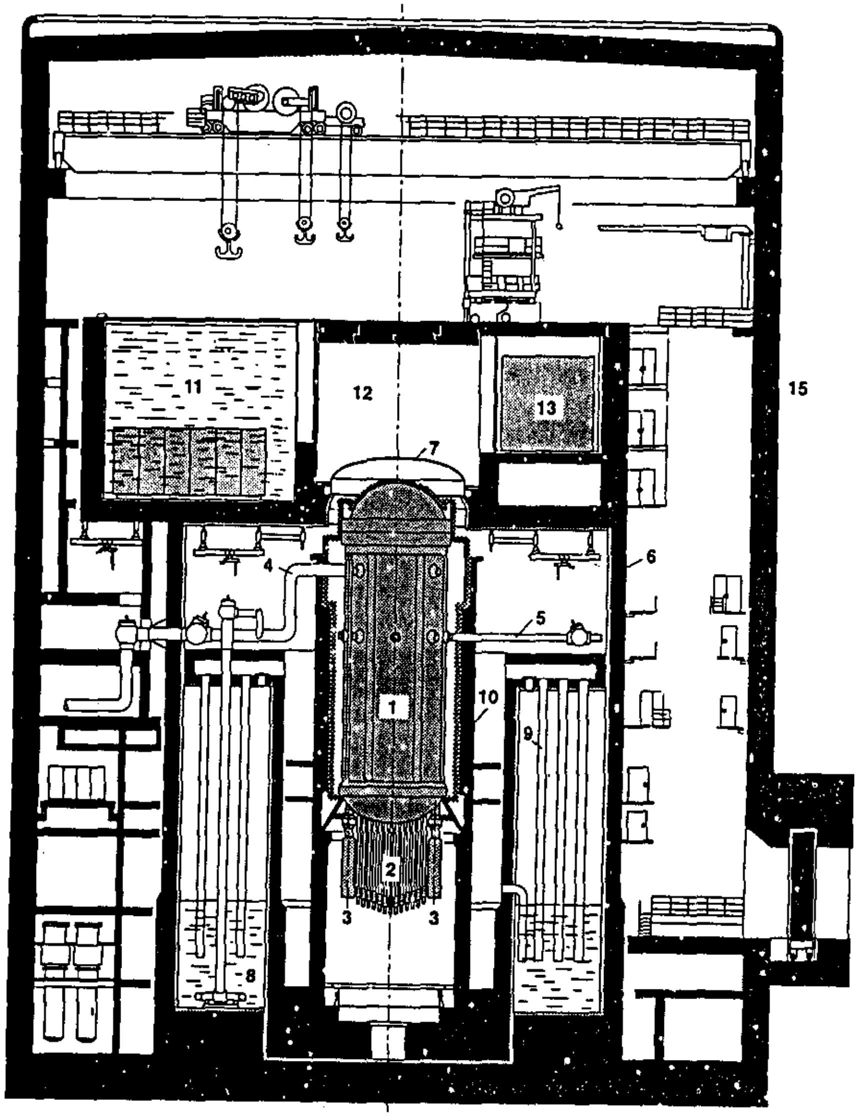
PHWR
*negative pressure containment.*




1 Containment
2 Dousing tank and spray system
3 Filtered air discharge system

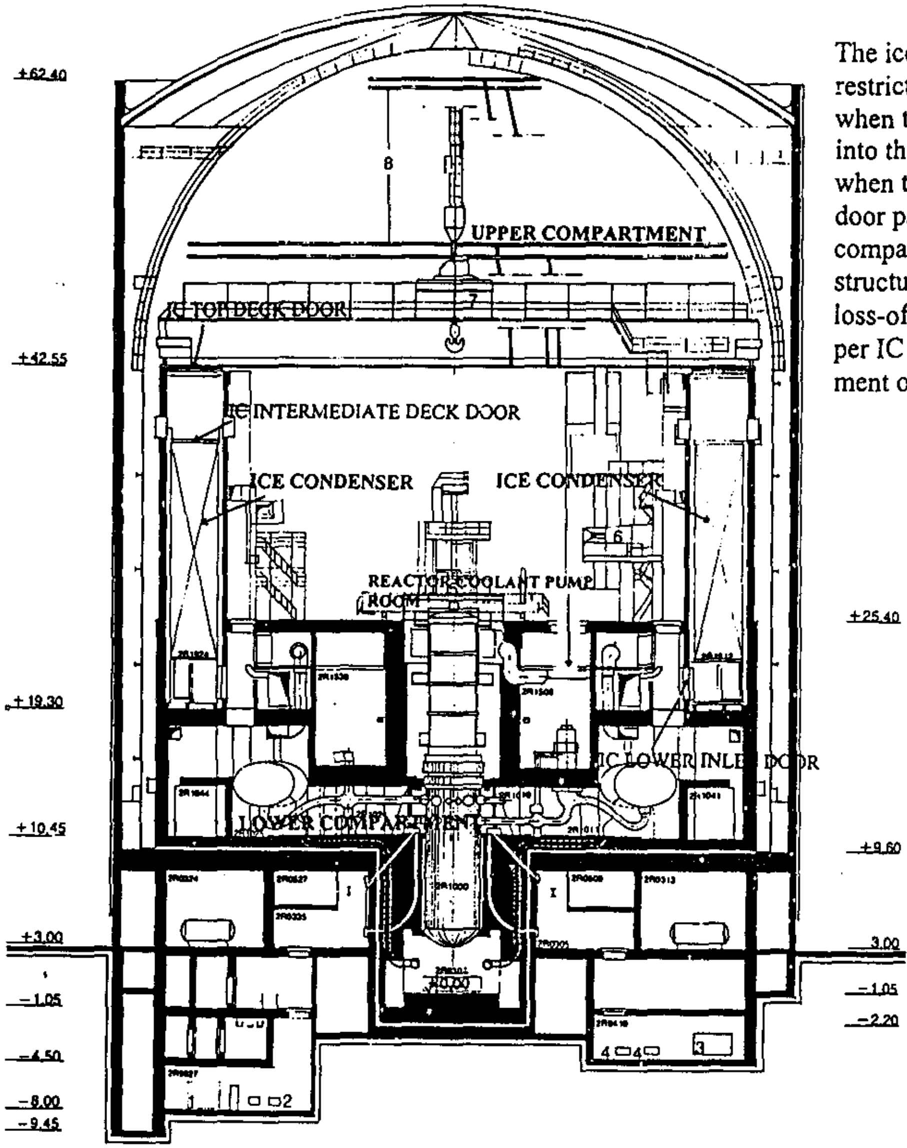
PHWR *pressurized containment.*

W. Reim, D. Hurlebaus / Nuclear Engineering and Design 157 (1995) 321–335




1 Reactor pressure vessel
2 Control rod drives
3 Recirculation pumps
4 Primary steam line
5 Feedwater line
6 Prestressed containment
7 Refueling Lid
8 Pressure suppression pool
9 Pressure suppression pipes
10 Biological shield
11 Fuel pool
12 Reactor well
13 Steam separator pool
14 Refueling machine
15 Reactor building

Nuclear steam supply system with pressure suppression inside the containment.




Ice condenser containment of the Loviisa NPP

The ice condenser **lower inlet, intermediate deck,** and **top deck doors** are important flow restrictions in the containment. The vertical lower inlet doors open into the ice condensers, when the pressure difference across the doors increases due to gas and energy injection into the lower compartment. They have springs attached to them to create a closing torque, when the lower compartment overpressure has been relieved. The lower inlet doors (8 door pairs per IC section) quite efficiently prevent a return flow of cold air to the lower compartment. The horizontal intermediate deck doors (72 doors per IC section) are heavy structures that remain in place except during the initial blowdown period of a large break loss-of-coolant accident. The top deck doors are large non-rigid horizontal flaps (18 flaps per IC section). There are narrow bypasses at the intermediate and top decks for replacement of air previously being pushed out of the ice bed into the upper compartment

H. Karwat / Nuclear Engineering and Design 157 (1995) 363-374

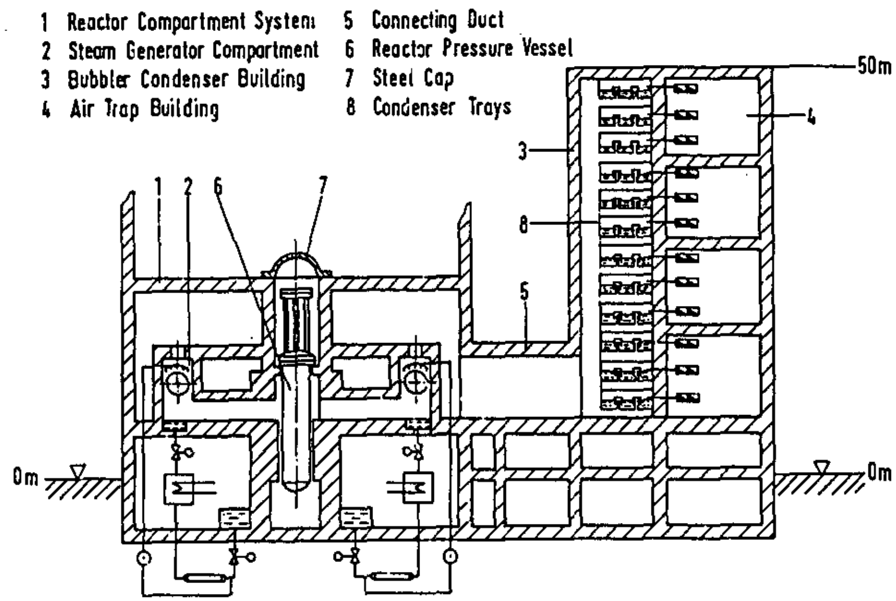
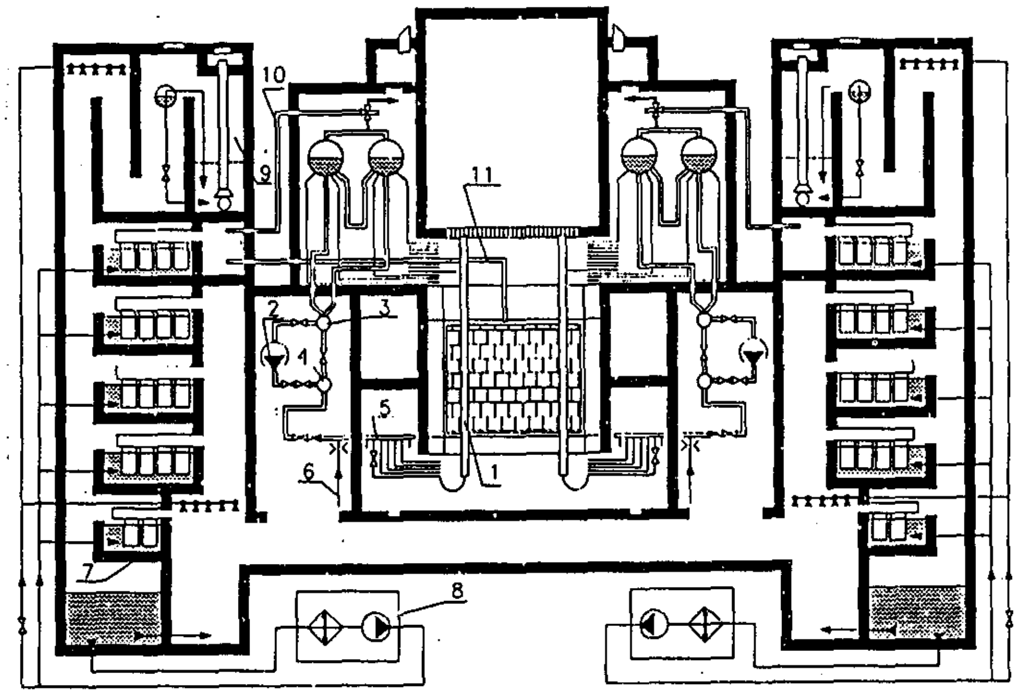


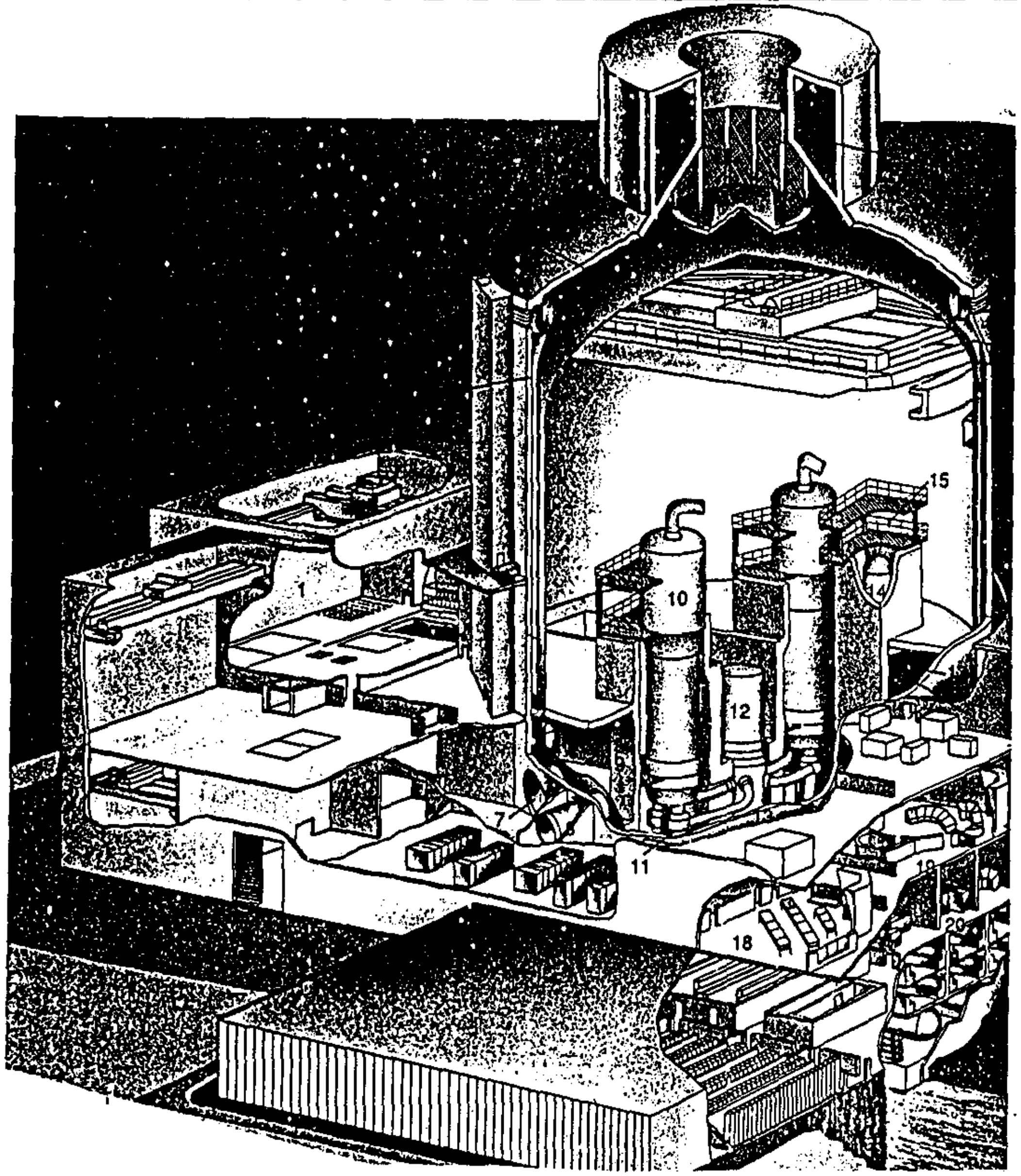

Fig. 1. Evaluation of the building of a VVER-440/W-213 plant.

E. Ušpuras et al. / Nuclear Engineering and Design 157 (1995) 353–361




RBMK (Ignalina)

Principal ACS schematic: 1, fuel channel; 2, main circulation pump; 3, suction header; 4, pressure header; 5, group distribution header; 6, ECCS header; 7, condensing pools; 8, ACS head exchanger; 9, air discharge pipe section; 10, pipe for removal of contaminated steam from protection valve; 11, pipe for removal of contaminated steam from broken fuel channel.




Legend:
1. Fuel Handling Area
2. Concrete Shield Building
3. Steel Containment
4. Passive Containment Cooling Water Tank
5. Passive Containment Cooling Air Baffles
6. Passive Containment Cooling Air Inlets
7. Equipment Hatches (2)
8. Personnel Hatches (2)
9. Core Make-up Tanks (2)
10. Steam Generators (2)
11. Reactor Coolant Pumps (4)
12. Integrated Head Package
13. Reactor Vessel
14. Pressurizer
15. Depressurization Valve Module Location
16. Passive Residual Heat Removal Heat Exchangers
17. Refueling Water Storage Tank
18. Technical Support Center
19. Main Control Room
20. Integrated Protection Cabinets

AP600

Sectional view of the 600 MWe pressurized water reactor (PWR) expected to be operational by 1995. Considered the PWR of the future, the plant is designed for a minimum useful life span of 60 years and features numerous economic and safety features, including passive systems for ultimate protection. *(Joint project of Westinghouse, the Electric Power Research Institute, and the U.S. Department of Energy.)*

. CANDU Containment with Passive Emergency Water System
(Conceptual)