Joint ICTP-IAEA Nuclear Safety Institute Workshop

Assessment of Major Systems - Containment

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Overview

- Design Requirements
- Typical current generation LWR Containment Designs
  - Several Examples of BWRs
  - Several Examples of PWRs
  - Several Examples of VVERs
  - Caution: This is NOT a comprehensive survey (several designs are not discussed)
- Understand Basic Configuration of Containment Heat Removal System

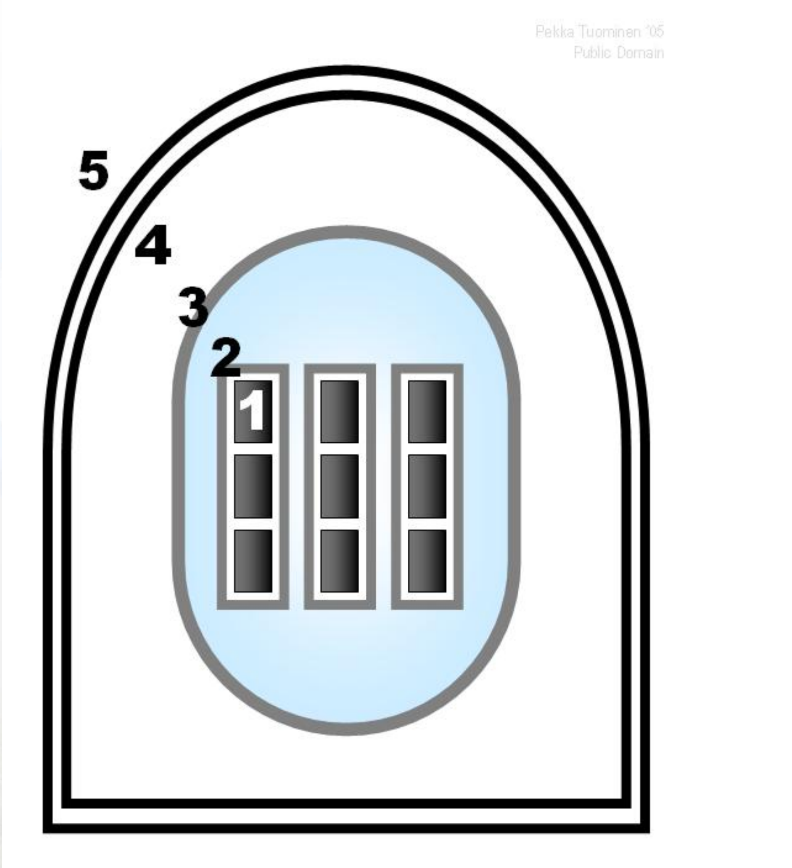
Radiation Protection Mechanisms

- **Barriers**
  - Contain radioactive materials and prevent human exposure or release to the environment
- **Distance**
  - Provide spatial margins to reduce the intensity of radiation exposure
- **Time**
  - Isolate radioactive material until it has decayed to a stable or less harmful state

Defense in depth concept

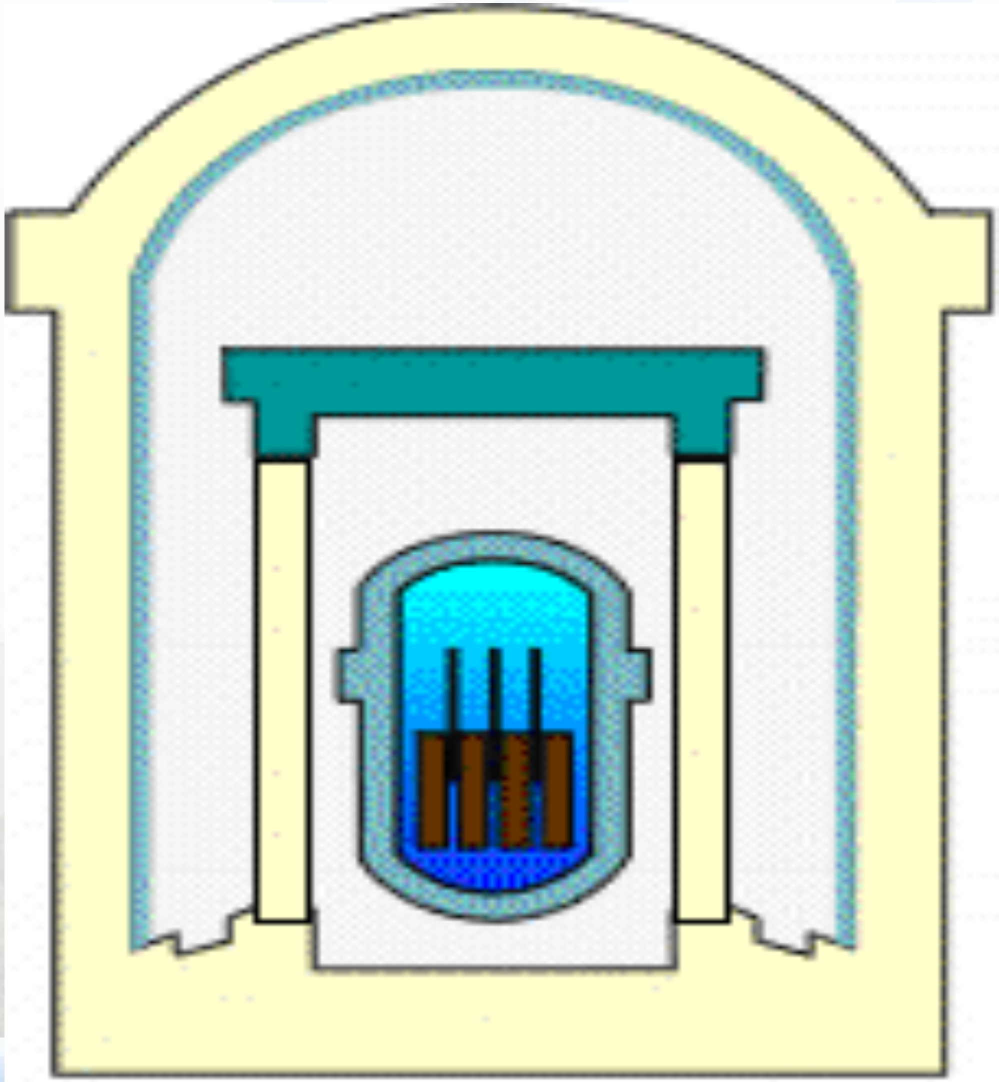
Defense in depth in the term of five protection barriers:

- Fuel
- Fuel Cladding
- Primary Circuit Pressure Boundary
- Containment
- Emergency Measures



Defense in depth concept

- 1.2m concrete containment building
- 0.9m concrete shield
- 0.2m steel reactor vessel
- solid nuclear fuel inside steel tubes



IAEA SSR-2/1 Containment Design Requirements

- A containment system shall be provided in order to ensure that any release of radioactive materials to the environment in a design basis accident would be below prescribed limits.
- This system may include, depending on design requirements:
  - leaktight structures;
  - associated systems for the control of pressures and temperatures;
  - features for the isolation, management and removal of fission products, hydrogen, oxygen and other substances that could be released into the containment atmosphere.
- All identified design basis accidents shall be taken into account in the design of the containment system. In addition, consideration shall be given to the provision of features for the mitigation of the consequences of selected severe accidents in order to limit the release of radioactive material to the environment.

IAEA SSR-2/1 Containment Design Requirements

- **The strength of the containment structure, including access openings and penetrations and isolation valves, shall be calculated with sufficient margins of safety on the basis of the potential internal overpressures, underpressures and temperatures, dynamic effects such as missile impacts, and reaction forces anticipated to arise as a result of design basis accidents.**

- **The effects of other potential energy sources, including, for example, possible chemical and radiolysis reactions, shall also be considered.**

IAEA SSR-2/1 Containment Design Requirements

- In calculating the necessary strength of the containment structure, natural phenomena and human induced events shall be taken into consideration, and provision shall be made to monitor the condition of the containment and its associated features.

- Provision for maintaining the integrity of the containment in the event of a severe accident shall be considered. In particular, the effects of any predicted combustion of flammable gases shall be taken into account.

IAEA SSR-2/1 Containment Design Requirements

Capability for containment pressure tests

- The containment structure shall be designed and constructed so that it is possible to perform a pressure test at a specified pressure to demonstrate its structural integrity before operation of the plant and over the plant's lifetime.

Containment leakage

- The containment system shall be designed so that the prescribed maximum leakage rate is not exceeded in design basis accidents. The primary pressure withstanding containment may be partially or totally surrounded by a secondary confinement for the collection and controlled release or storage of materials that may leak from the primary containment in design basis accidents.

IAEA SSR-2/1 Containment Design Requirements

Containment Penetrations

- The number of penetrations through the containment shall be kept to a practical minimum.
- All penetrations through the containment shall meet the same design requirements as the containment structure itself. They shall be protected against reaction forces stemming from pipe movement or accidental loads such as those due to missiles, jet forces and pipe whip.
- If resilient seals (such as elastomeric seals or electrical cable penetrations) or expansion bellows are used with penetrations, they shall be designed to have the capability for leak testing at the containment design pressure, independent of the determination of the leak rate of the containment as a whole, to demonstrate their continued integrity over the lifetime of the plant.

Containment Isolation

- Each line that penetrates the containment as part of the reactor coolant pressure boundary or that is connected directly to the containment atmosphere shall be automatically and reliably sealable in the event of a design basis accident in which the leaktightness of the containment is essential to preventing radioactive releases to the environment that exceed prescribed limits.
- These lines shall be fitted with at least two adequate containment isolation valves arranged in series (normally with one outside and the other inside the containment, but other arrangements may be acceptable depending on the design), and each valve shall be capable of being reliably and independently actuated.

IAEA SSR-2/1 Containment Design Requirements

Containment Isolation

- Isolation valves shall be located as close to the containment as is practicable. Containment isolation shall be achievable on the assumption of a single failure. If the application of this requirement reduces the reliability of a safety system that penetrates the containment, other isolation methods may be used.
- Each line that penetrates the primary reactor containment and is neither part of the reactor coolant pressure boundary nor connected directly to the containment atmosphere shall have at least one adequate containment isolation valve. This valve shall be outside the containment and located as close to the containment as practicable.
- Adequate consideration shall be given to the capability of isolation devices to maintain their function in the event of a severe accident.

Internal structures of the containment

- The design shall provide for ample flow routes between separate compartments inside the containment.
- The cross-sections of openings between compartments shall be of such dimensions as to ensure that the pressure differentials occurring during pressure equalization in design basis accidents do not result in damage to the pressure bearing structure or to other systems of importance in limiting the effects of design basis accidents.
- Adequate consideration shall be given to the capability of internal structures to withstand the effects of a severe accident.

IAEA SSR-2/1 Containment Design Requirements

Residual Heat Removal from the Containment

- The capability to remove heat from the reactor containment shall be ensured.
- The safety function shall be fulfilled of reducing the pressure and temperature in the containment, and maintaining them at acceptably low levels, after any accidental release of high energy fluids in a design basis accident.
- The system performing the function of removing heat from the containment shall have adequate reliability and redundancy to ensure that this can be fulfilled, on the assumption of a single failure.
- Adequate consideration shall be given to the capability to remove heat from the reactor containment in the event of a severe accident.

IAEA SSR-2/1 Containment Design Requirements

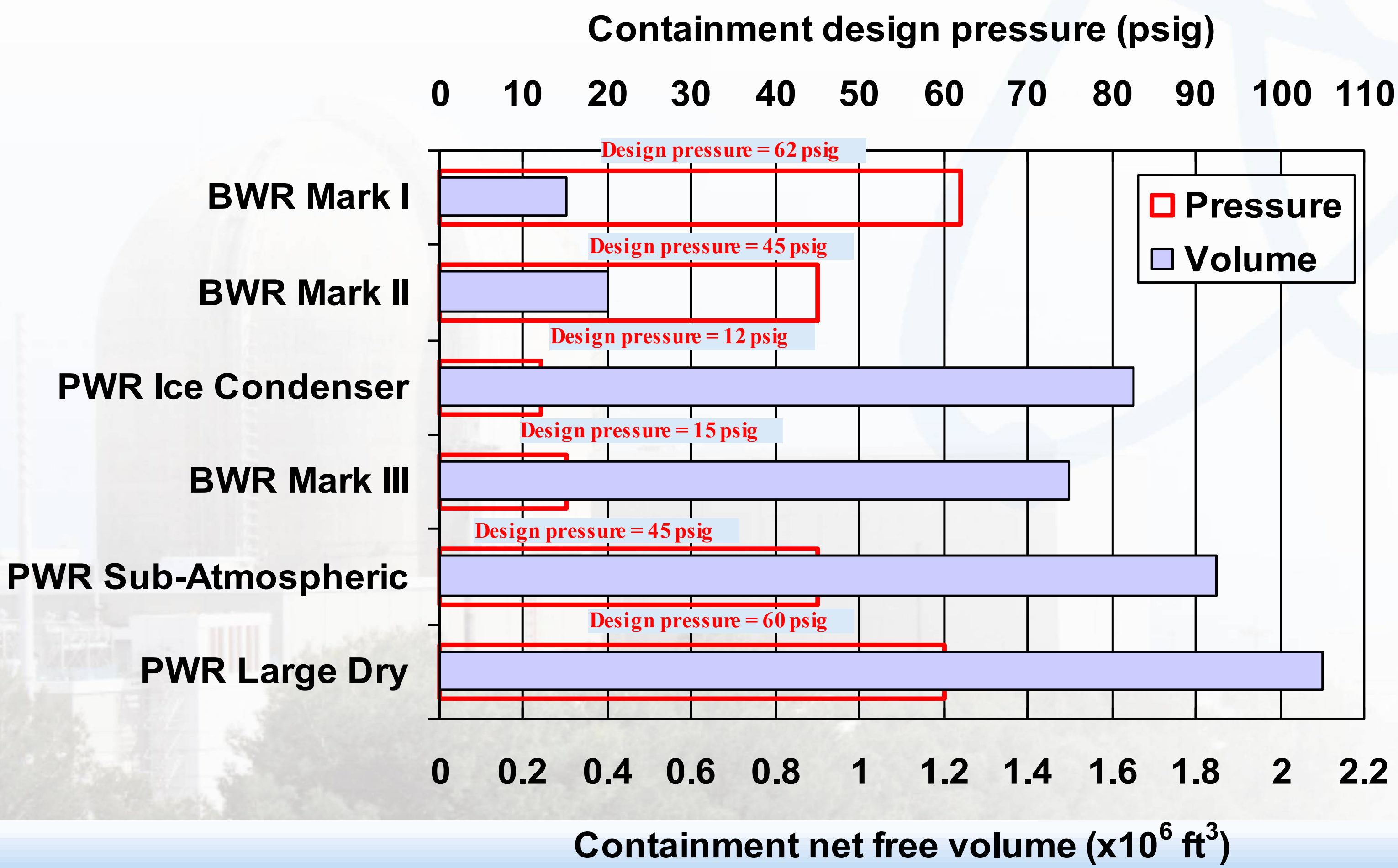
Control and cleanup of the containment atmosphere

- Systems to control fission products, hydrogen, oxygen and other substances that may be released into the reactor containment shall be provided as necessary:
  - to reduce the amount of fission products that might be released to the environment in design basis accidents; and
  - to control the concentration of hydrogen, oxygen and other substances in the containment atmosphere in design basis accidents in order to prevent deflagration or detonation which could jeopardize the integrity of the containment.
- Systems for cleaning up the containment atmosphere shall have suitable redundancy in components and features to ensure that the safety group can fulfil the necessary safety function, on the assumption of a single failure.
- Adequate consideration shall be given to the control of fission products, hydrogen and other substances that may be generated or released in the event of a severe accident.

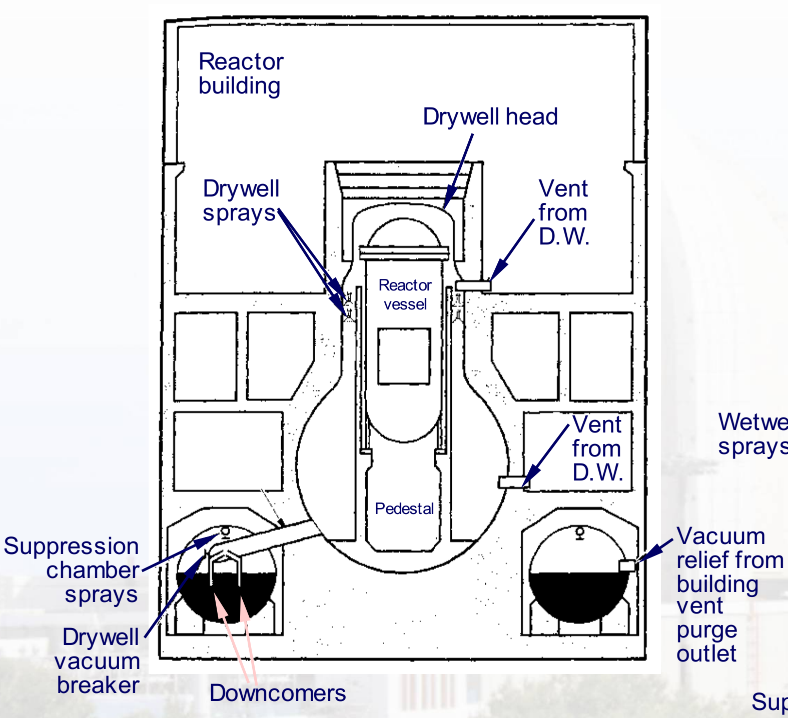
Major Types of LWR Containment Designs

- **Boiling Water Reactors (BWRs)**
  - GE Mark I -- Peach Bottom (USA), Mühleberg (CH)
  - GE Mark II -- Limerick (USA), Laguna Verde (Mexico)
  - GE Mark III -- Grand Gulf (USA), Cofrentes (ES), Leibstadt (CH)
  - KWU Type-69 – Krümmel (D), Type-72 Gundremmingen (D)
- **Pressurized Water Reactors (PWRs)**
  - Large Dry Cylindrical –
    - ✓ (Westinghouse): Indian Point (USA), Vandellos (ES)
    - ✓ (Framatome N4):
  - Large Dry Spherical (Siemens/KWU)– Borssele (NL),Isar-2 (D)
  - Ice Condensers – Sequoyah (W-USA), Loviisa (WWER-FI)

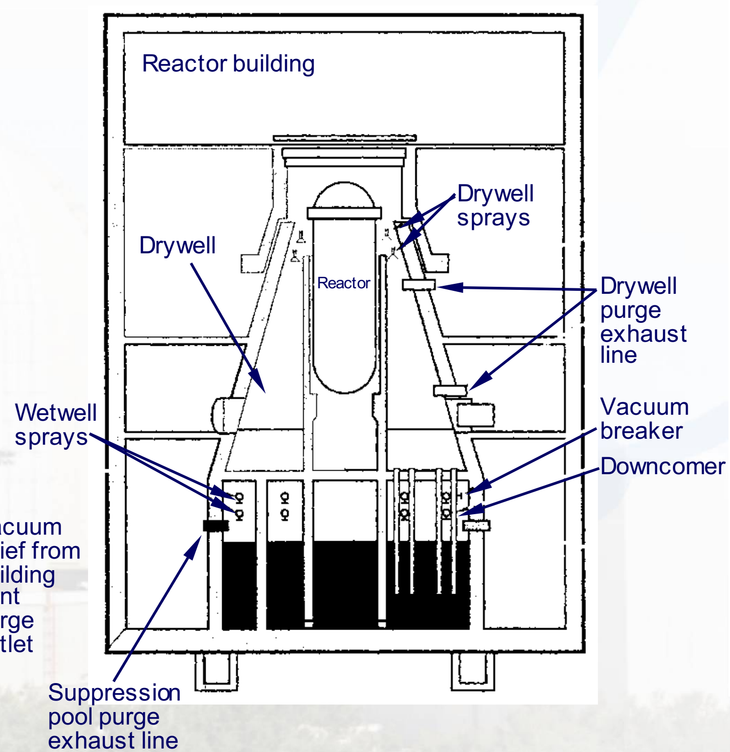
Containment Free Volumes and Design Pressures Differences



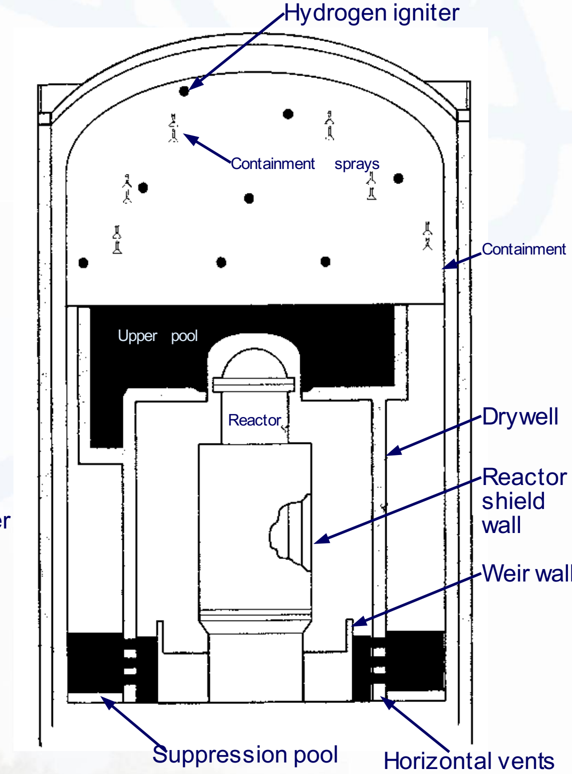
Categories of Current (GE) BWR Containments



Mark I

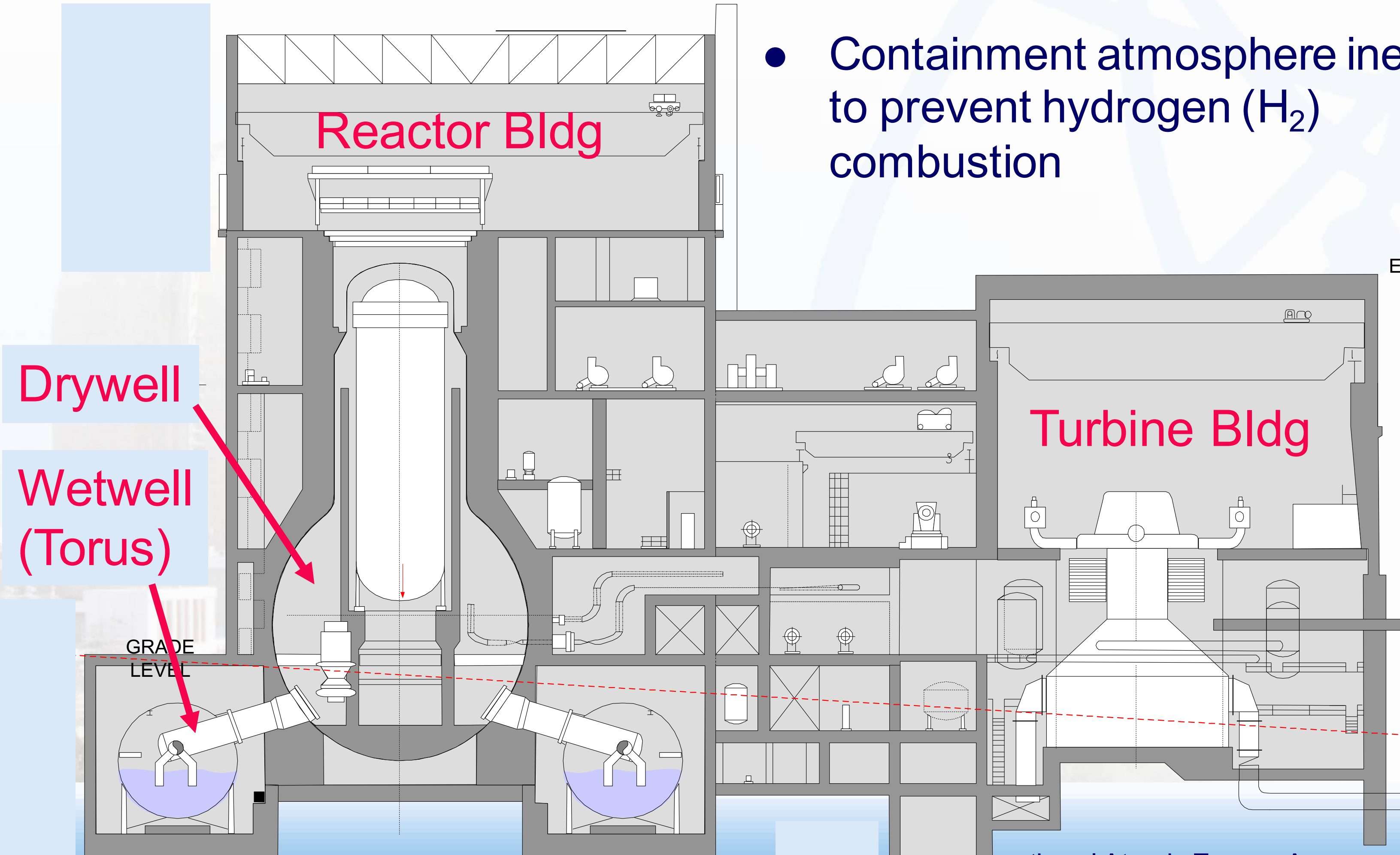


Mark II



Mark III

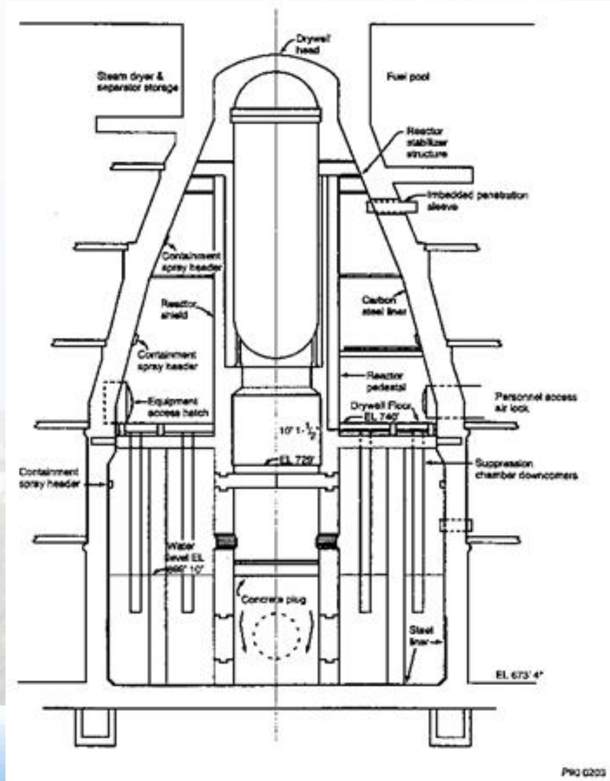
Most Common & Oldest Design is Mark I



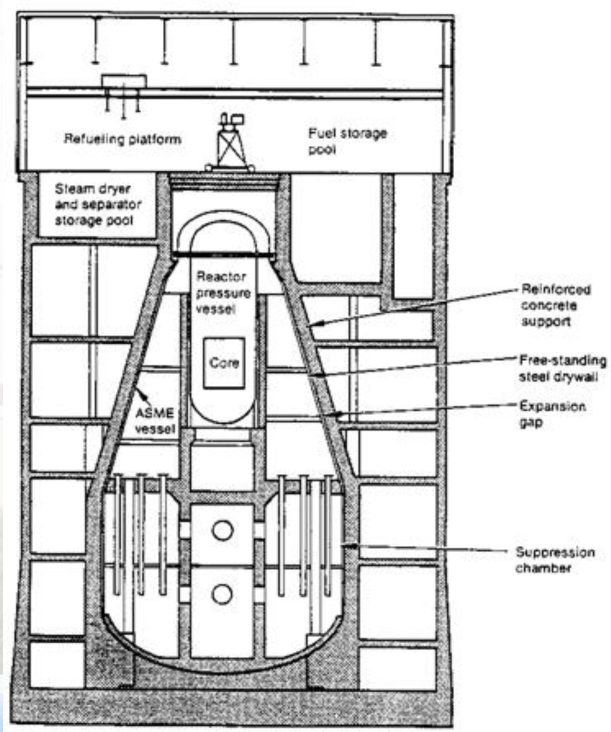
- Containment atmosphere inerted to prevent hydrogen (H_2) combustion

Mark II Design More Unified than Mark I Design

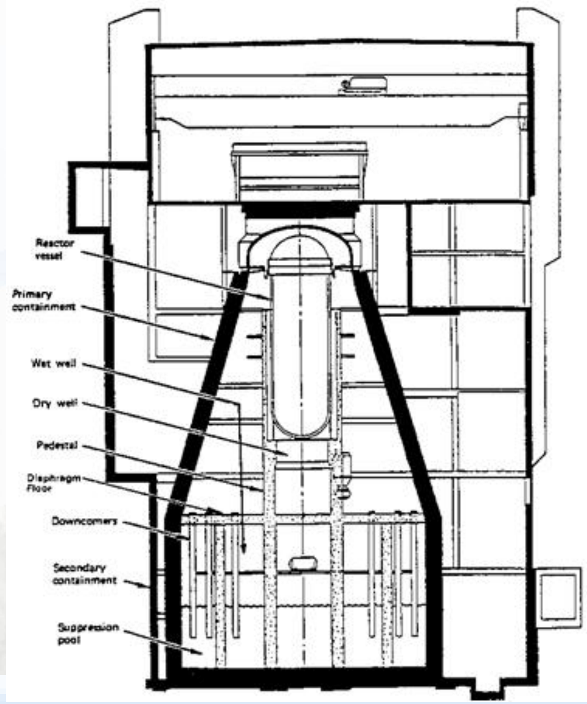
- **Single structure divided into two volumes by concrete floor**
  - **Drywell is directly above wetwell**
  - **Drywell and wetwell connected by vertical pipes**
- **Reinforced or post-tensioned concrete structures with steel liner**
- **Containment atmosphere inerted to prevent H_2 combustion**



LaSalle Units 1 & 2



Columbia (WNP-2)

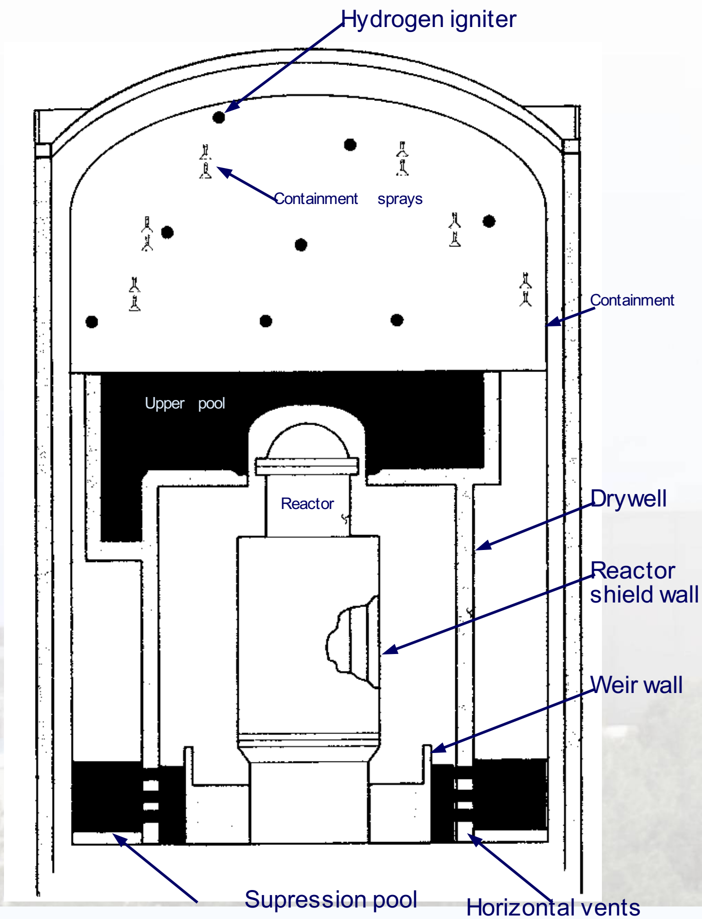


Limerick 1 & 2

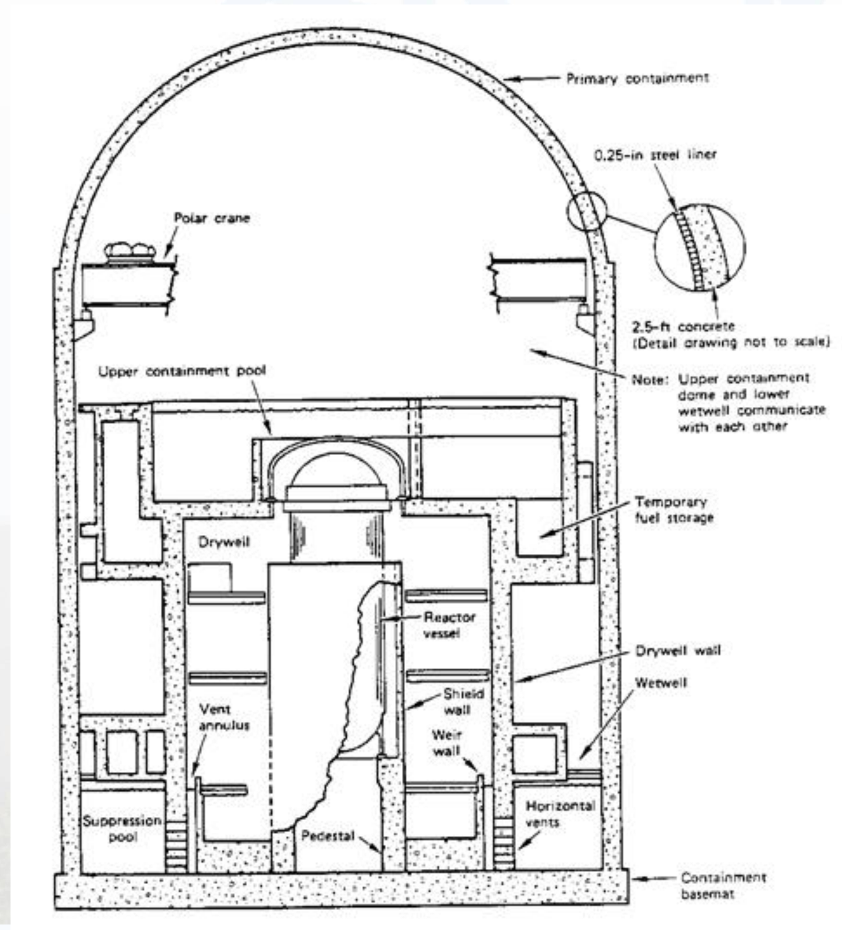
Mark III Differs in Many Significant ways

- Two volumes (drywell and 'containment') connected by horizontal vents through suppression pool
- Significantly larger volume than Mark I and Mark II designs
  - but lower design pressure
- Containment atmosphere NOT inerted
  - relies on hydrogen igniters
- Two types of primary containment designs
  - free-standing steel structure
  - reinforced concrete with steel liner

Two Types of Mark III Primary Containments

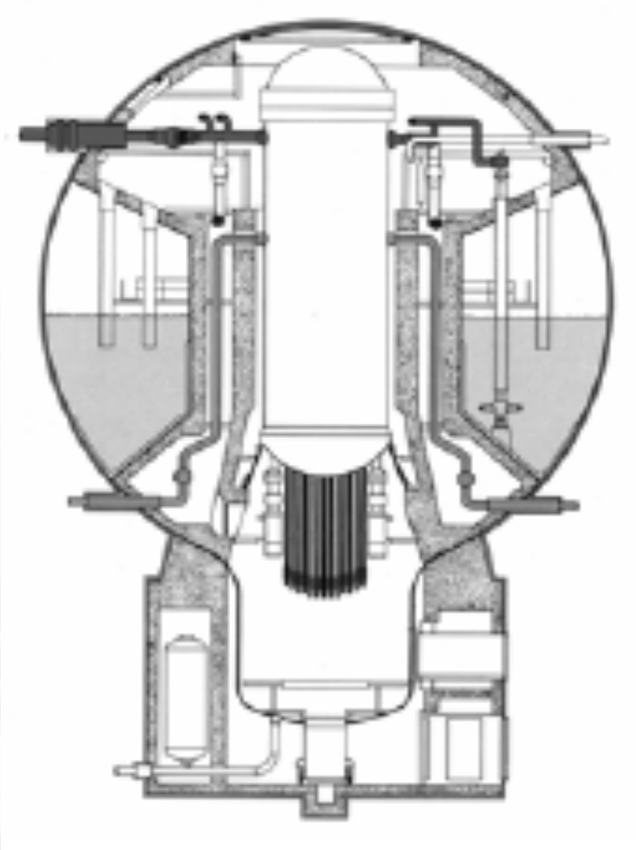


Free standing steel structure

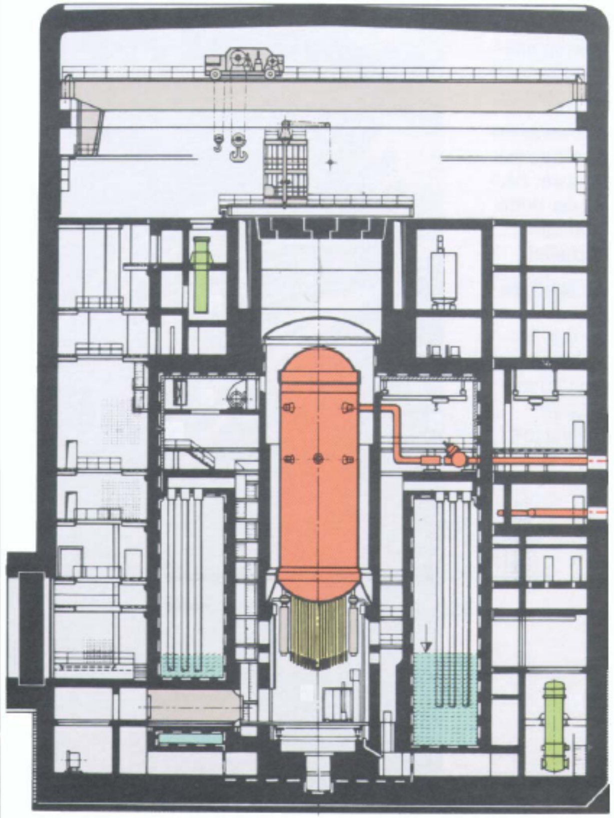


Reinforced concrete

Siemens/KWU Designs

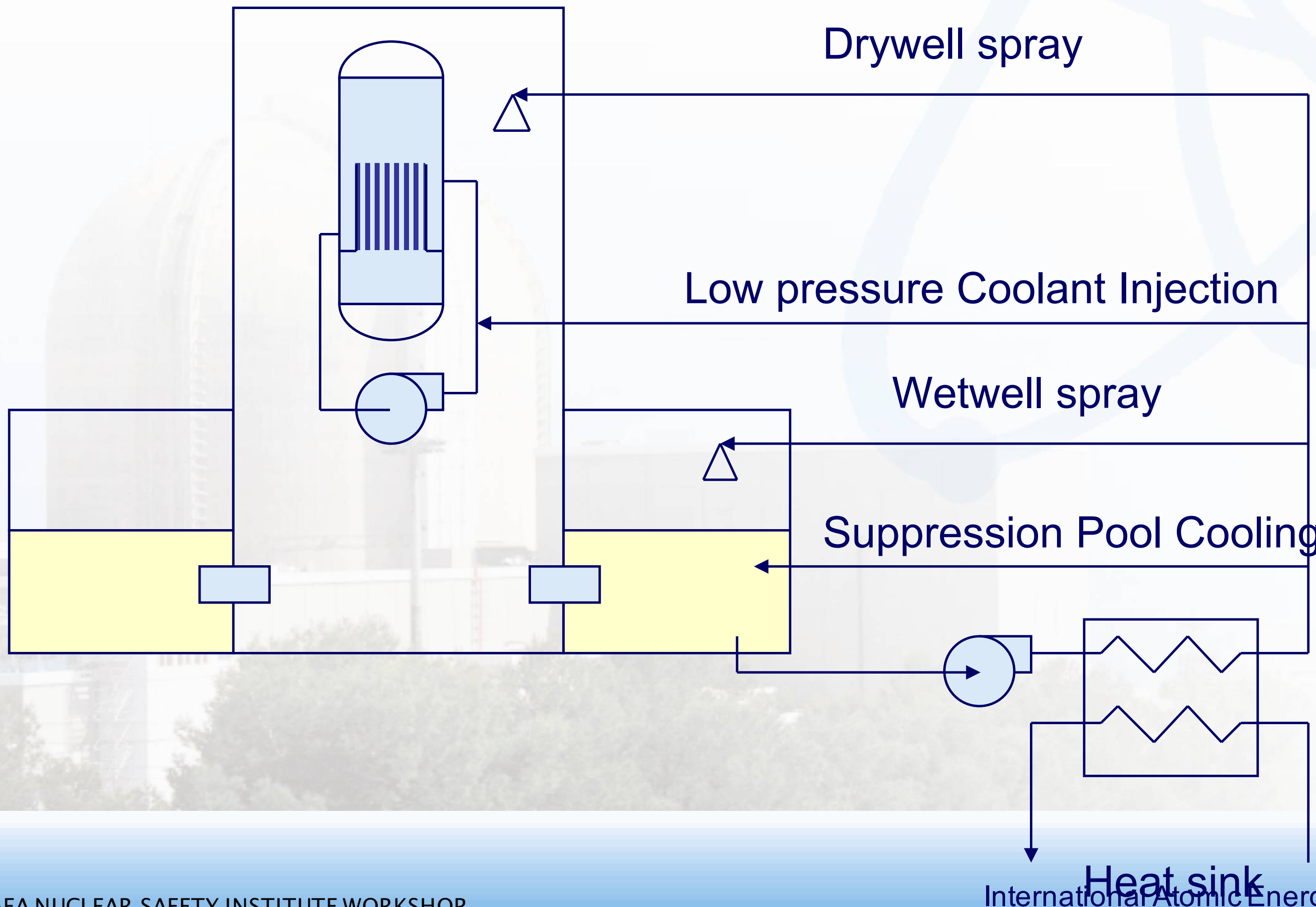


Type 69



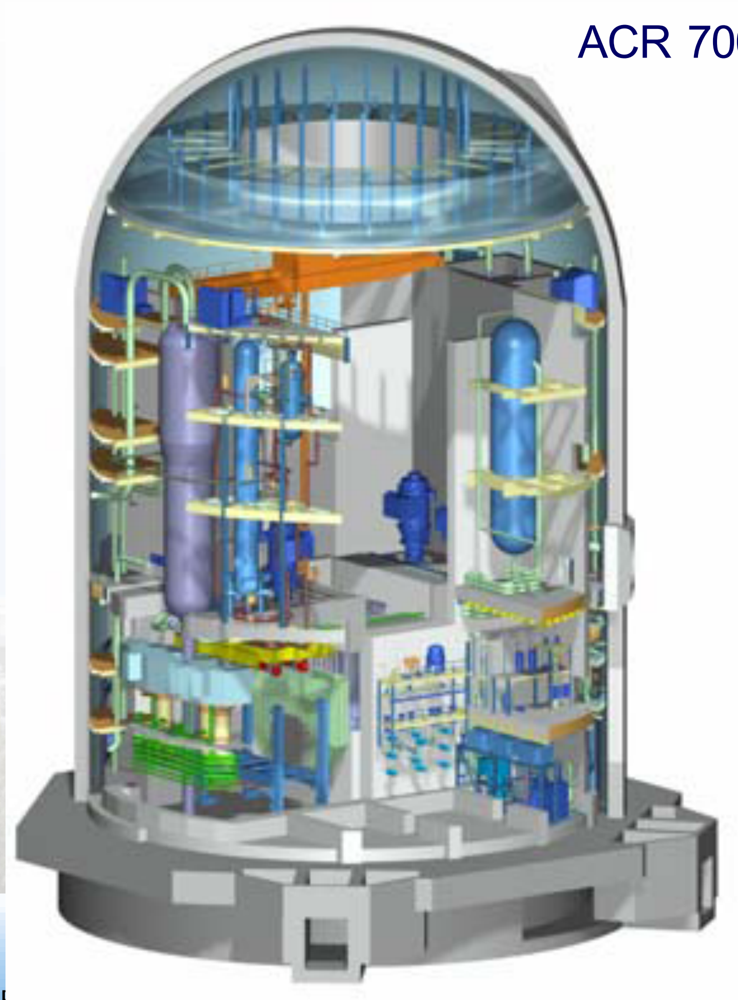
Type 72

BWR Residual Heat Removal System typically has Multiple Configurations & Functions

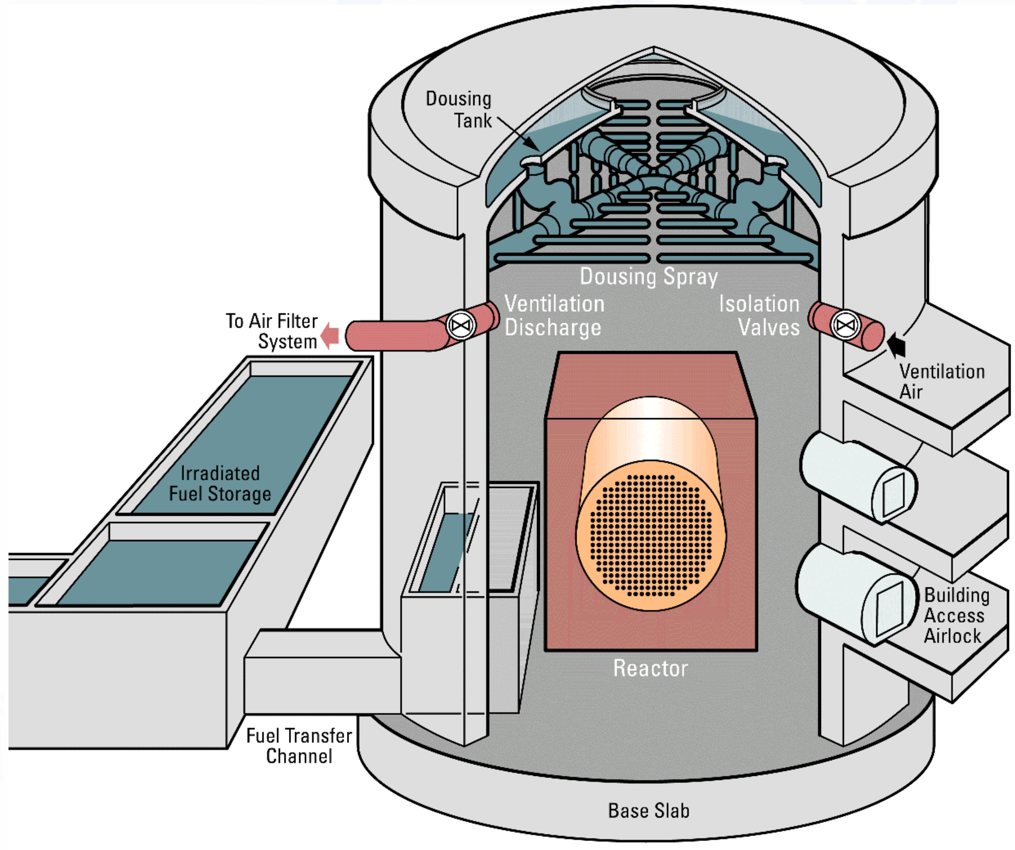


CANDU Systems

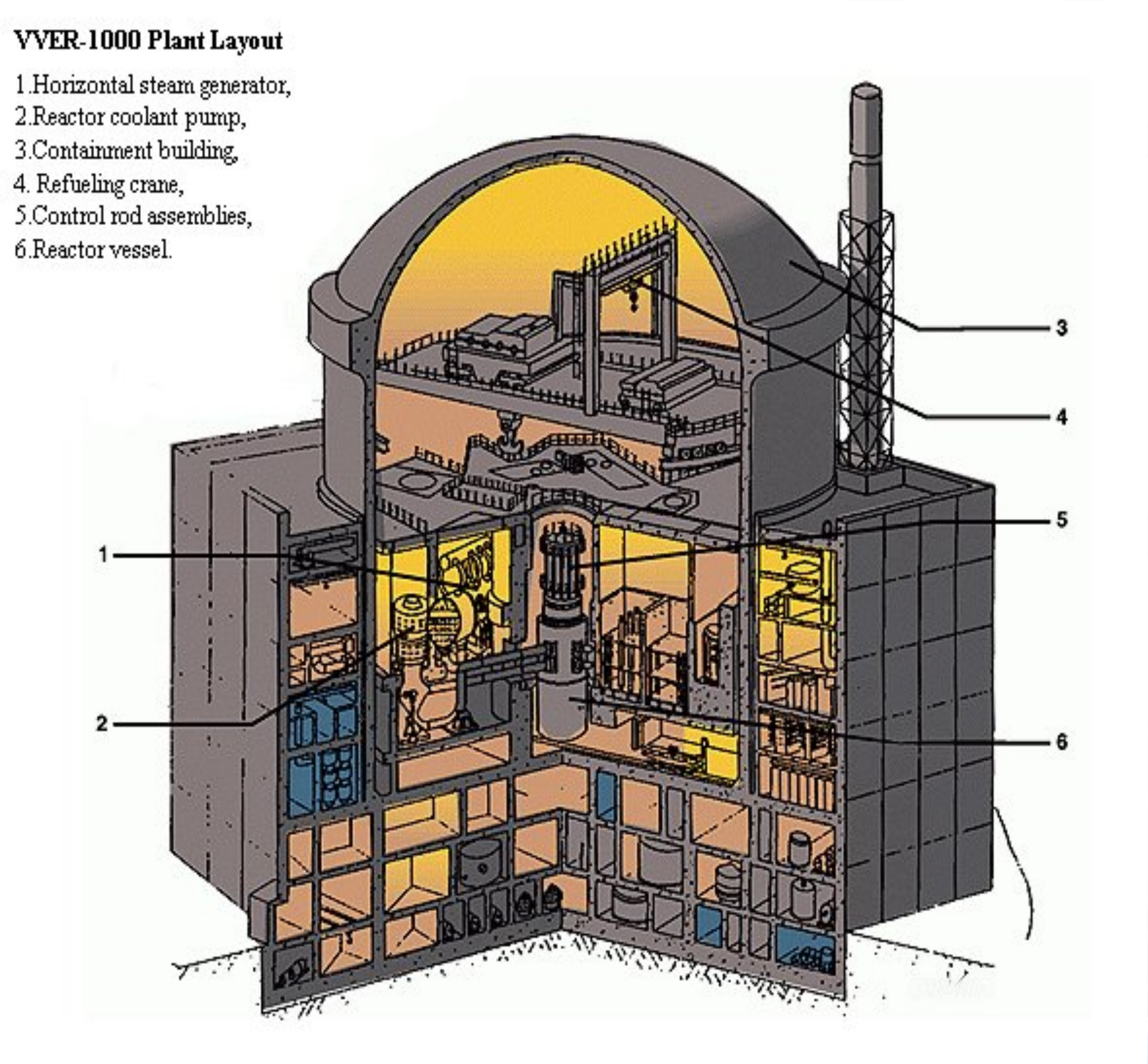
ACR 700



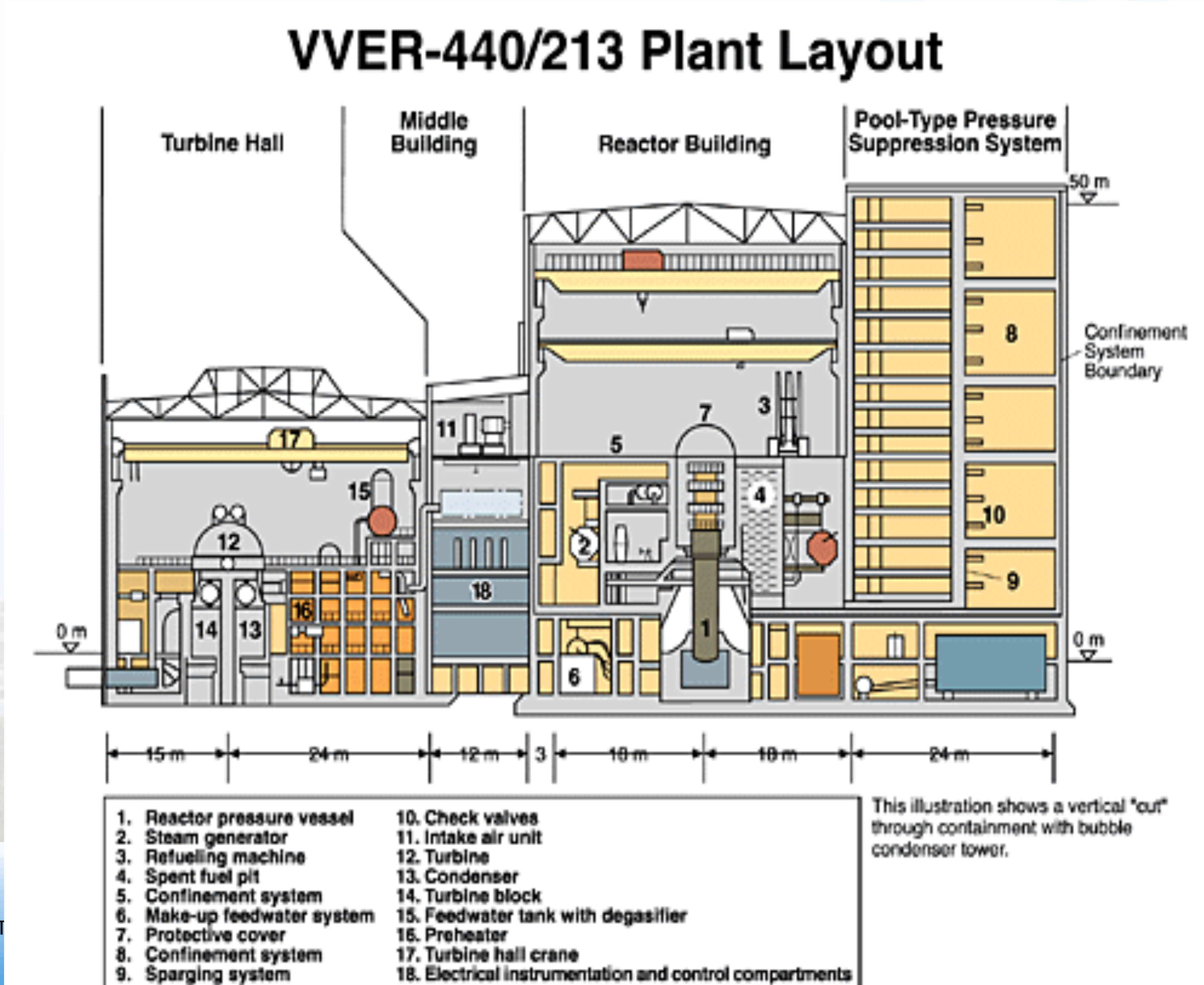
CANDU 6



VVER1000 Containments



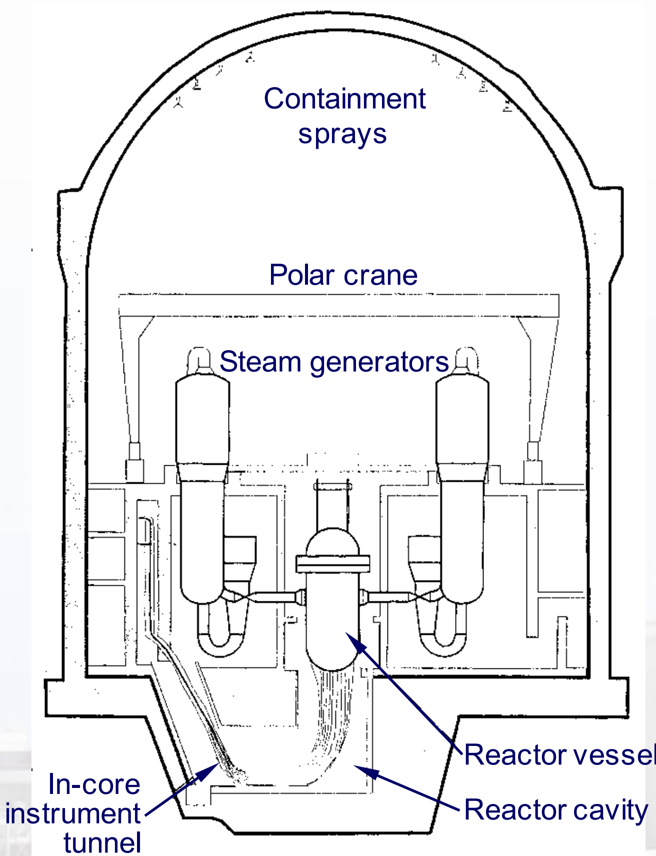
VVER1000 Containments



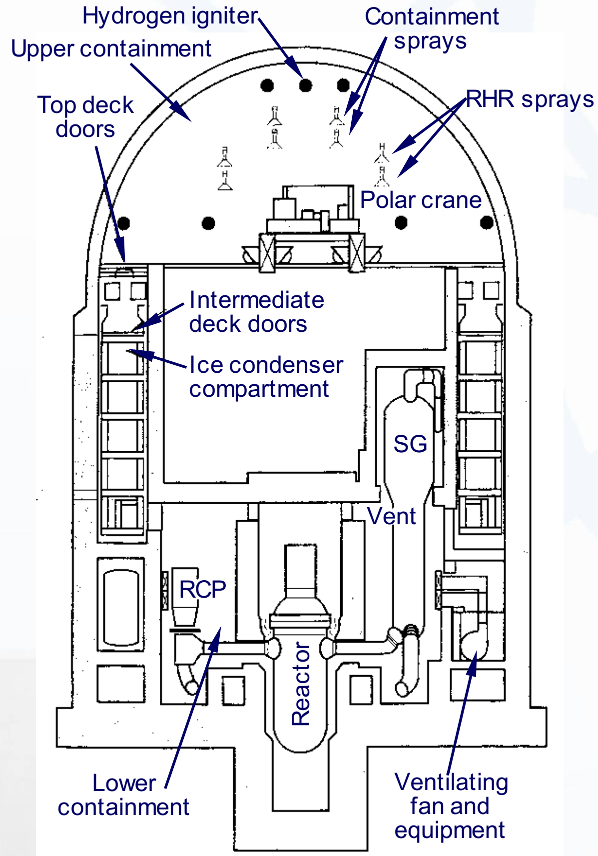
PWR Containments Vary in at Least Two Features

- **Containment function**
  - "Large-dry" versus Pressure Suppression
- **Structural configuration**
  - Steel versus concrete
  - Reinforced concrete versus tensioned concrete

PWR Containment Functions

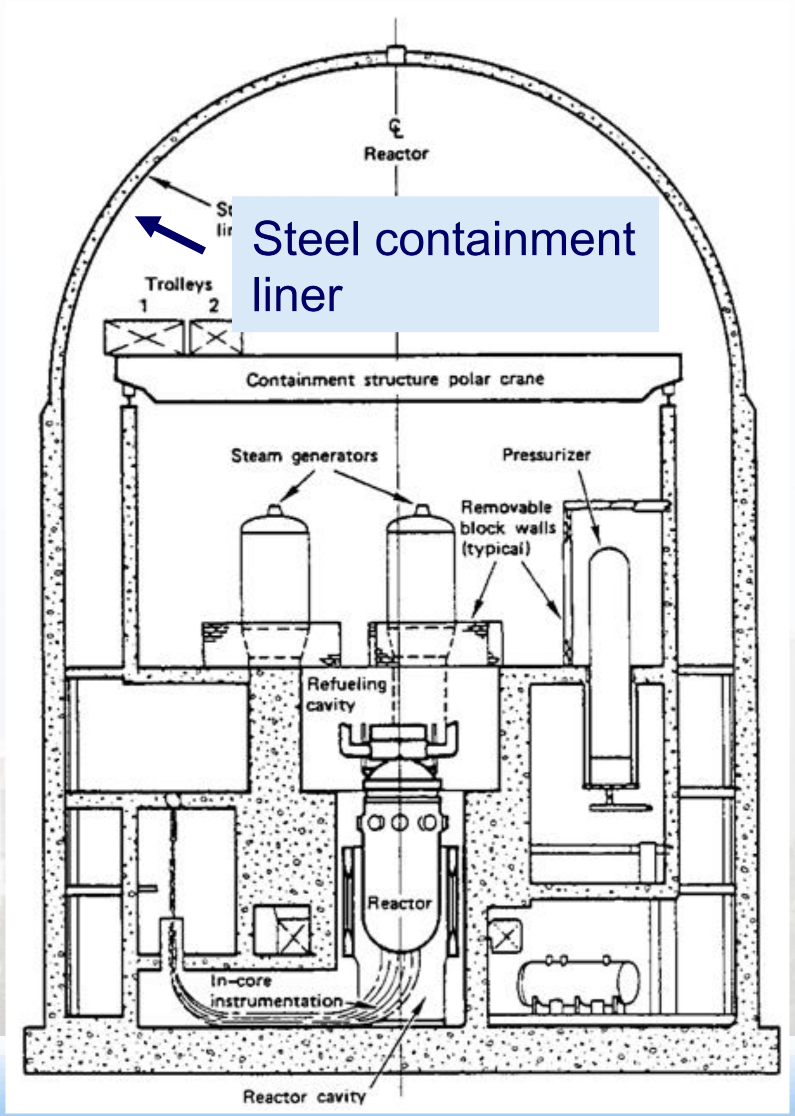


Large dry



Pressure Suppression

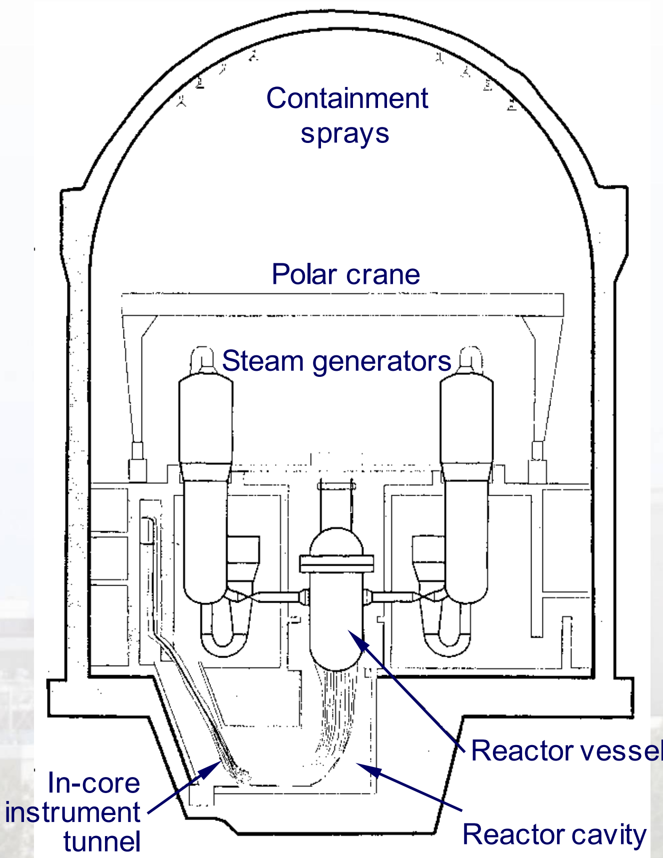
Large Dry Reinforced Concrete Containment

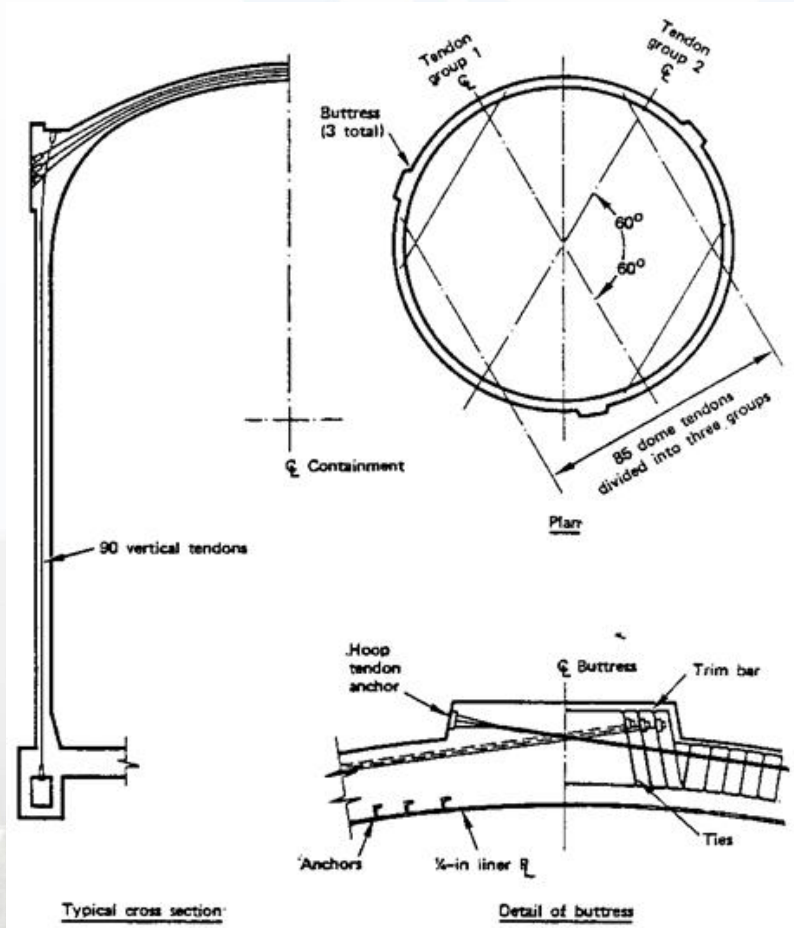


Large open airspace for equipment movement and accommodating coolant discharge during postulate accident conditions

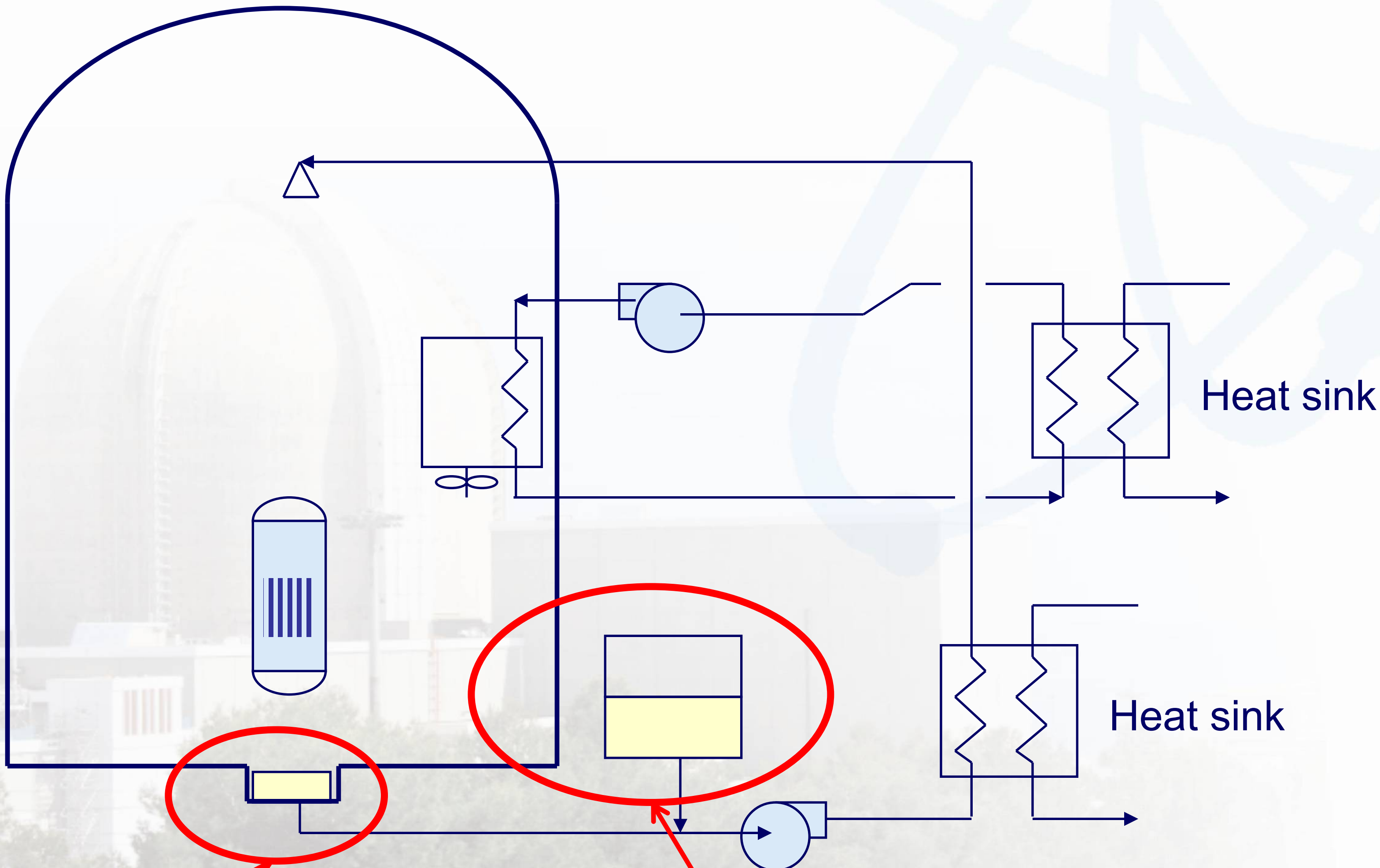
Several connected lower compartments housing essential plant systems

Large Dry Pre-stressed (or Post-tensioned) Concrete Containment





Containment Heat Removal for Large Dry Containment Uses Sprays and Fans Coolers



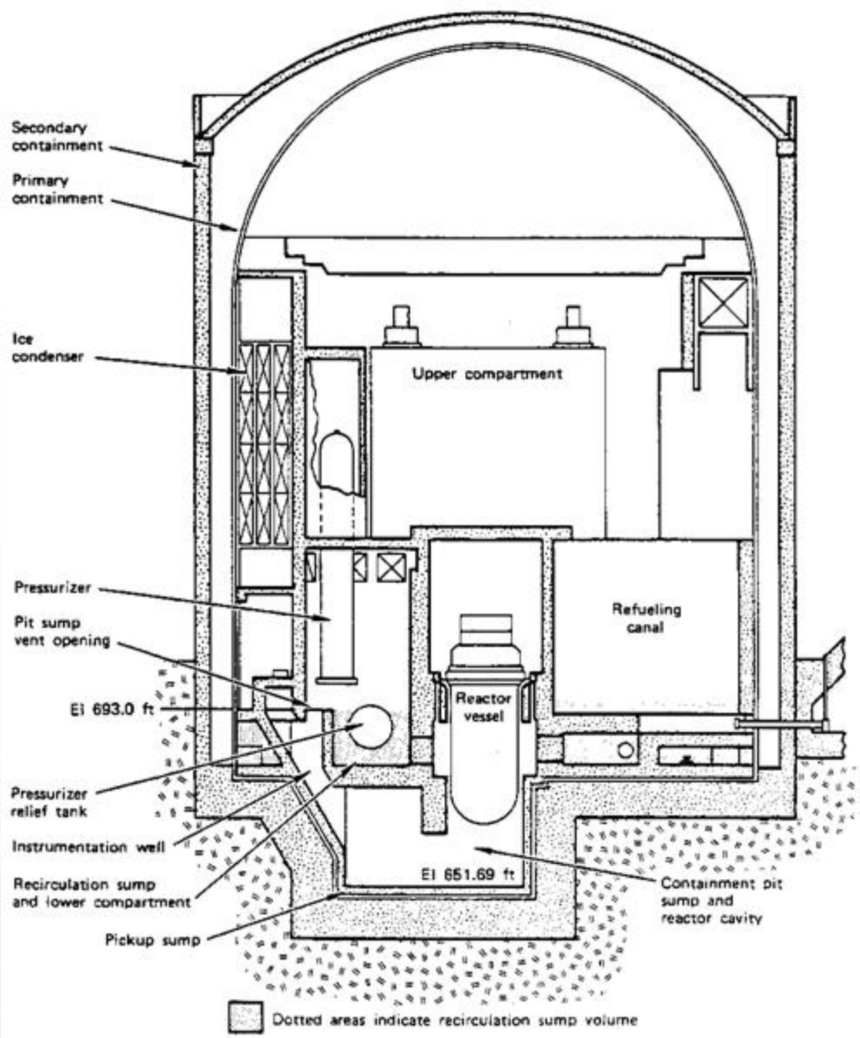
Late phase - recirculation

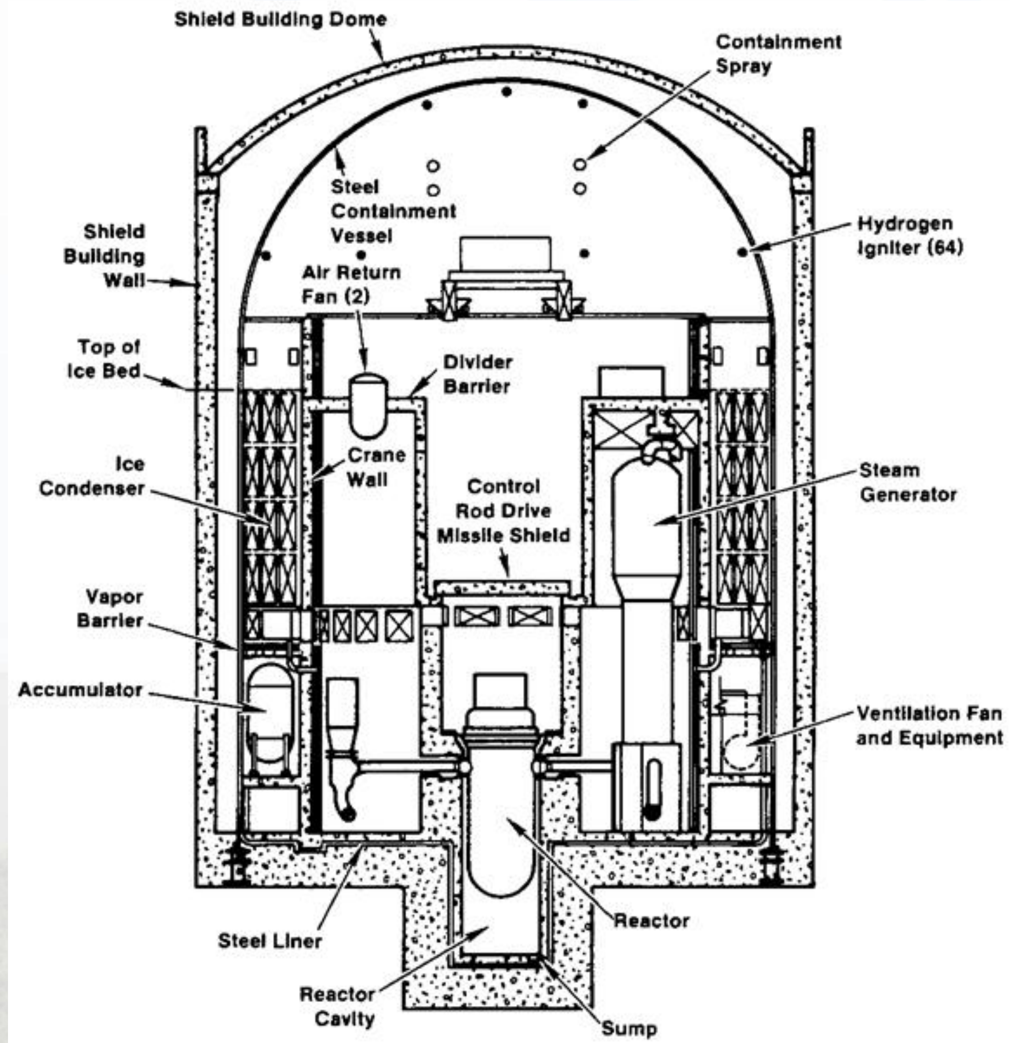
Early phase – injection from RWST

Common Features of Ice Condenser Containments

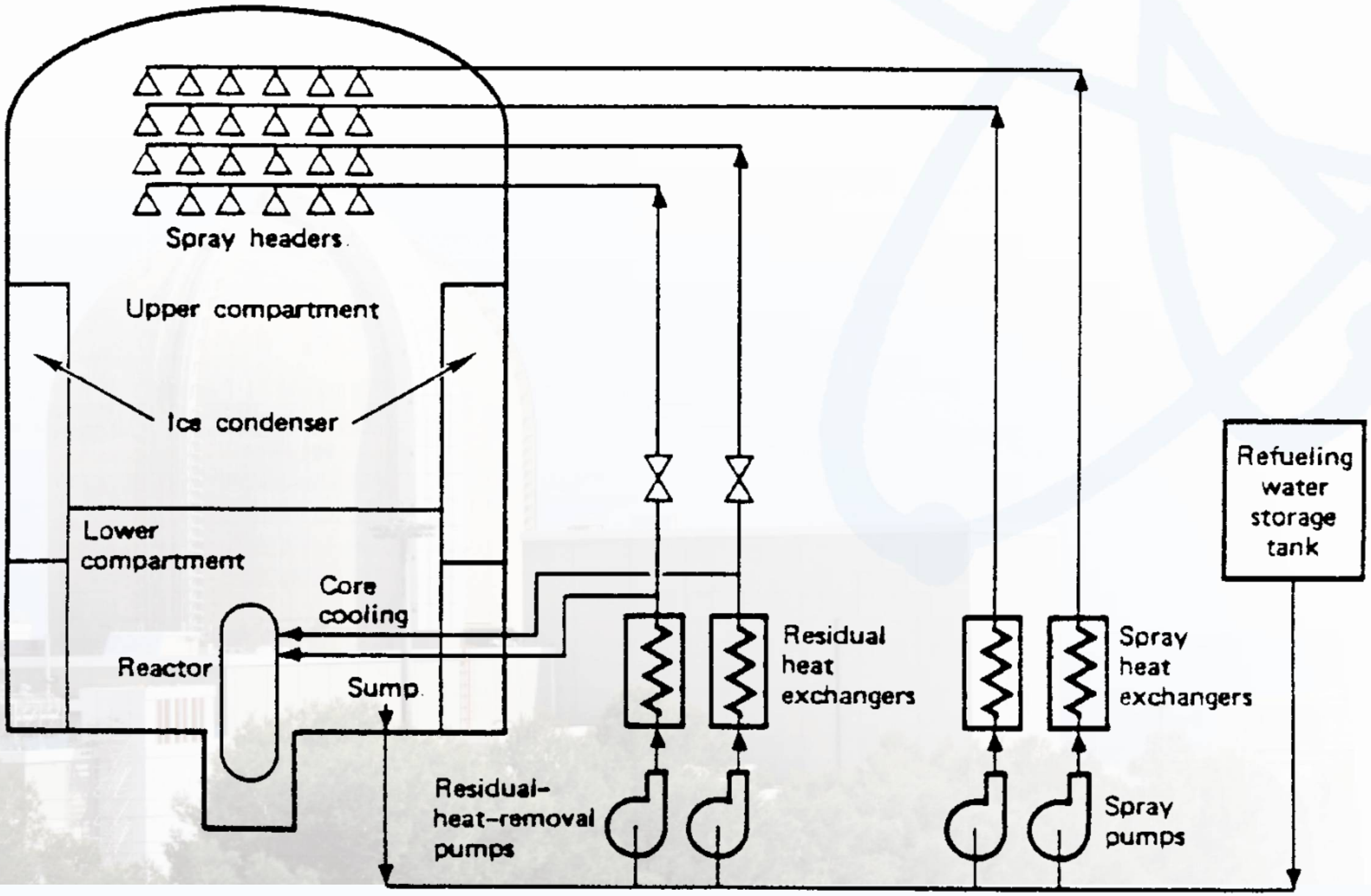
- Three volumes: lower compartment, upper compartment, ice condenser
  - Ice condenser connects lower compartment containing RPV and RCS to upper compartment
  - Ice condenser holds approximately 2×10^6 lb of borated ice in perforated metal baskets
- Relies on igniters for hydrogen control
- Most have cylindrical steel containment surrounded by concrete secondary containment
  - D. C. Cook: concrete containment with steel liner

Cross Section of Typical Ice Condenser Containment





Containment Heat Removal Achieved with Ice Condenser and Sprays



Deterministic Safety Analysis Assessment

- **Equipment Failures:** Initiating events can be individual equipment failures that could directly or indirectly affect the safety of the plant. The list of these events adequately represents all credible failures of plant systems and components.

- **Human Failures.** The consequences of human errors can be similar to the consequences of failures of components. Human errors may range from faulty or incomplete maintenance operations, to incorrect setting of control equipment limits or wrong or omitted operator actions (errors of commission and errors of omission).

- **Other internal events.** Fires, explosions and floods of internal origin also have the potential to be important influences on the safety performance of the plant and are normally included in the compilation of the list of PIEs.

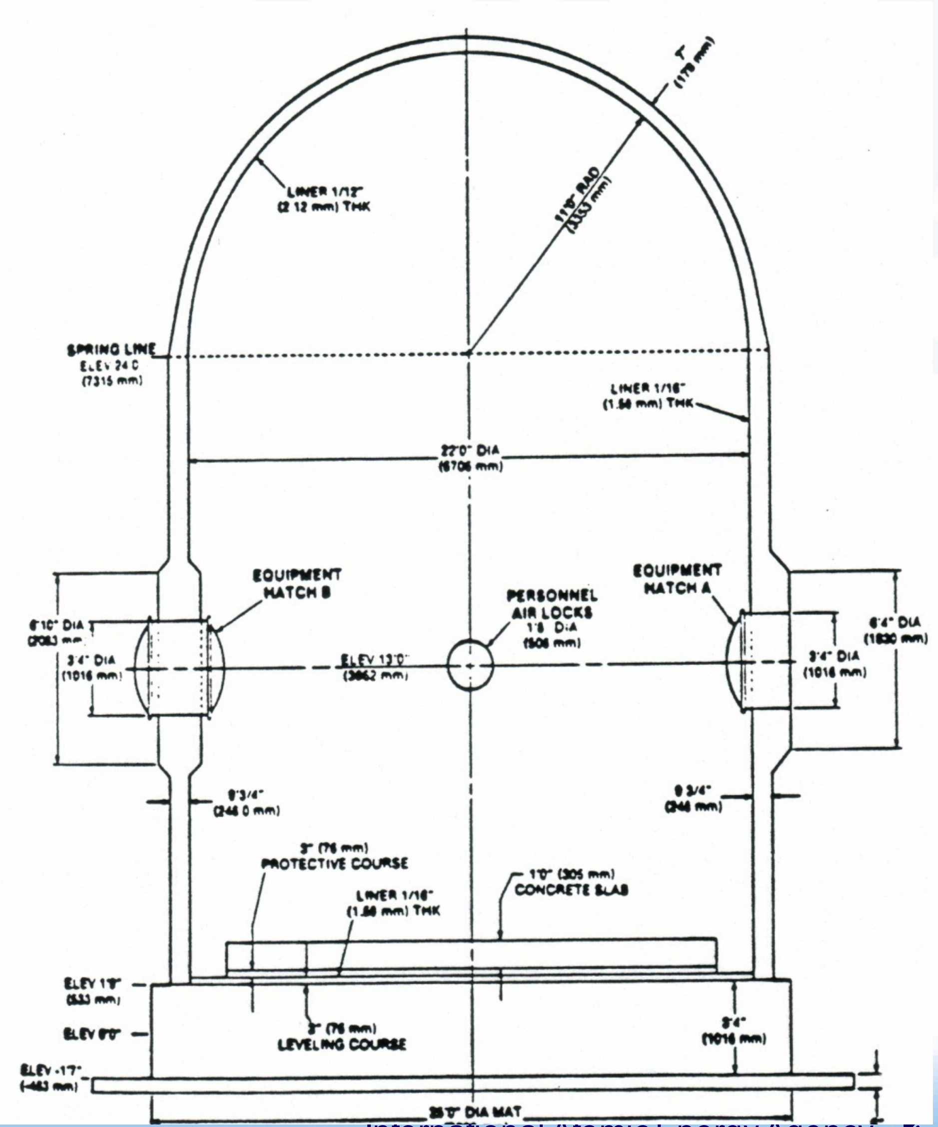
Deterministic Safety Analysis Assessment

- **External Events. If the likelihood of failure of a structure, system or component important to safety due to natural or human induced external events can be inferred to be acceptably low because of adequate design and construction, failure caused by that event need not be included in the design basis for the plant.**

- **Combination of events. Care needs to be taken in combining individual events in analyzing accidents to ensure that there is some rationale for the particular combination.**

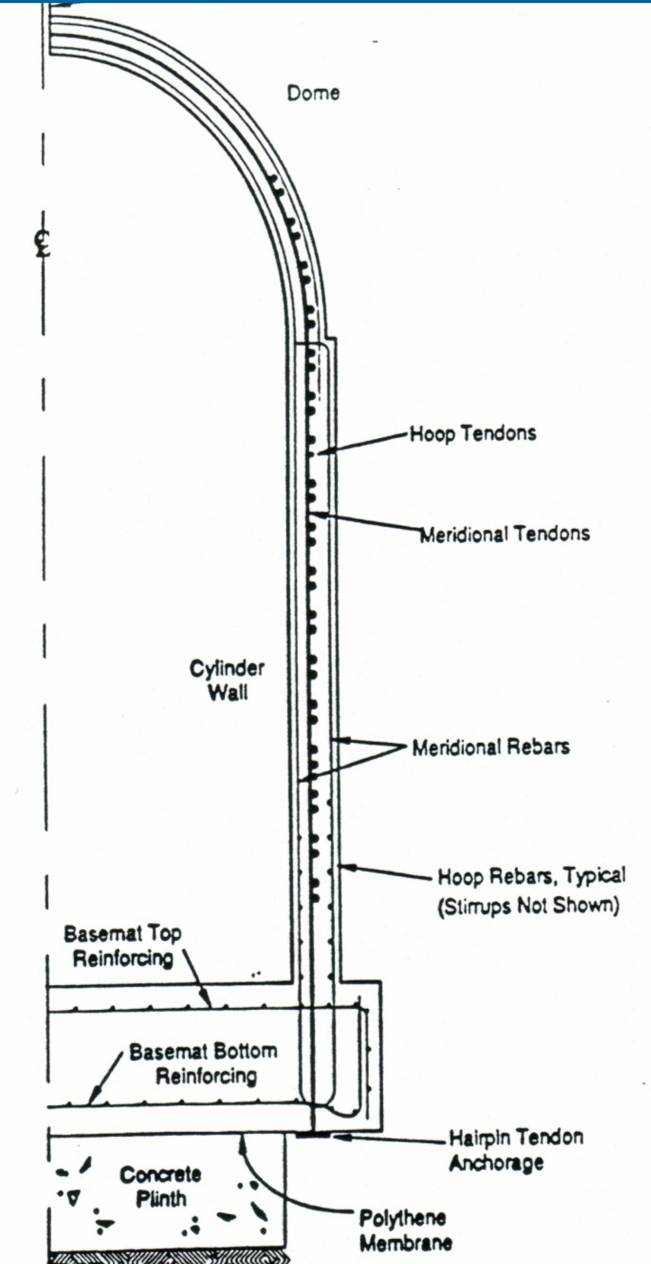
Data Required to Perform Realistic Failure Analysis

- **Geometric data**
  - General configuration
  - Details of structural discontinuities
  - Penetration details
  - Weld locations



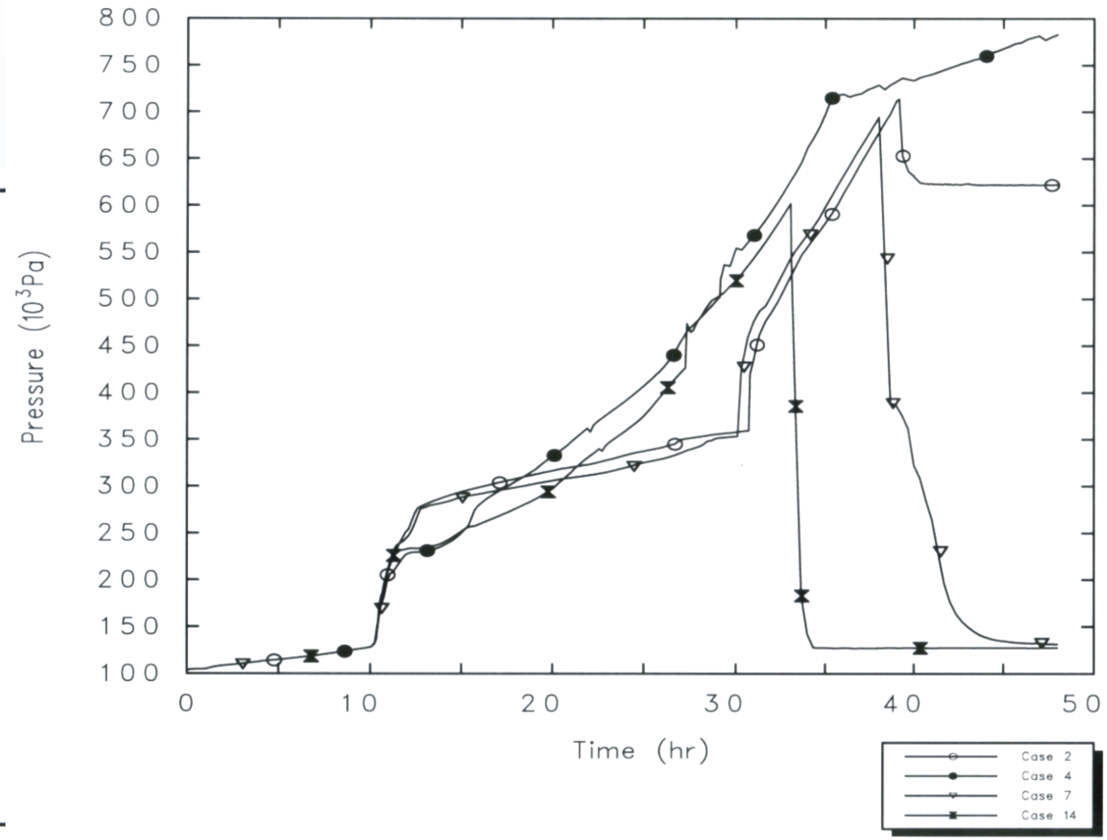
Data Requirements

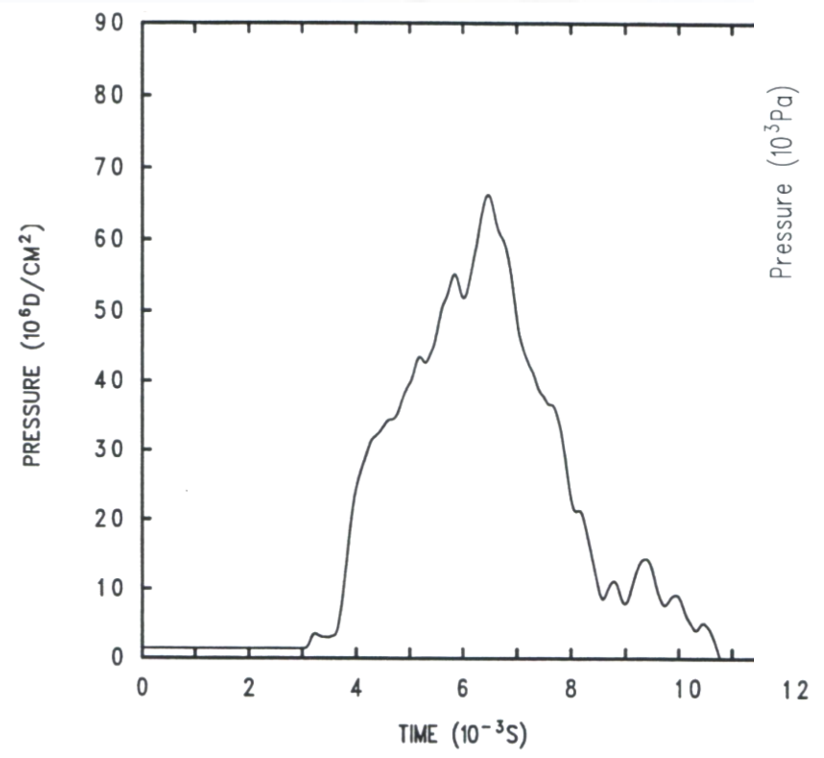
- **Construction materials**
  - Rebar, stiffeners, aggregate for concrete
  - Steel type(s) and tension
  - Results of component testing (if any)
  - Seal design/composition



Data requirements

- **Definition of loads**
  - **Pressure & temperature history (quasi-static load)**





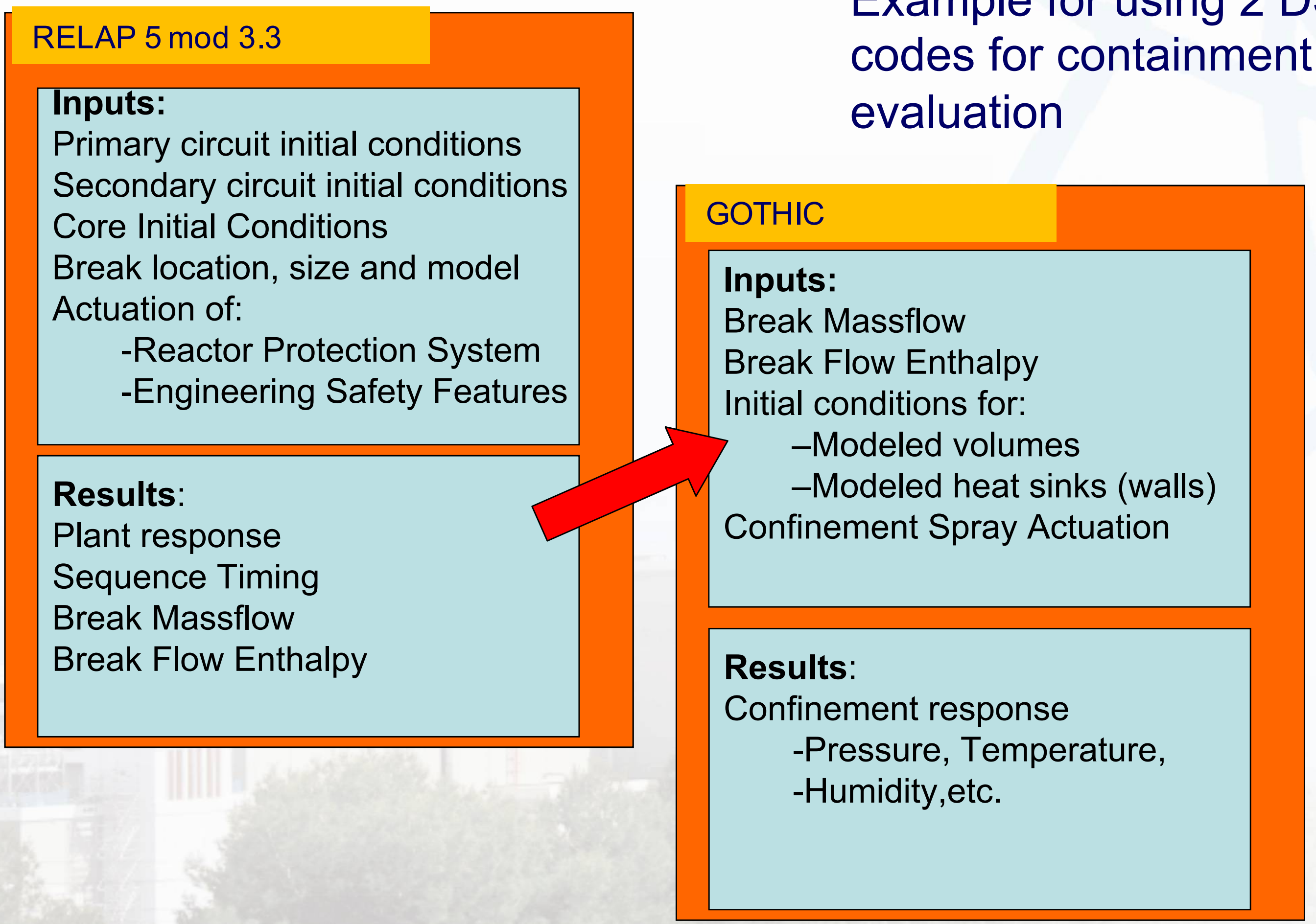
  - Impulse (dynamic load)

Load calculation uncertainties

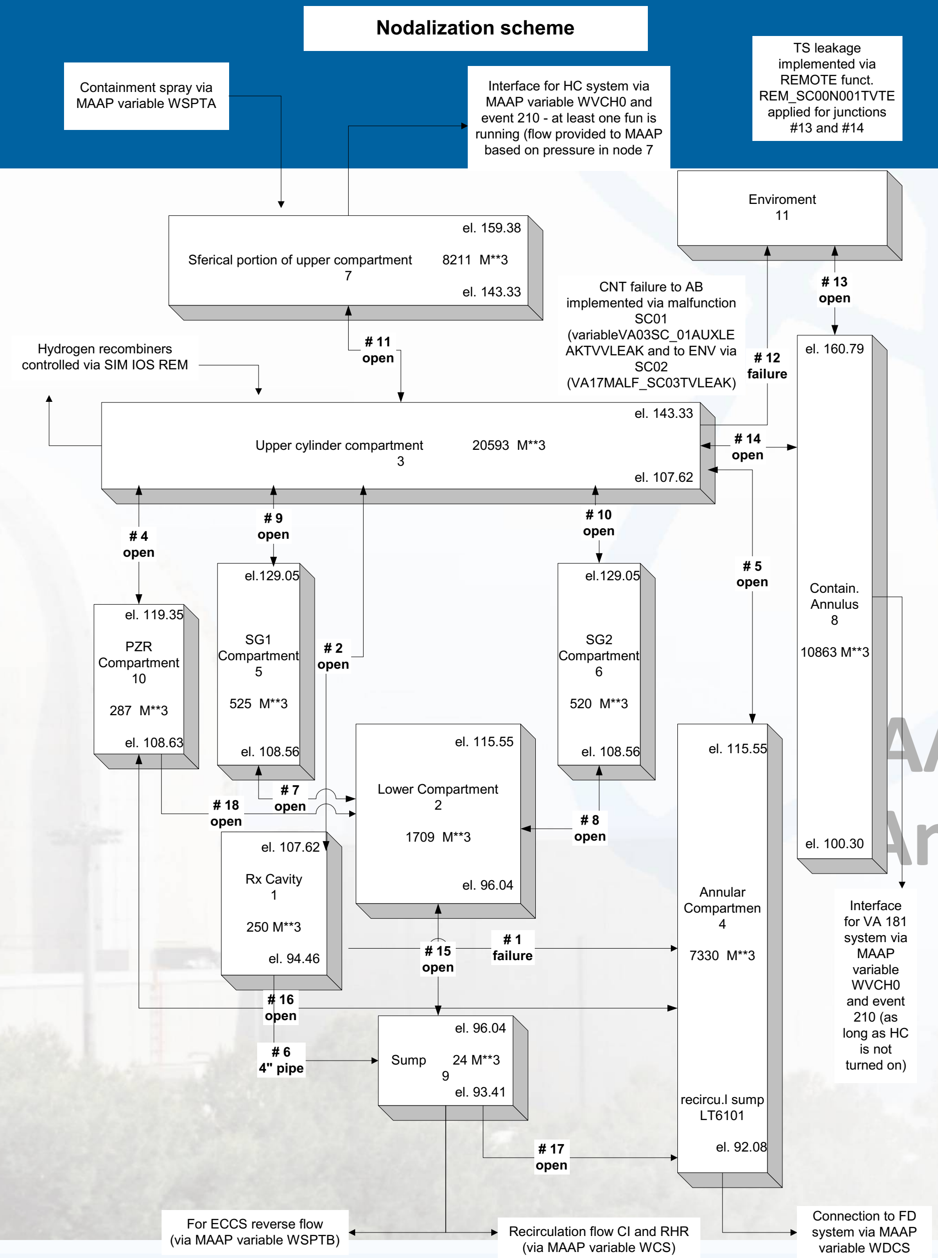
- **Models and nodalization scheme**
  - Free volumes (junctions)
  - Heat structures
  - Initiating and boundary conditions
  - Heat transfer condition
- **Verification and validation of codes DBA and SA (MAAP, MELCOR, GOTHIC,..)**
  - Containment heat removal
  - Steam explosion
  - Direct containment heating
  - Molten core concrete interaction (MCCI)
  - Hydrogen behaviour (other combustible material)
  - Containment melt through
- **User effects**

Deterministic Safety Analysis Assessment

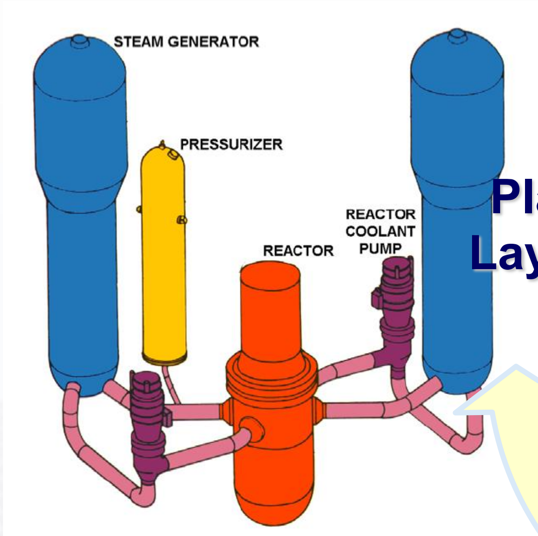
Example for using 2 DSA codes for containment evaluation



MAAP 4.0.5 Model

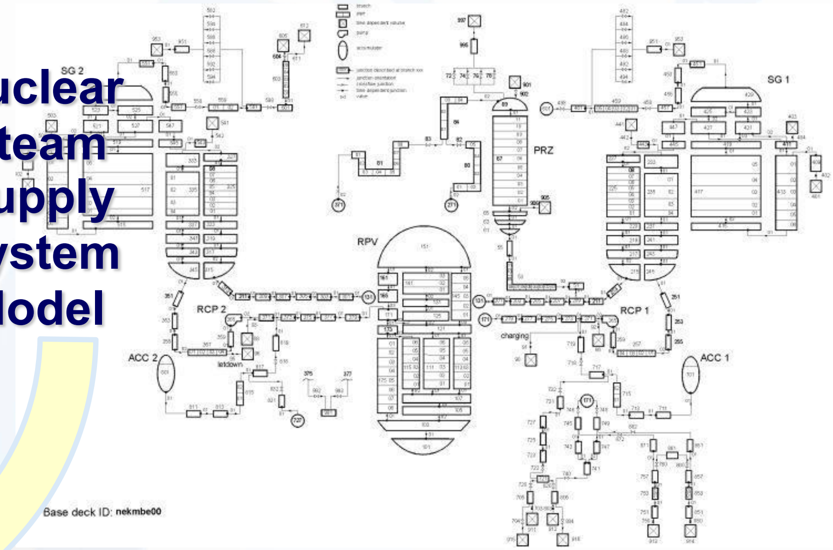


Deterministic Safety Analysis Assessment

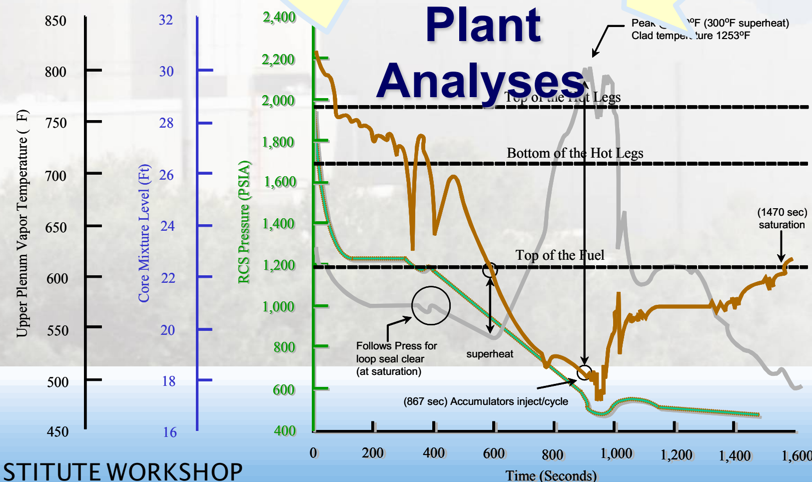


Plant Layout

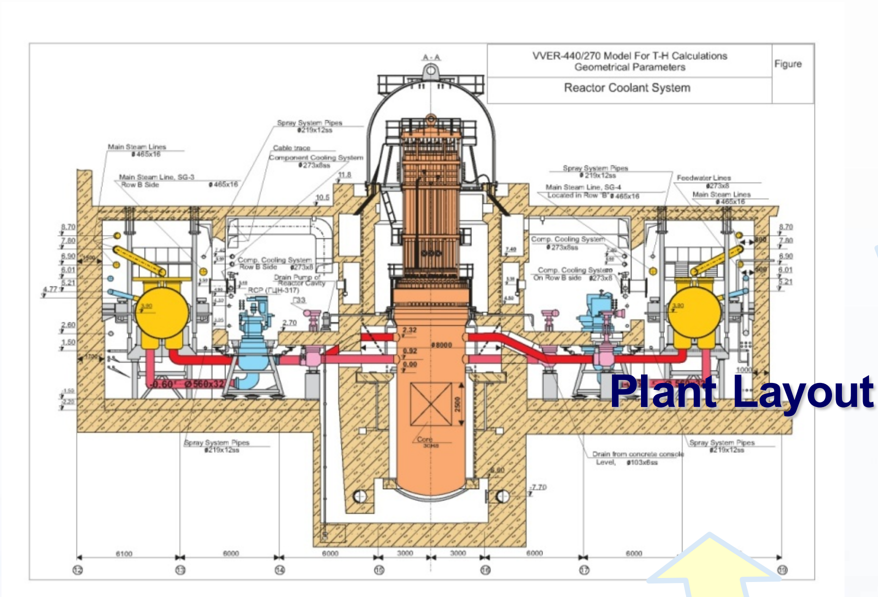
Nuclear Steam Supply System Model

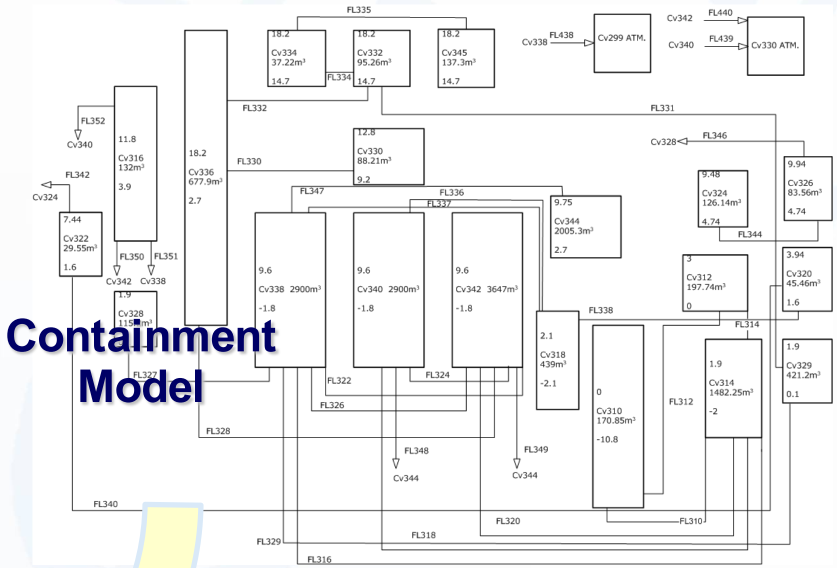


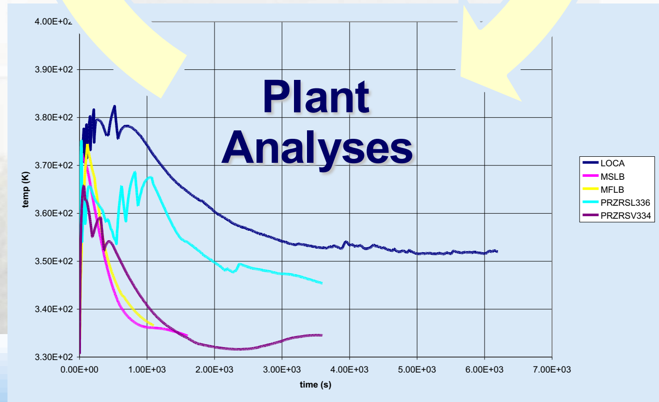
Plant Analyses



Deterministic Safety Analysis Assessment







DBA Containment Pressure Analyses

Chapter 13: Conduct of Operations
Chapter 14: QA

Organizational
Training
Emergency Planning
Review and Audit

Chapter 15: Accident Analyses

- Assumptions and inputs (table 15.0.3-2a/b)
- Computer codes and initial conditions summary (table 15.0.3-3)
- Trip setpoints and time delays (table 15.0.6-1)
- Systems and Equipment Available for Transients and Accidents (table 15.0.8-1)
- Source Term (table 15.0.9-1)
- Atmospheric Conditions (table 15.0.12-1)
- Single Failures Assumed in Accident Analyses (table 15.0.13-1)

Chapter 2: Site Characteristics
Chapter 4: Reactor (T&H Design)
Chapter 5: RCS

Chapter 6: Engineering Safety Features

- Containment
- ECCS (SI and RHR)
- MCR Habitability Systems

Chapter 3: Design of SSC

- Classification
- Misile Protection
- Seismic Design
- Environmental Design
- Flooding, Wind, etc.

Support Systems

- **Chapter 7: Instrumentation and Control (RTS and ESFAS)**
- **Chapter 8: Electrical Systems**
- **Chapter 9: Auxiliray systems**
- **Chapter 10: Steam and Power Conversion systems**
- **Chapter 11: Radioactive Waste Management**

DBA Containment Pressure Analyses

Accident: Main Steam Line Break (MSLB)
USAR: Chapter 15.1.5 and 6.2

↓

SLB Core Response
SLB CNT Response
EQ

Verification and validation

↓

Calcnotes
NPSH from RWST to CI pump
CI pump NPSH from CNT sump
SLB MER

Early phase – injection from RWST

Late phase - recirculation

DBA Containment Pressure Analyses

- Necessary protection against a MSLB:
- MSLB - ANS Condition IV - Limiting Faults - USAR 15.1.5
- ECCS actuation
  - PRZR Press Low
  - CNT Press High
  - SL Press Low
- RTS
  - SI, PRZR press low, OTDT, OPDT, High neutron flux, High Neutron Flux rate, Low-low SG NR LVL
- Redundant isolation of the main feedwater lines
- Main steam isolation
- Codes and methodology: LOFTRAN and THINC (DNBR criteria)
- Table 15.0.6-1 Trip points and time delays to trip assumed in accident analyses
- Table 15.0.8-1 Plant systems and equipment available for transient and accident (15.1.5 - ESFAS: AF + SI)
- Table 15.0.13-1 Single failures assumed in accident analyses (worst failure: one SI train)
- Table 15.1.5-5 Equipment Most Likely to be used following a MSLB
- Table 6.2-50 Containment Isolation Valving Application
- Dynamic Accident Effects:
- 3B.3 Incident Analysis for the effects of pipe whip, jet spray and missiles on shutdown and ESFAS
- 3B.4 Incident Analysis for the environmental pipe break effects of pressure, temperature, humidity on electrical and ventilation

DBA Containment Pressure Analyses

LB LOCA CI Actuation Times

Break size Power Level	DEPSG[1] 102%	DEPSG[1] 102%
SI	MIN	MAX
CI spray	1	1
CI Actuation Time	55s	55s
RCFC	2	4
RCFC Actuation Time	39.5s	39.4s
Peak Pressure	2.83kp/cm²	2.83kp/cm²
Time to Peak Pressure	11.8s	11.8s

[1] Double Ended Pump Suction Guillotine LOCA

MSLB CI Actuation Times

Break size Power Level	0.129m² 102%	0.129m² 70%	0.129m² 30%	0.129m² 0%	0.01066m² 102%	0.0439m² 70%
CI spray	1	1	1	1	1	1
CI Actuation Time	81.1s	80.9s	75.2s	76.5s	151.0s	247.4s
RCFC	2	2	2	2	2	2
RCFC Actuation Time	39.5s	39.4s	39.4s	39.3s	44.2s	46s
Peak Pressure	2.86kp/cm²	2.91kp/cm²	2.89kp/cm²	2.90kp/cm²	2.31kp/cm²	2.01kp/cm²
Time to Peak Pressure	148s	172s	158s	225s	1200s	450s

DBA Containment Pressure Analyses

Figure 1 Criteria for CI pumps stop - MSLB

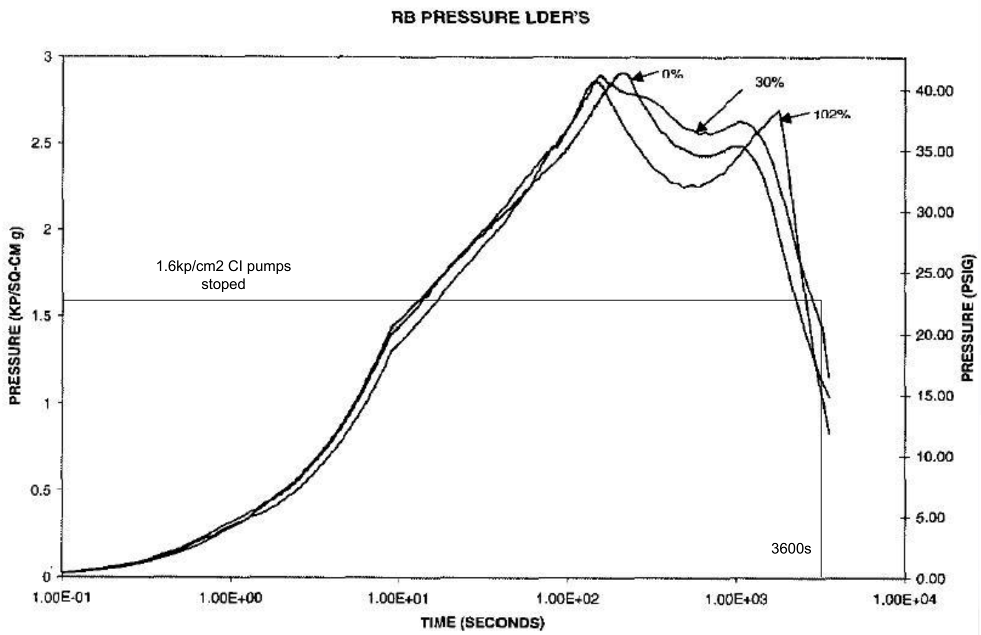
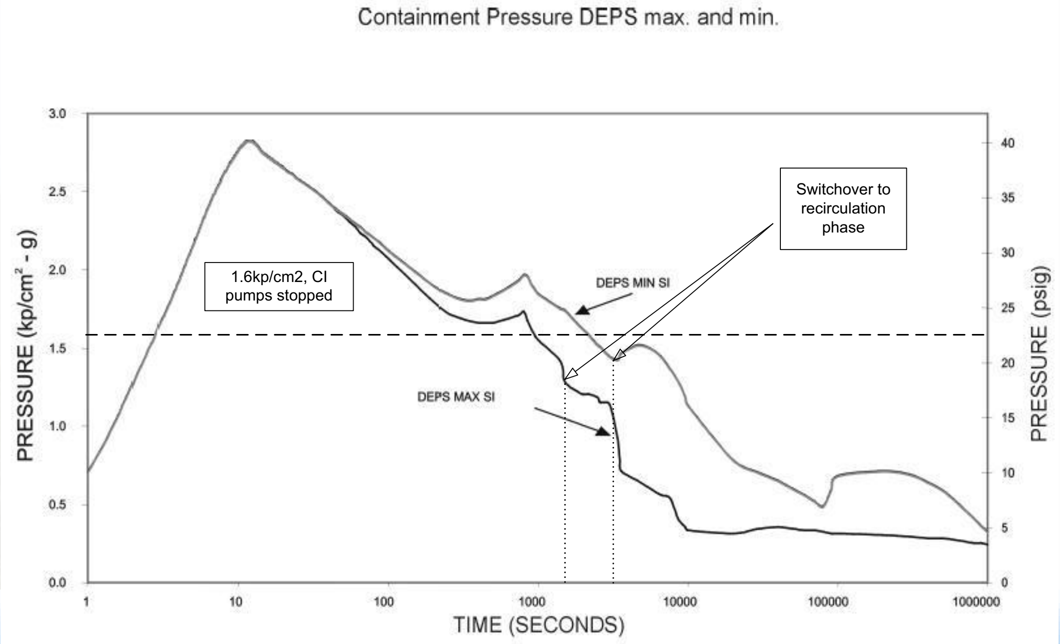
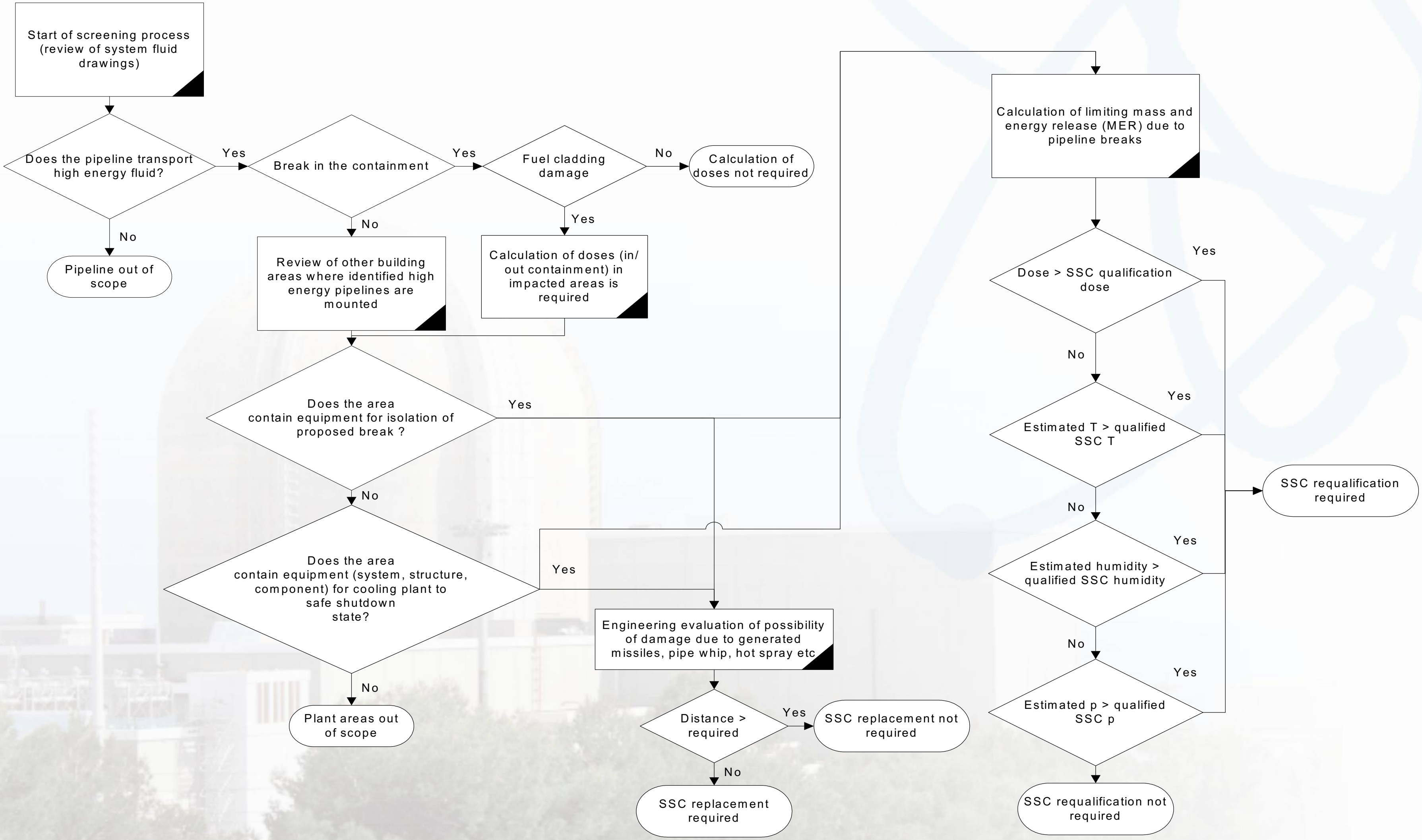


Figure 2 Criteria for CI pumps stop - LOCAs



Equipment Qualification



Equipment Qualification

Identification of potential high energy line breaks

T-h Analyses

Source Term Analyses

Identification of impact to safety equipment

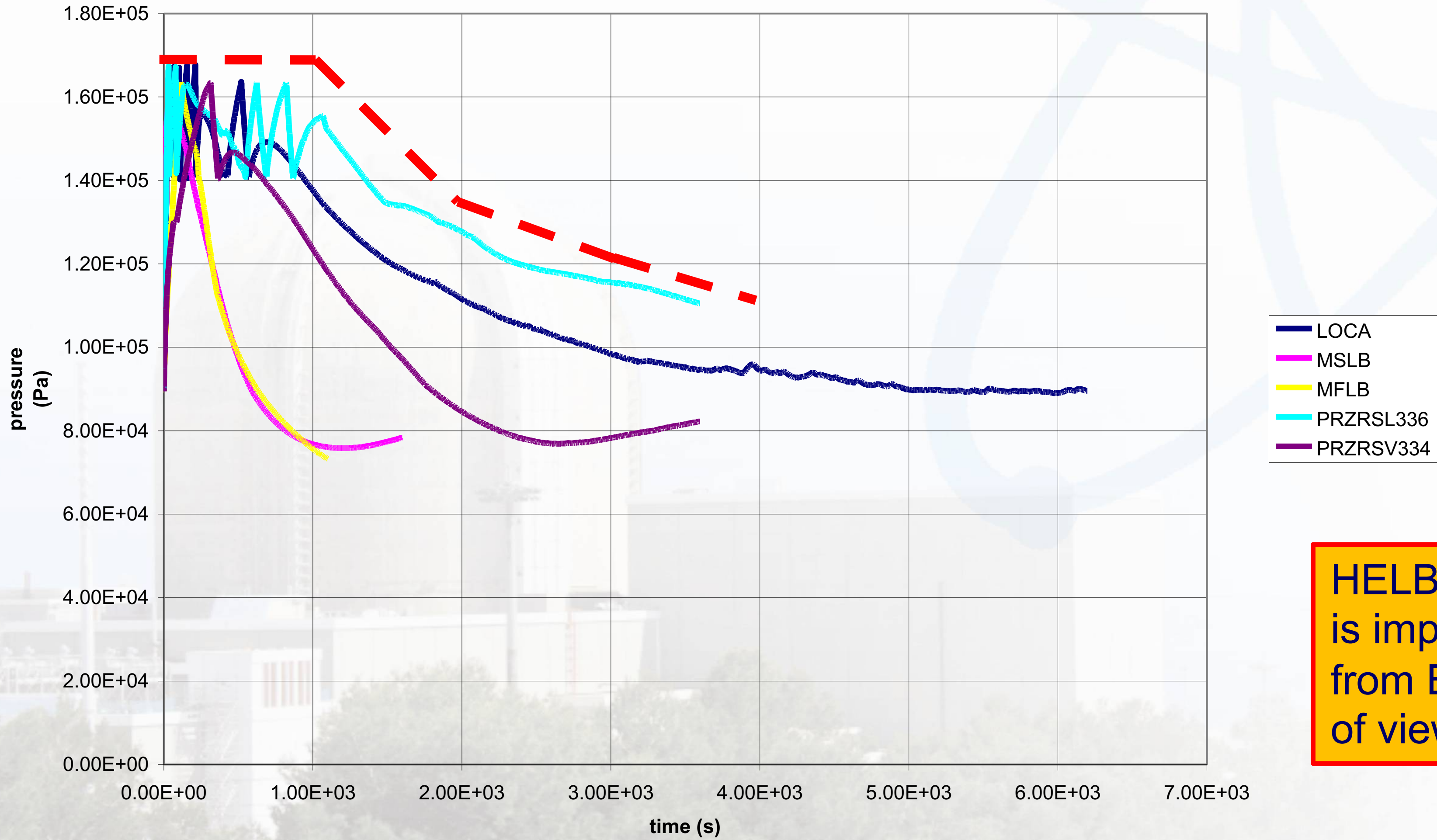
Equipment Qualification – VVER example

HELB	A (m^2)	RELAP node	MELCOR node	References
Reactor coolant cold leg break	0.00785 (100mm)	158	CV314	A-SCALC-CL100
RCS hot leg break (surge line)	0.00785 (100mm)	702	CV336	B-SCALC-PRZRSL
Line from PRZR to SV	2* 0.0063 (DEGB)	720	CV322 and CV334	C-SCALC-PRZSVDE
Instrument Line break	2*0.000254 (DEGB)	142	A004 (separate model)	D-SCALC-ICLOCA
Feedwater Line Break	2*0.04562 (DEGB)	190	CV314	E-SCALC-FWLB
Break in RCS blowdown line	0.000487	0.000487	A009 (separate model)	F-SCALC-MUBA009
Main Steam Line Break	2* 0.1473 (DEGB)	184	CV314	G-SCALC-MSDE

HELB location is important from EQ point of view!!

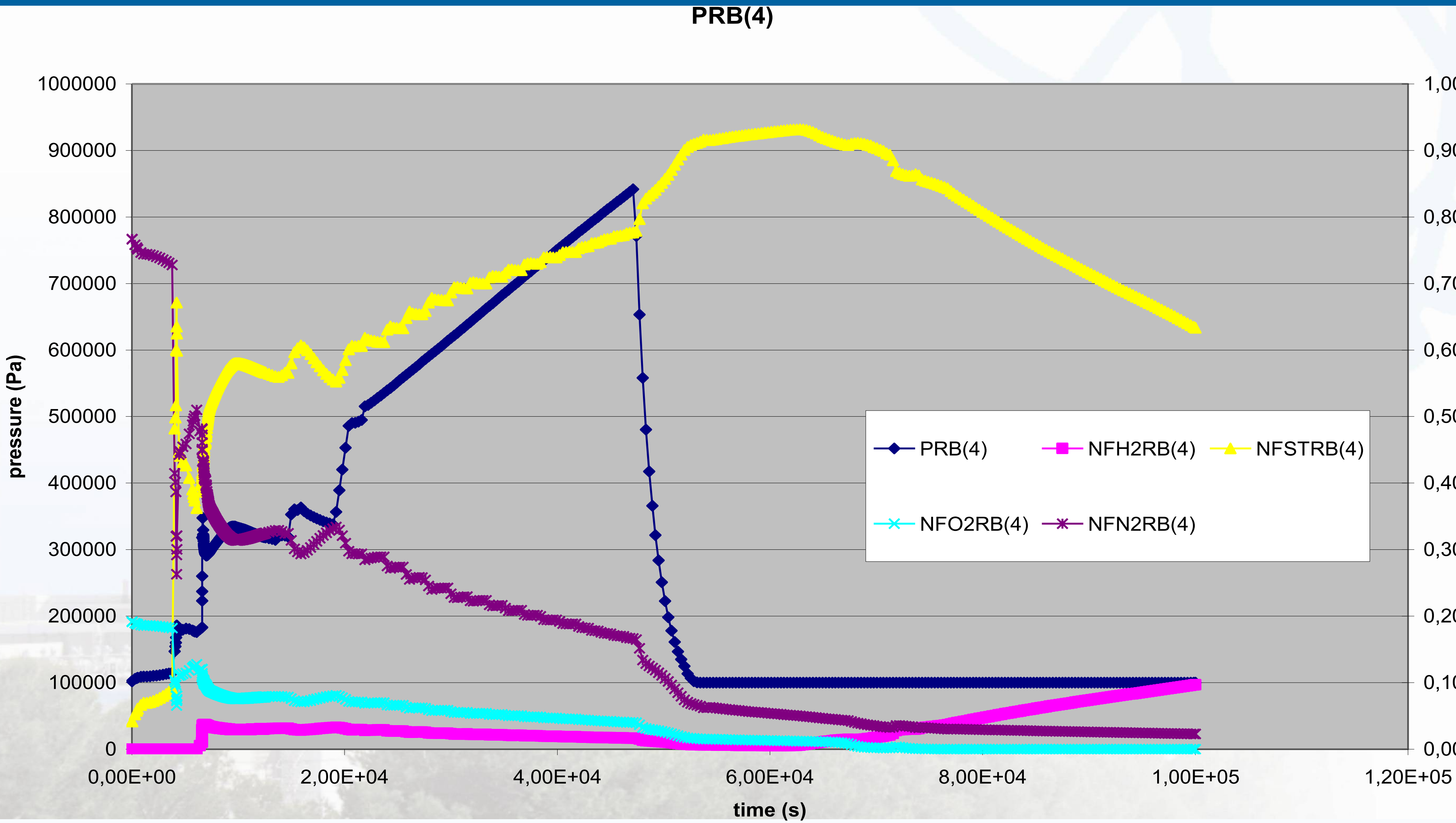
		A-SCALC-CL100			B-SCALC-PRZRSL			C-SCALC-PRZSVDE			E-SCALC-FWLB			G-SCALC-MSDE		
Control volume	Room	p (Pa)	T (K)	Q	p (Pa)	T (K)	Q	p (Pa)	T (K)	Q	p (Pa)	T (K)	Q	p (Pa)	T (K)	Q
Cv 310	A001/2	1.68E+05	382	0.09	1.67E+05	375	0.27	1.63E+05	366	0.54	1.64E+05	374	0.45	1.58E+05	373	0.49
Cv 312	A001/2	1.68E+05	366	0.87	1.67E+05	386	0.90	1.63E+05	360	0.92	1.64E+05	356	0.91	1.57E+05	354	0.92

Equipment Qualification – VVER Example



HELB location is important from EQ point of view!!

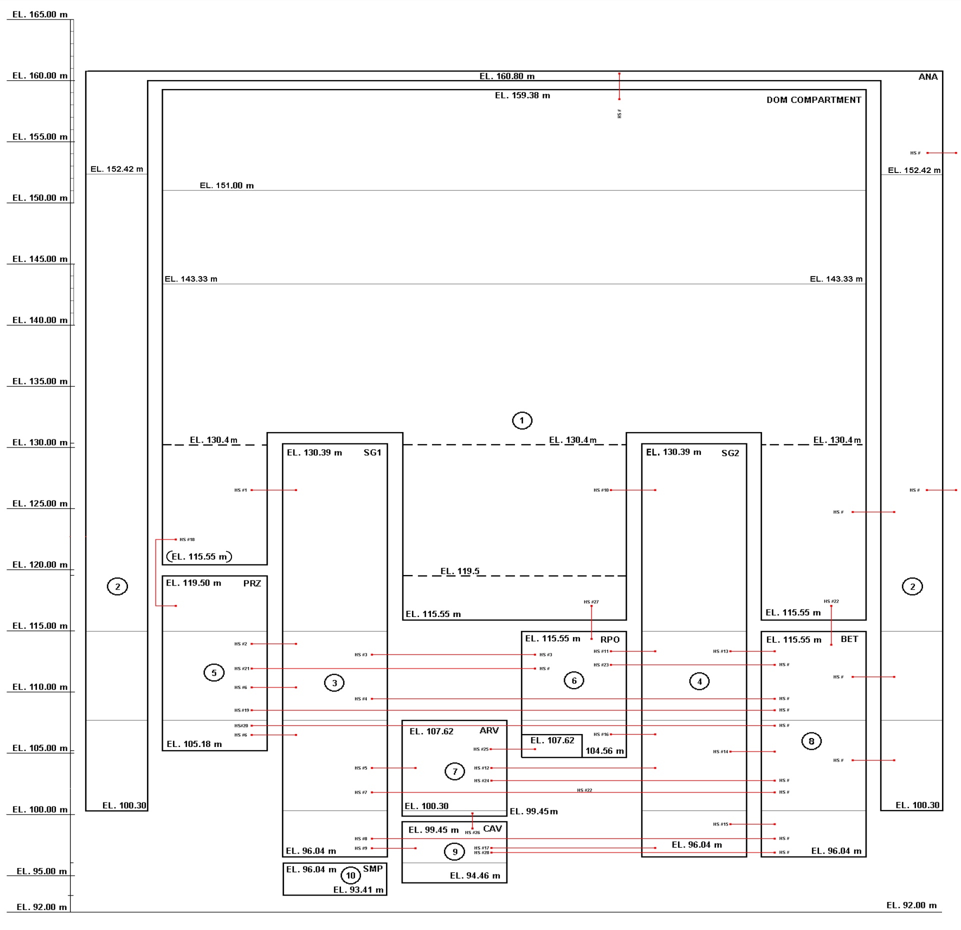
Hydrogen Evaluation - Example



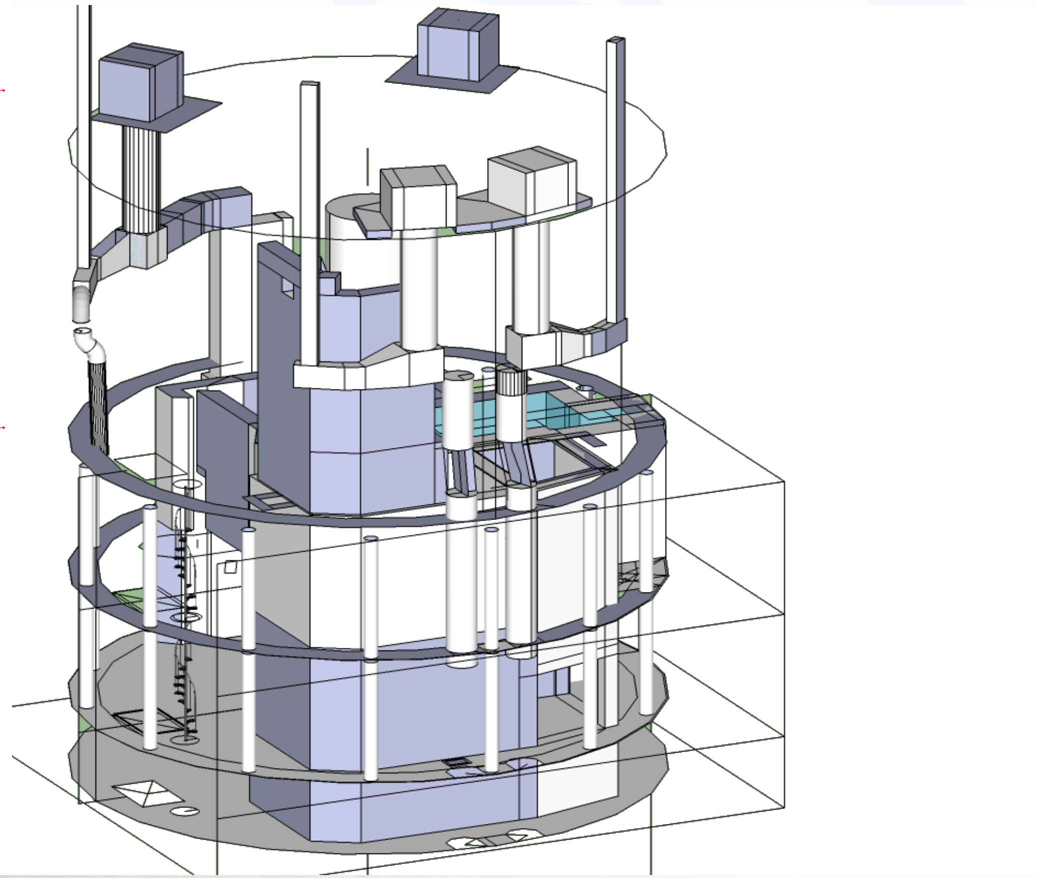
Small LOCA (HSLOCA2) MAAP Results, Containment Pressure, Hydrogen, Nitrogen, Steam Mole Fraction in the Upper Cylinder Compartment

Hydrogen Evaluation - Example

Reference: Hydrogen Distribution in NPP Krško Containment Report number (NEK ESD TR 13/10), D. Grgic and T. Fancev (FER)

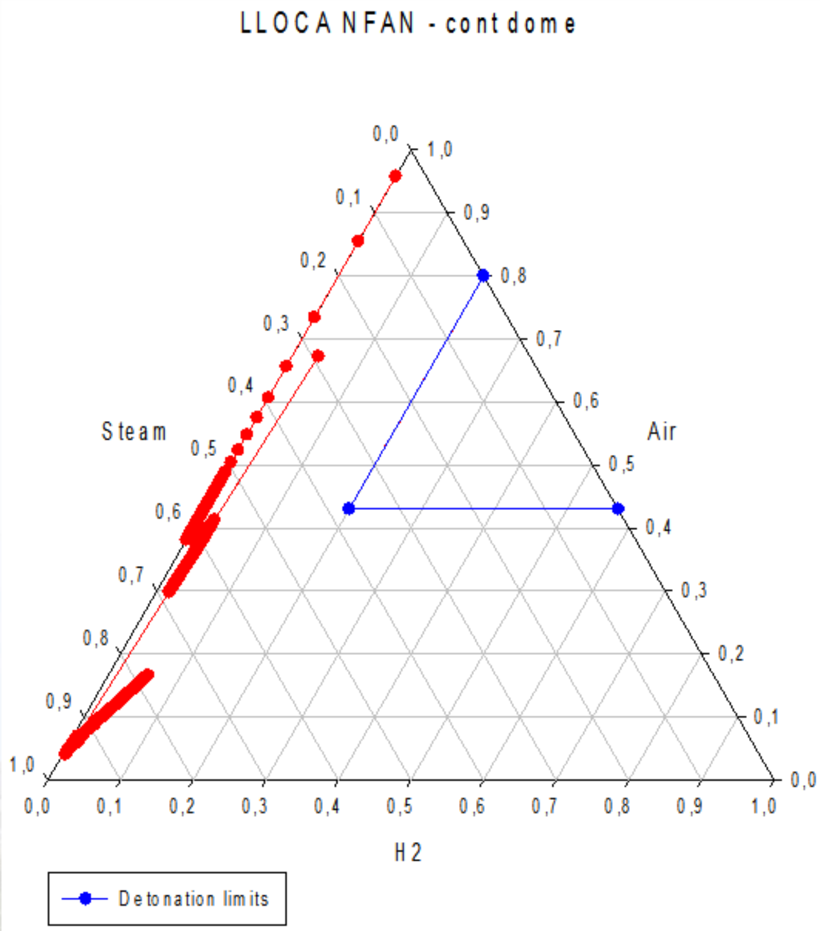


GOTHIC nodalization with subdivided containment dome

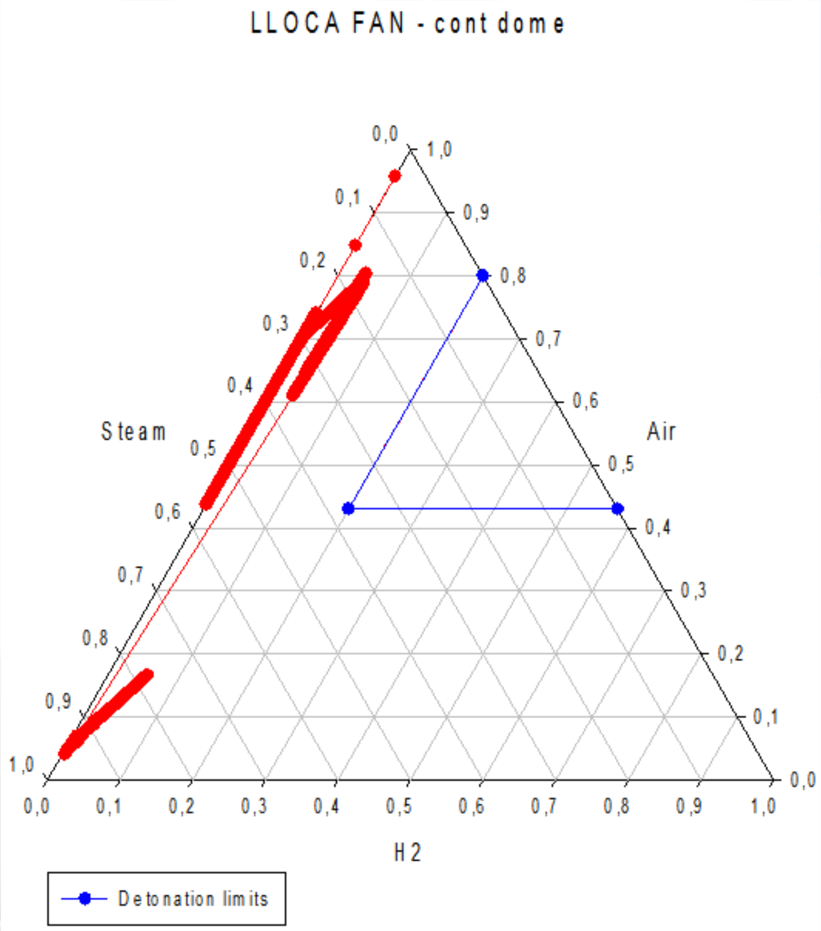


3D view of containment with SG1 compartment

Hydrogen Evaluation - Example



H2-air-steam diagram for containment dome, LLOCA NFAN, GOTHIC run



H2-air-steam diagram for containment dome, LLOCA FAN, GOTHIC run

Analysis - Results

- General behaviour in terms of pressure increase, atmosphere temperatures and hydrogen concentrations in large volumes are similar (especially for scenarios without RCFC fans).
- The highest peak in LLOCA FAN case was around 35%.
- In SLOCA cases H2 concentrations of 25 and 35% were present, but that was after containment failure and with low oxygen content.
- The cases with fans have generally higher H2 concentrations (H2 mass present in containment was actually lower) due to steam condensation caused by RCFC operation (benefit of RCFC operation is in lower containment pressure and temperatures, making some additional space for expansion after hypothetical hydrogen burn). .

Summary

- **Containment design features vary considerably among world's population of nuclear plants**
- **Details of design features are important to understanding containment response during design basis accidents (DBA) and severe (beyond design basis BDBA) accidents**