Joint ICTP-IAEA Essential Knowledge Workshop on Deterministic Safety Analysis and Engineering Aspects Important to Safety

Trieste,12-23 October 2015*Safety*

Assessment of Major Systems Coolant System

Marco GASPARINI (IAEA Consultant)

IAEA

International Atomic Energy Agency

Outline

- Reactor coolant system and associated systems (RCSASs)
- Functions and extent of the RCSASs
- General Concepts of RCSASs for PWR and BWR
- IAEA SSR-2/1 Design Requirements for RCSASs and their practical implementation

IAEA Safety Guide NS-G-1.9


IAEA SAFETY STANDARDS SERIES

Design of the Reactor Coolant System and Associated Systems in Nuclear Power Plants

SAFETY GUIDE

No. NS-G-1.9

IAEA

- NS-G-1.9 was published in 2004
- It is being revised to make it consistent with the latest Requirements SSR-2/1

Functions of the RCSASs

- To contain the coolant providing a barrier to the release of radioactive materials
- To remove the heat from the core and from components in all plant states considered in the design
- To transfer the heat to the ultimate heat sink
- To maintain the specified physical and chemical characteristics of the coolant.

Extent of the RCS and Associated Systems

The RCSASs consist of:

- the Reactor Coolant System (RCS)
- the systems for residual heat removal
  - In normal operations
  - In accident conditions
- the chemistry, inventory and reactivity control systems
- the ultimate heat sink.

Reactor coolant systems and associated systems for a PWR

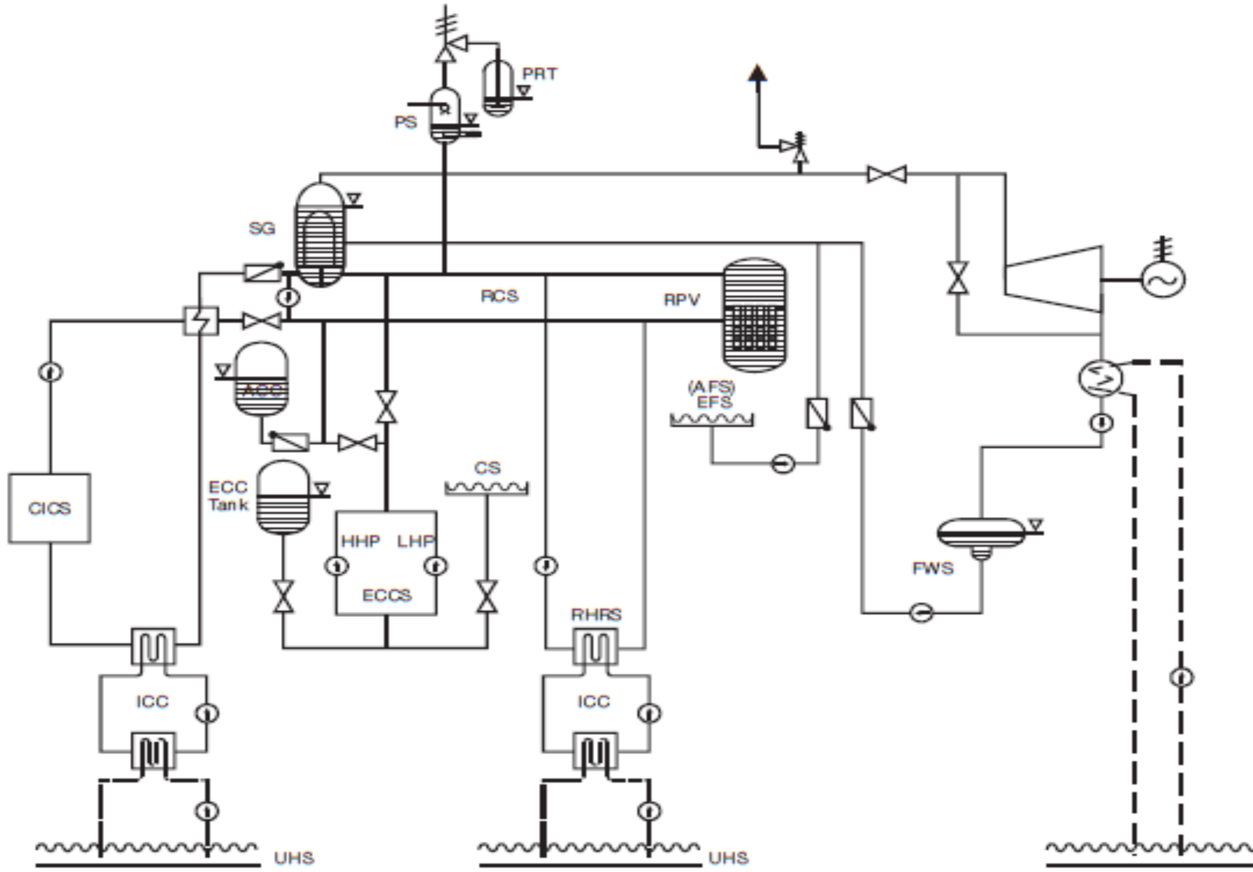


FIG. II–2. RCSASs for a PWR.

Reactor coolant systems and associated systems for a BWR

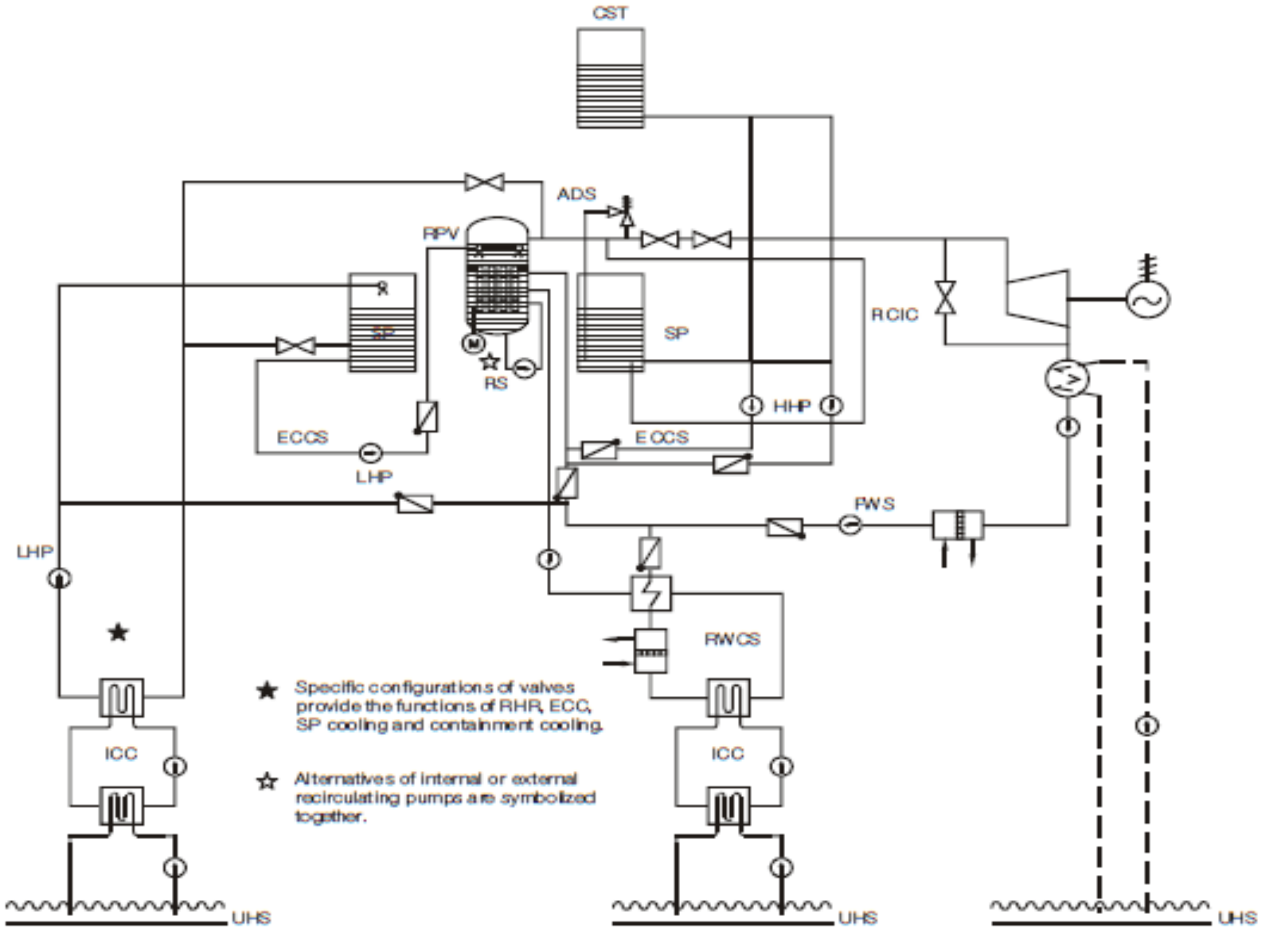
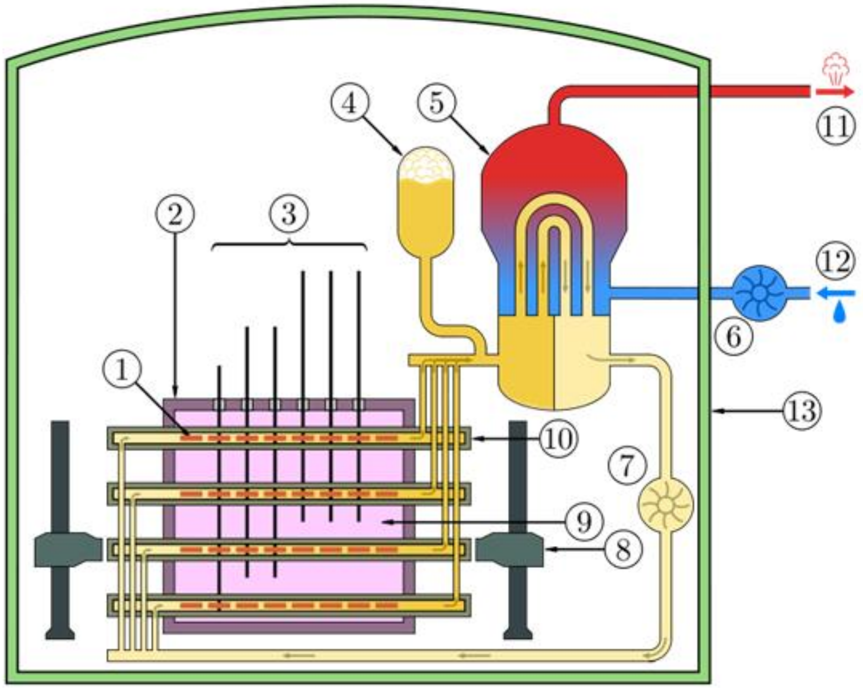
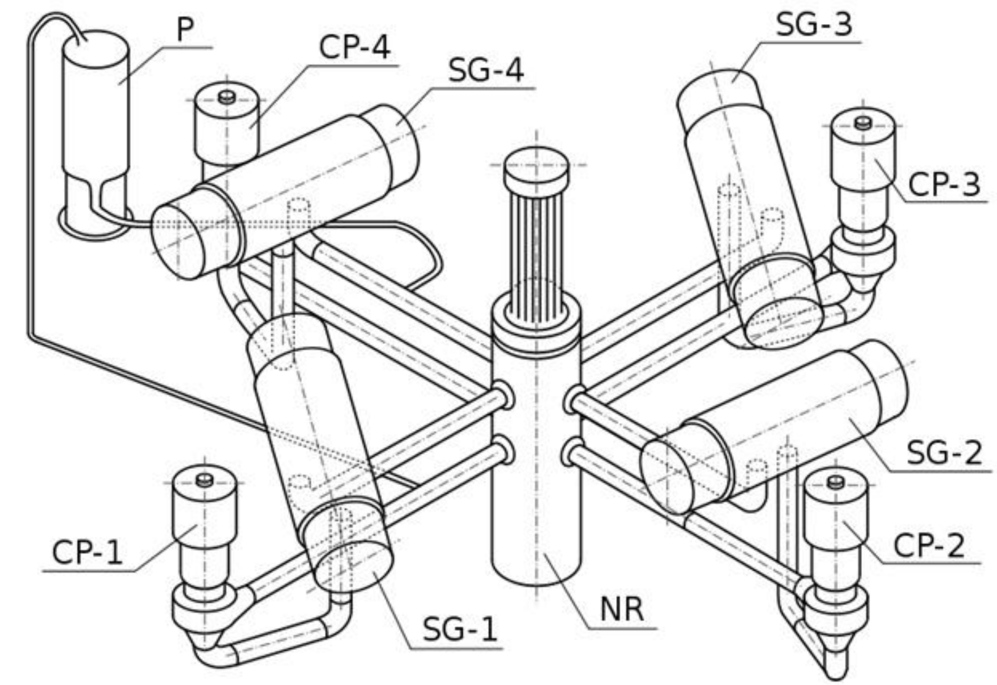


FIG. II–3. RCSASs for a BWR.

Reactor coolant system of CANDU and VVER





Design Basis of the RCSASs

- The safety function(s)
- The postulated initiating events they have to deal with
- The safety classification and associated design and fabrication codes
- Loads and load combinations
- The protection against external hazards (e.g. seismic category)
- The protection against internal hazards
- Design criteria (e.g. single failure criteria)
- Environmental conditions in which the equipment is expected to operate
- Selection of materials
- Requirements for testing, inspection and maintenance

Functions of the RCS

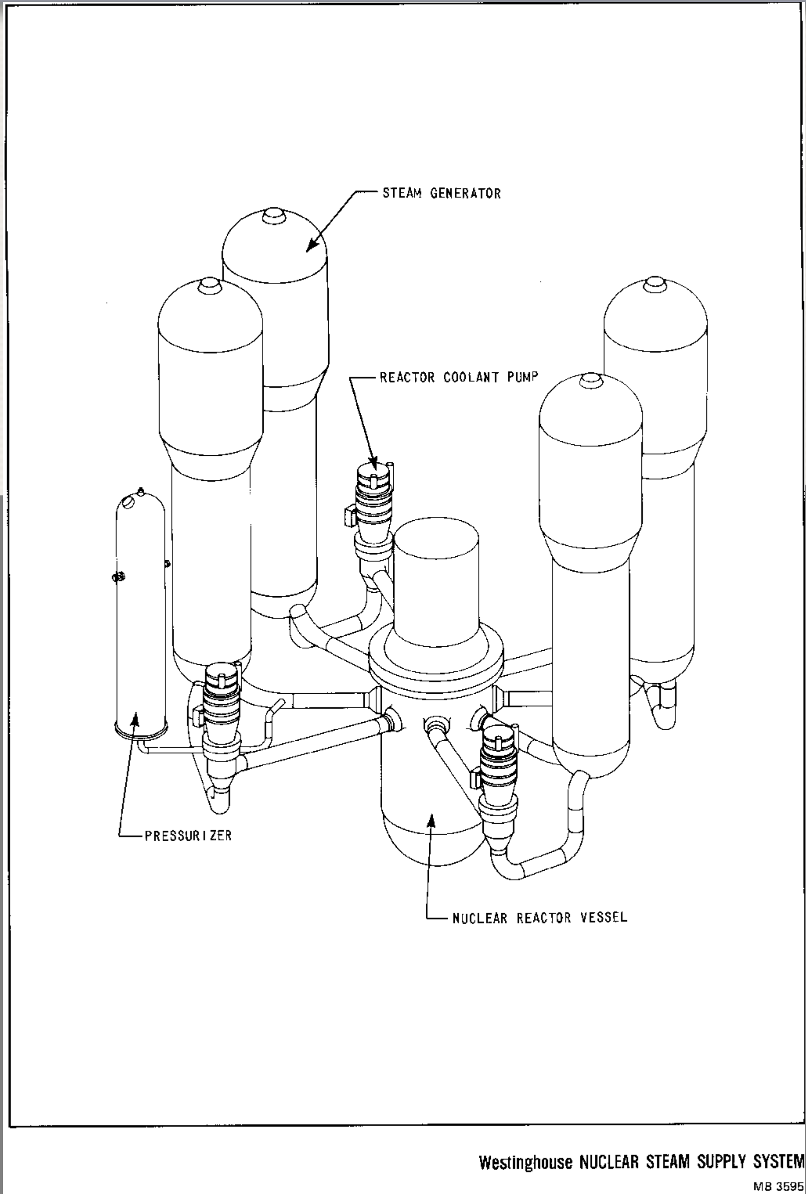
The Reactor Coolant System has three major functions:

- Transfer the heat from the reactor to the steam generators (PWR) or to the turbine (BWR)
- Maintain the pressure of the coolant within specified limits
- Contain the coolant providing an effective barrier to the release of radioactive materials (integrity of the pressure boundary)

Major components of the Reactor Coolant System

The Reactor Coolant System (PWR example) consists of the following major components:

- Reactor vessel
- Steam Generator (Primary side)
- Reactor Coolant Pump
- Pressurizer
- Piping (hot leg, cold leg, surge line)
- Overpressure protection system
- Depressurization systems



Reactor coolant systems and associated systems for a PWR

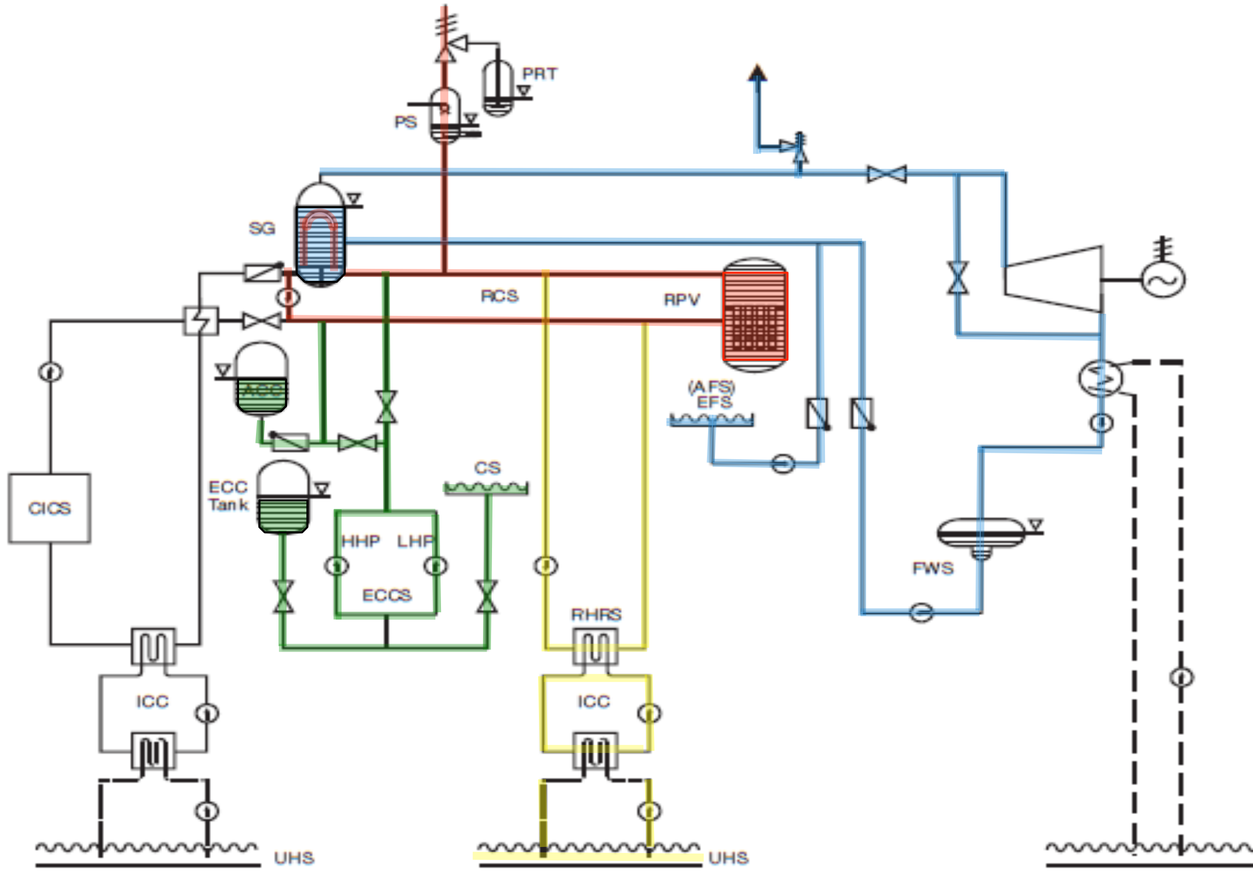
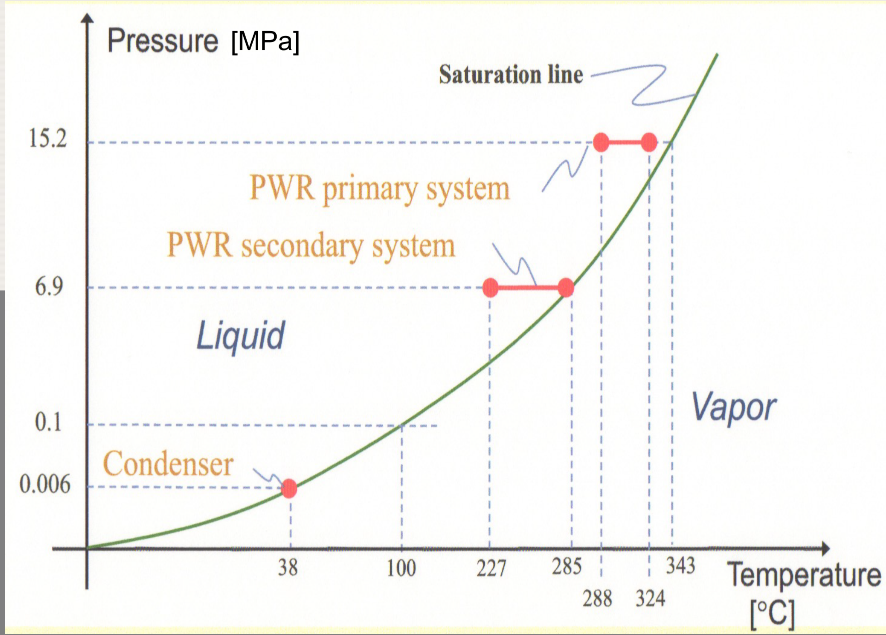
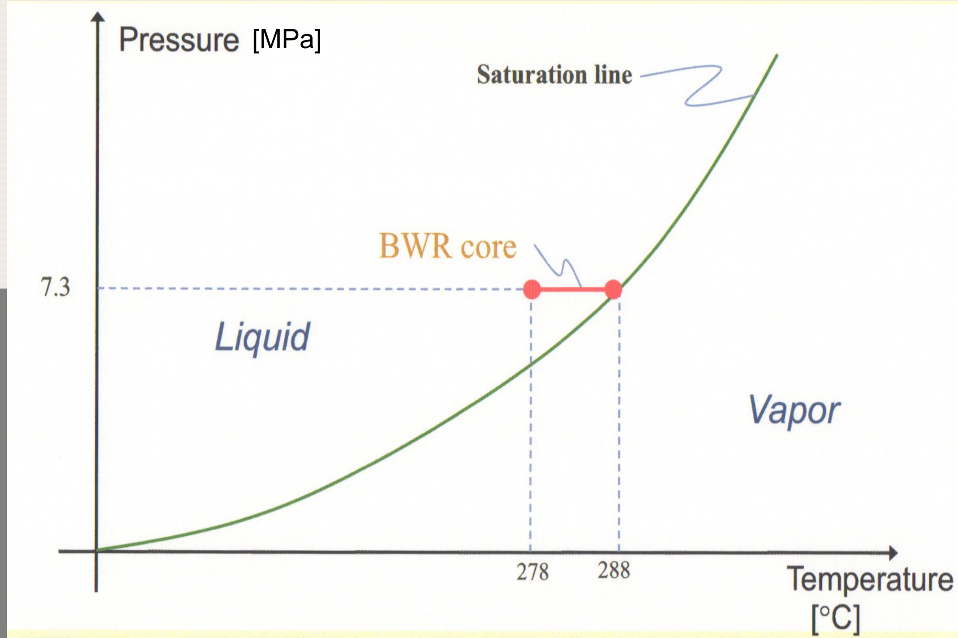


FIG. II–2. RCSASs for a PWR.

Pressure-Temperature diagrams for PWR and BWR



PWR



BWR

IAEA SSR-2/1 Requirements for the design of the Reactor Coolant Systems

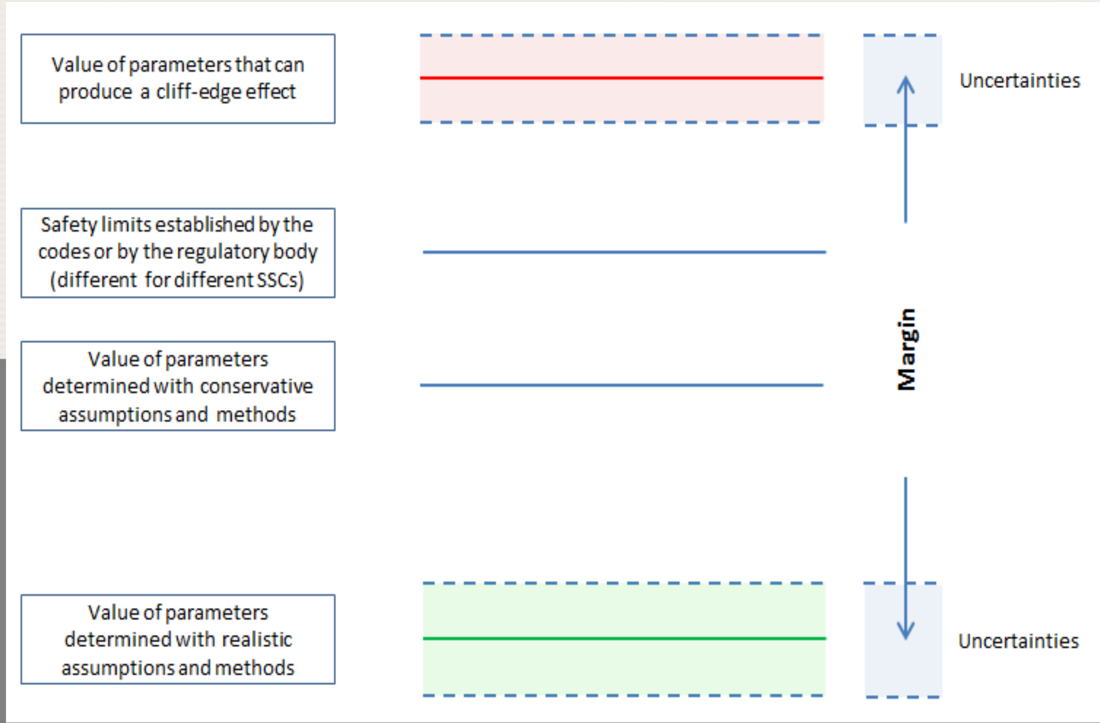
Requirement 47: Design of reactor coolant system

The components of the reactor coolant systems for the nuclear power plant **shall be designed and constructed** so **that the risk of faults** due to inadequate quality of materials, inadequate design standards, insufficient capability for inspection or inadequate quality of manufacture **is minimized**.

6.13 Pipework connected to the pressure boundary of the reactor coolant systems for the nuclear power plant shall be equipped with adequate isolation devices to limit any loss of radioactive fluid (primary coolant) and to prevent the loss of coolant through interfacing systems.

6.14 The design of the reactor coolant pressure boundary shall be such that flaws are very unlikely to be initiated, and any flaws that are initiated would propagate in a regime of high resistance to unstable fracture and to rapid crack propagation, thereby permitting the timely detection of flaws.

Design margins (e.g. design pressure)

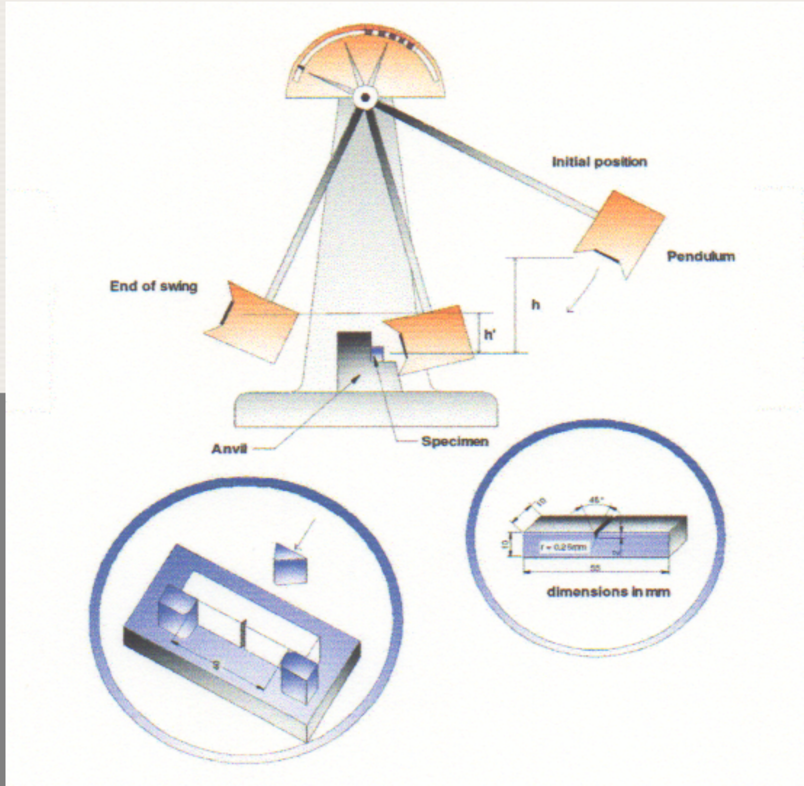


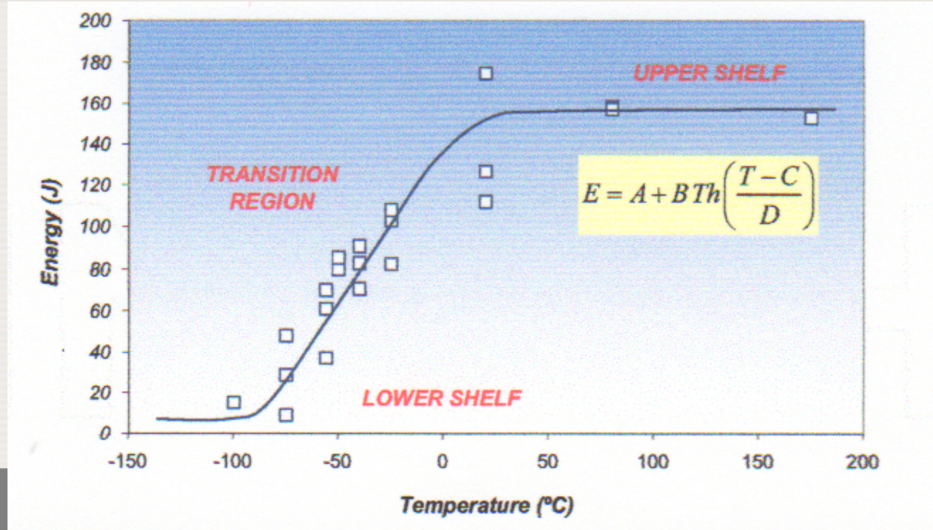
IAEA SSR-2/1 Requirements for the design of the Reactor Coolant System

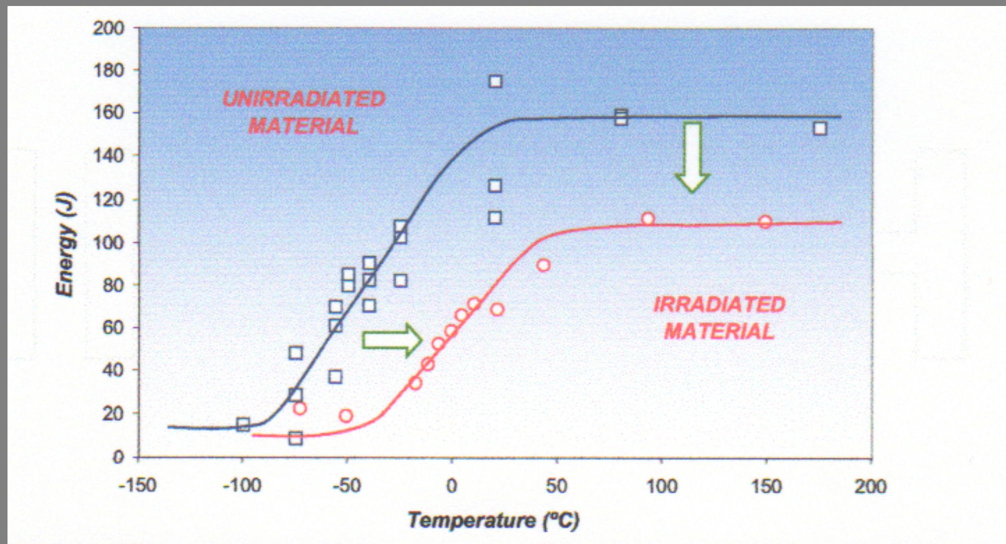
- The design of the reactor coolant systems shall be such as to ensure that plant states in which components of the reactor coolant pressure boundary could exhibit embrittlement are avoided.

- The design of the components contained inside the reactor coolant pressure boundary, such as pump impellers and valve parts, shall be such as to minimize the likelihood of failure and consequential damage to other components of the primary coolant system that are important to safety, in all operational states and in design basis accident conditions, with due allowance made for deterioration that might occur in service.

Embrittlement due to neutron irradiation







Example of measures implemented to increase the life of the RPV (VVER-1000/320)

RPV life extension to 60 years has been implemented by improving standard VVER-1000/320 design (design lifetime 40 years):

- new program of surveillance specimens (placement of irradiated SS's directly on the reactor vessel wall);
- limitation of nickel content in welds;
- limitation of harmful impurities in basic metal and welds;
- modernization of manufacturing technique;
- decrease in neutron flux to the reactor vessel;
- increase in control reliability of fluence to the reactor vessel;

decrease in NDT (irradiation embrittlement) of the nozzle zone core barrels to minus 35 °C at the beginning of life time and +50 °C at the end

IAEA SSR-2/1 Requirements for the Design of the Reactor Coolant System

Requirement 48: Overpressure protection of the reactor coolant pressure boundary

- Overpressure protection of the reactor coolant pressure boundary Provision shall be made to ensure that the operation of pressure relief devices will protect the pressure boundary of the reactor coolant systems against overpressure and will not lead to the release of radioactive material from the nuclear power plant directly to the environment.

Requirement 49: Inventory of reactor coolant

- Provision shall be made for controlling the inventory, temperature and pressure of the reactor coolant to ensure that specified design limits are not exceeded in any operational state of the nuclear power plant, with due account taken of volumetric changes and leakage.

Functions of the overpressure protection system

- To preserve the structural integrity of the RCS boundary by keeping, in conjunction with the reactor scram, the pressure below the design limits specified for the different categories of postulated initiating events.
- To ensure the protection of the RCS structural integrity in case of ATWS
- To provide protection against unacceptable load combinations of high pressure and low temperature when the reactor coolant system is operated at low temperature (protection of RCS equipment with materials of less ductility at low temperature).

Functions of the depressurization system

The function depends on the type of reactor

PWRs

- For the practical elimination of the phenomena associated with the high pressure melt ejection in case of severe accidents, PWRs should be equipped with a fast depressurization of the primary circuit (System manually actuated)

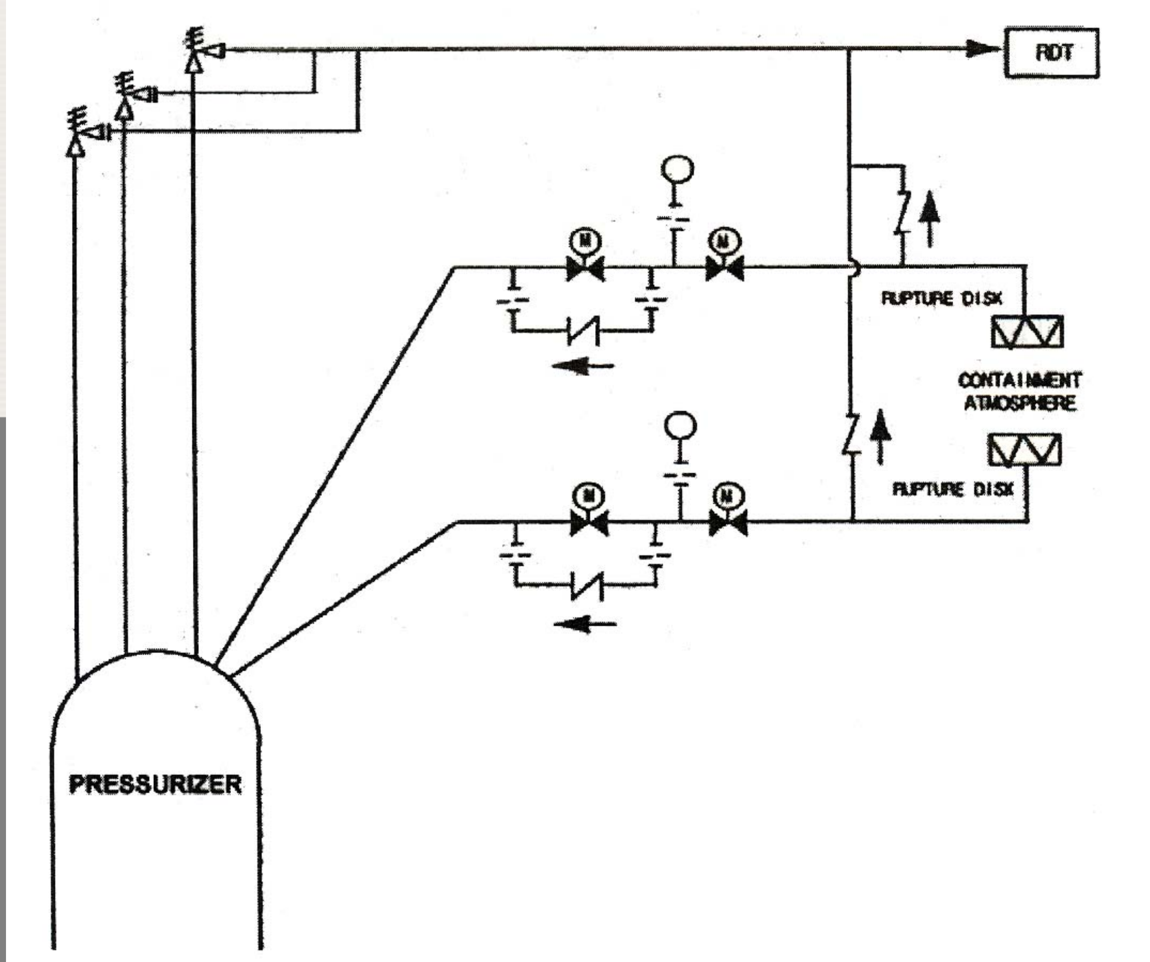
Safety feature designed to "practically eliminate" Direct Containment Heating (DCH)

BWRs

- To allow the operation of the low pressure coolant injection function and/or low pressure core spray system (System automatically actuated)

Safety system designed for mitigation of some design basis accidents

Overpressure protection system



IAEA SSR-2/1 Requirements for design of the Reactor Coolant System

Requirement 50: Cleanup of reactor coolant

- Adequate facilities shall be provided at the nuclear power plant for the removal from the reactor coolant of radioactive substances, including activated corrosion products and fission products deriving from the fuel, and non-radioactive substances.
- The capabilities of the necessary plant systems shall be based on the specified design limit on permissible leakage of the fuel, with a conservative margin to ensure that the plant can be operated with a level of circuit activity that is as low as reasonably practicable, and to ensure that the requirements are met for radioactive releases to be as low as reasonably achievable and below the authorized limits on discharges.

Reactor coolant systems and associated systems for a PWR

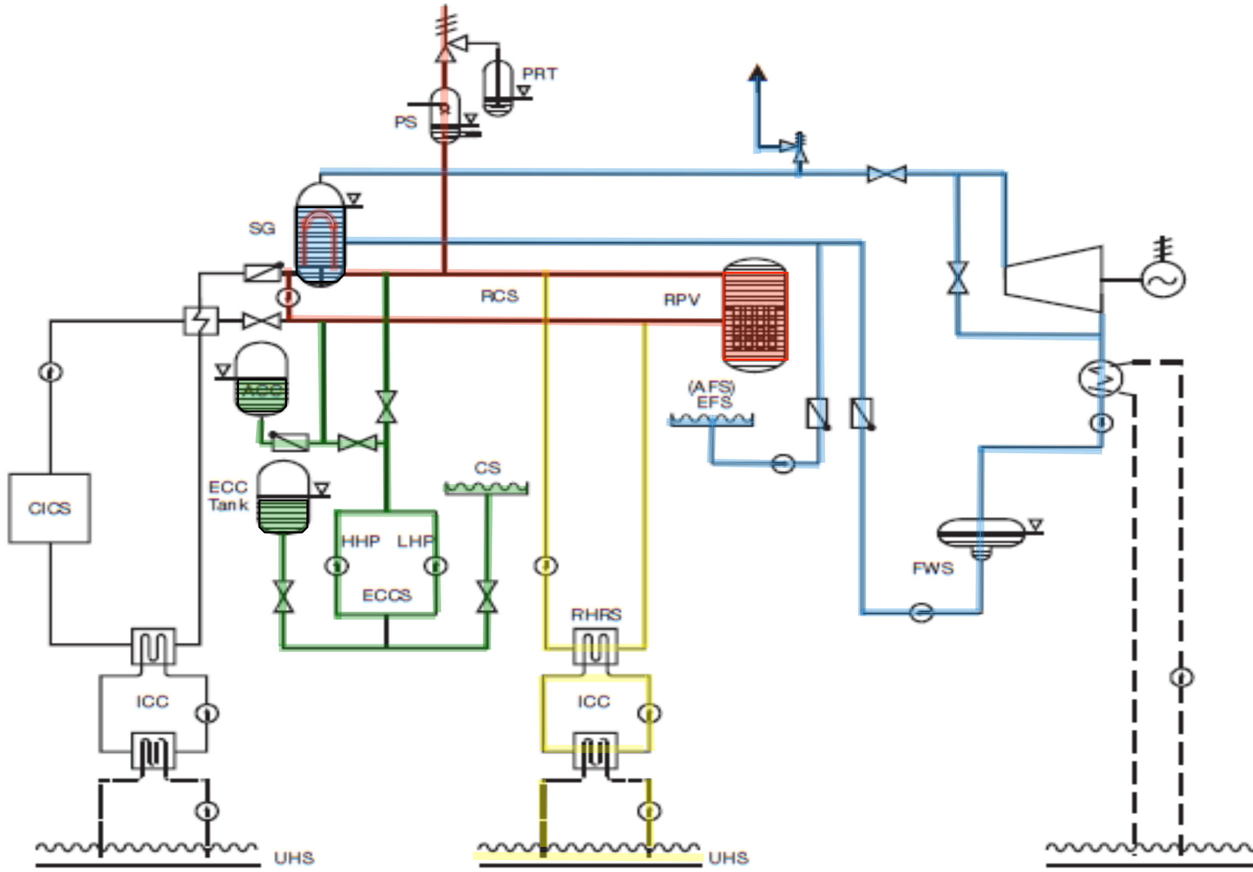


FIG. II–2. RCSASs for a PWR.

IAEA SSR-2/1 Requirements for design of the Reactor Coolant System

Requirement 51: Removal of residual heat from the reactor core

- Means shall be provided for the removal of residual heat from the reactor core in the shutdown state of the nuclear power plant such that the design limits for fuel, the reactor coolant pressure boundary and structures important to safety are not exceeded.

Reactor coolant systems and associated systems for a PWR

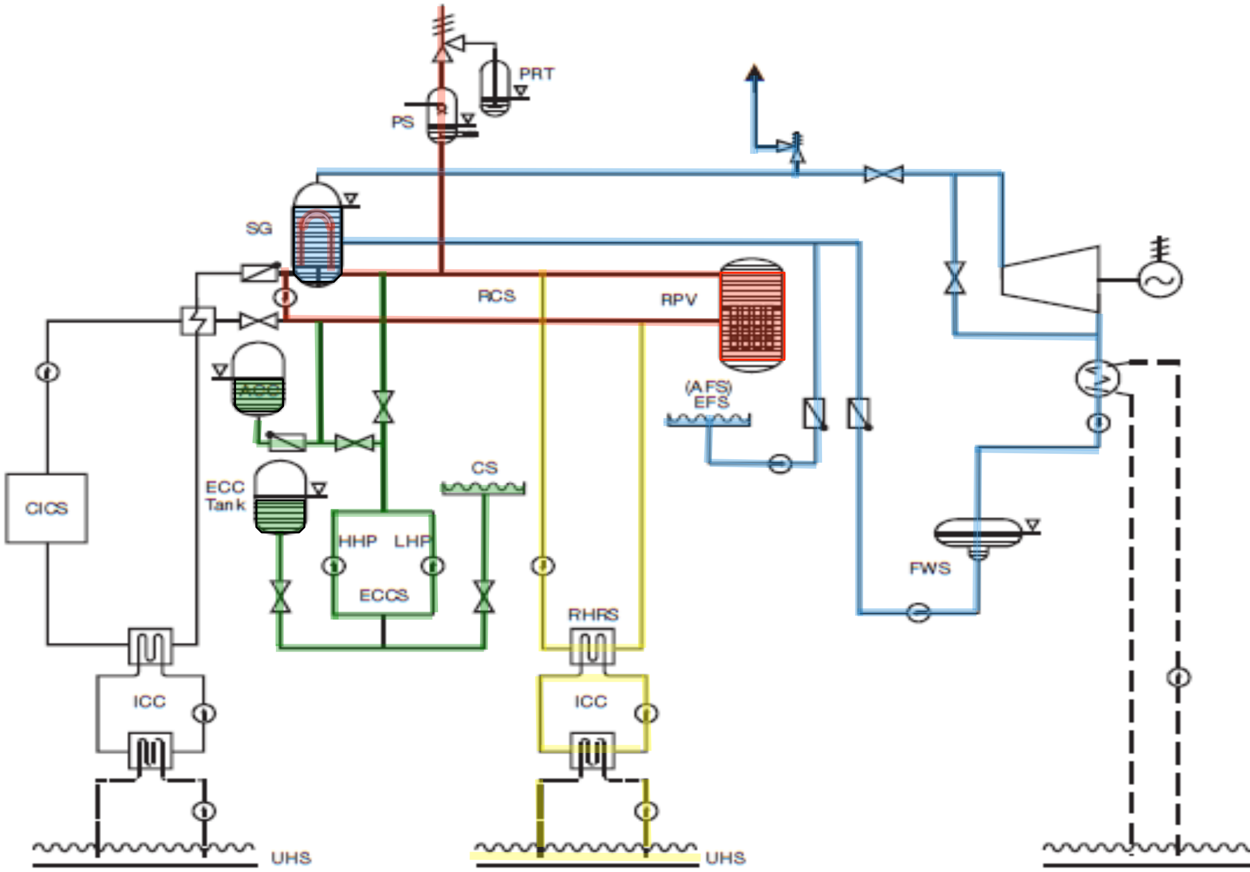


FIG. II–2. RCSASs for a PWR.

Decay Heat Removal via SG and Auxiliary Feedwater System

- The **auxiliary feedwater system (AFW)** supplies feedwater to the steamgenerator (SG) whenever the main feedwater system is unavailable during hot standby conditions and reactor cooldown to the point where the residual heat removal system (RHR) starts operation.
- The function of the AFW system is to provide adequate cooling water to the SG in event of a loss of main feedwater. Each auxiliary feedwater subsystem, aligned to feed its respective SG, will provide enough feedwater to cool the unit down safely to the temperature at which the shutdown cooling system can be utilized.

IAEA SSR-2/1 Requirements for design of the Reactor Coolant System

Requirement 52: Emergency cooling of the reactor core

- Means of cooling the reactor core shall be provided to restore and maintain cooling of the fuel under accident conditions at the nuclear power plant even if the integrity of the pressure boundary of the primary coolant system is not maintained.
- The means provided for cooling of the reactor core shall be such as to ensure that:
  - The limiting parameters for the cladding or for integrity of the fuel (such as temperature) will not be exceeded;
  - Possible chemical reactions are kept to an acceptable level;
  - The effectiveness of the means of cooling of the reactor core compensates for possible changes in the fuel and in the internal geometry of the reactor core;
  - Cooling of the reactor core will be ensured for a sufficient time.
- Design features (such as leak detection systems, appropriate interconnections and capabilities for isolation) and suitable redundancy and diversity shall be provided to fulfil the requirements above with adequate reliability for each postulated initiating event.

USNRC Acceptance Criteria (10CFR50.46)

10CFR50.46, or simply as “LOCA criteria”. The current LOCA criteria consist of five separate limits or requirements:

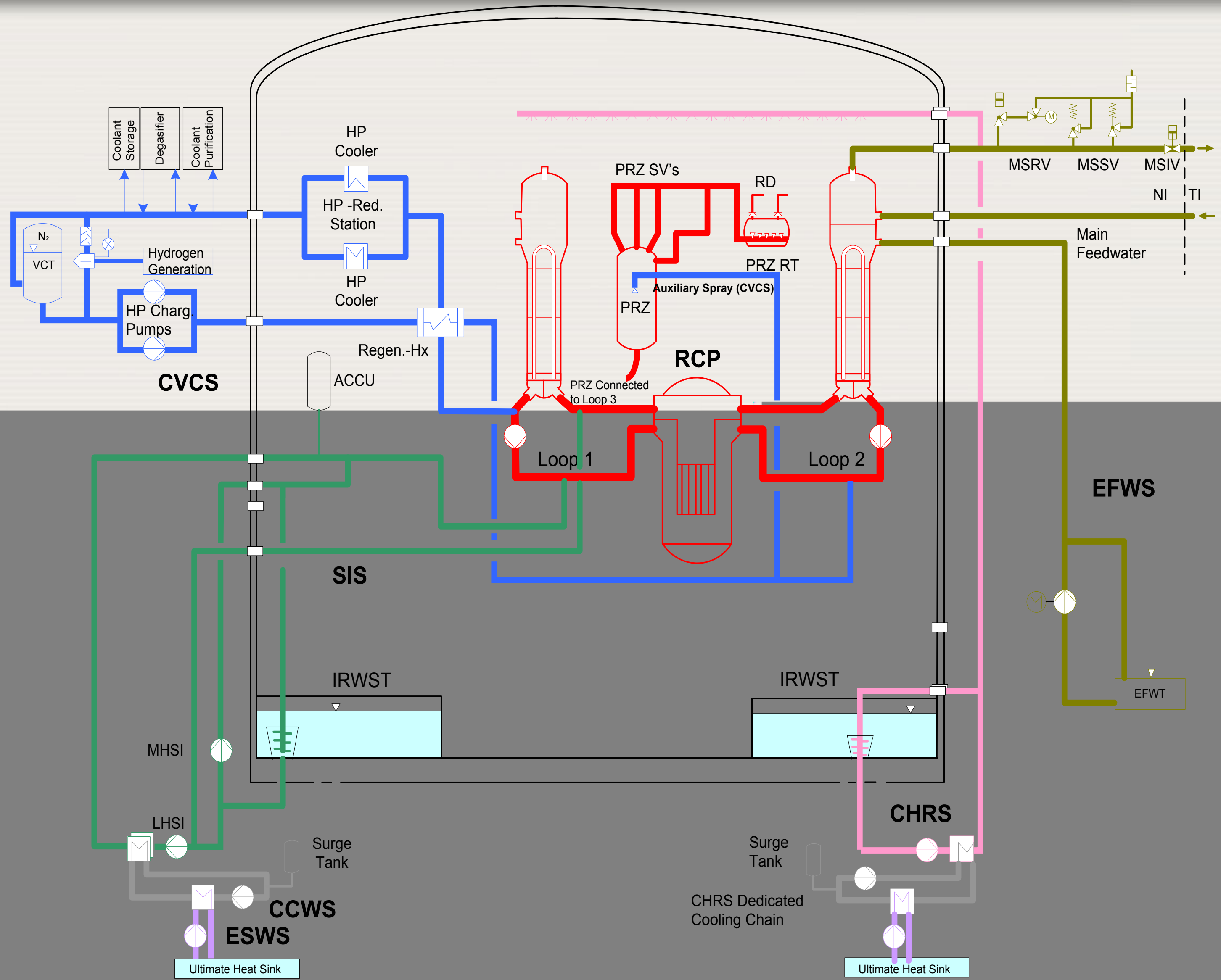
- (1) Peak cladding temperature. The calculated maximum fuel element cladding temperature shall not exceed 2200°F (1204°C).
- (2) Maximum cladding oxidation. The calculated total oxidation of the cladding shall nowhere exceed 0.17 times the total cladding thickness before oxidation.
- (3) Maximum hydrogen generation. The calculated total amount of hydrogen generated from the chemical reaction of the cladding with water or steam shall not exceed 0.01 times the hypothetical amount that would be generated if all the metal in the cladding cylinders surrounding the fuel, excluding the cladding surrounding the plenum volume, were to react.

USNRC Acceptance Criteria (10CFR50.46)

- (4) Coolable geometry. Calculated changes in core geometry shall be such that the core remains amenable to cooling.
- (5) Long-term cooling. After any calculated successful initial operation of the ECCS, the calculated core temperature shall be maintained at an acceptably low value and decay heat shall be removed for the extended period of time required by the long-lived radioactivity remaining in the core.

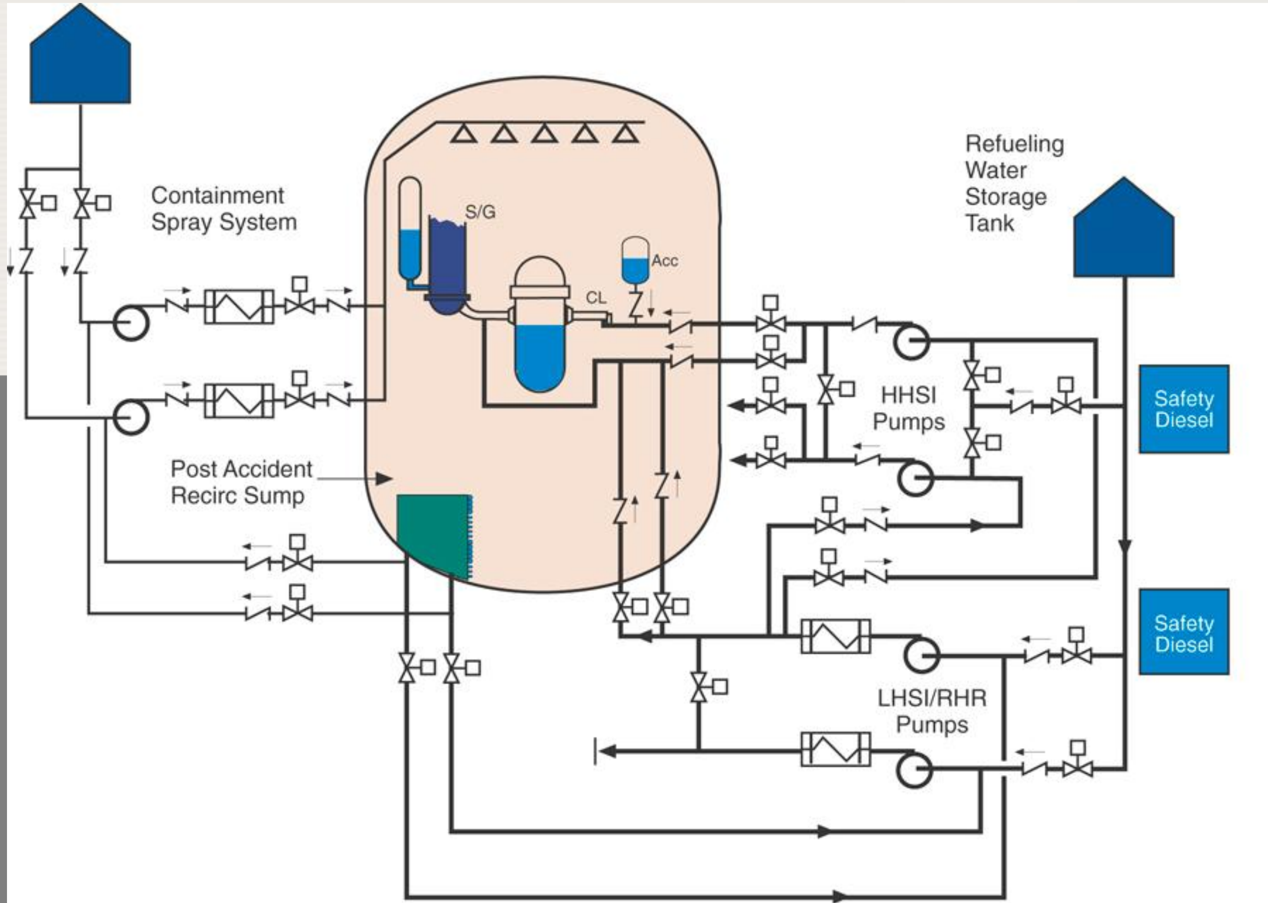
- **Note:** Appendix K to 10CFR Part 50 describes various models that must be used to calculate the five limits or requirements. The appendix specifies what models should be used for calculation of in-core processes, such as initial stored energy in fuel, fission heat, decay heat, metal-water reaction, reactor internals heat transfer, fuel cladding ballooning and rupture, and others associated with blowdown phenomena.

Examples of safety systems

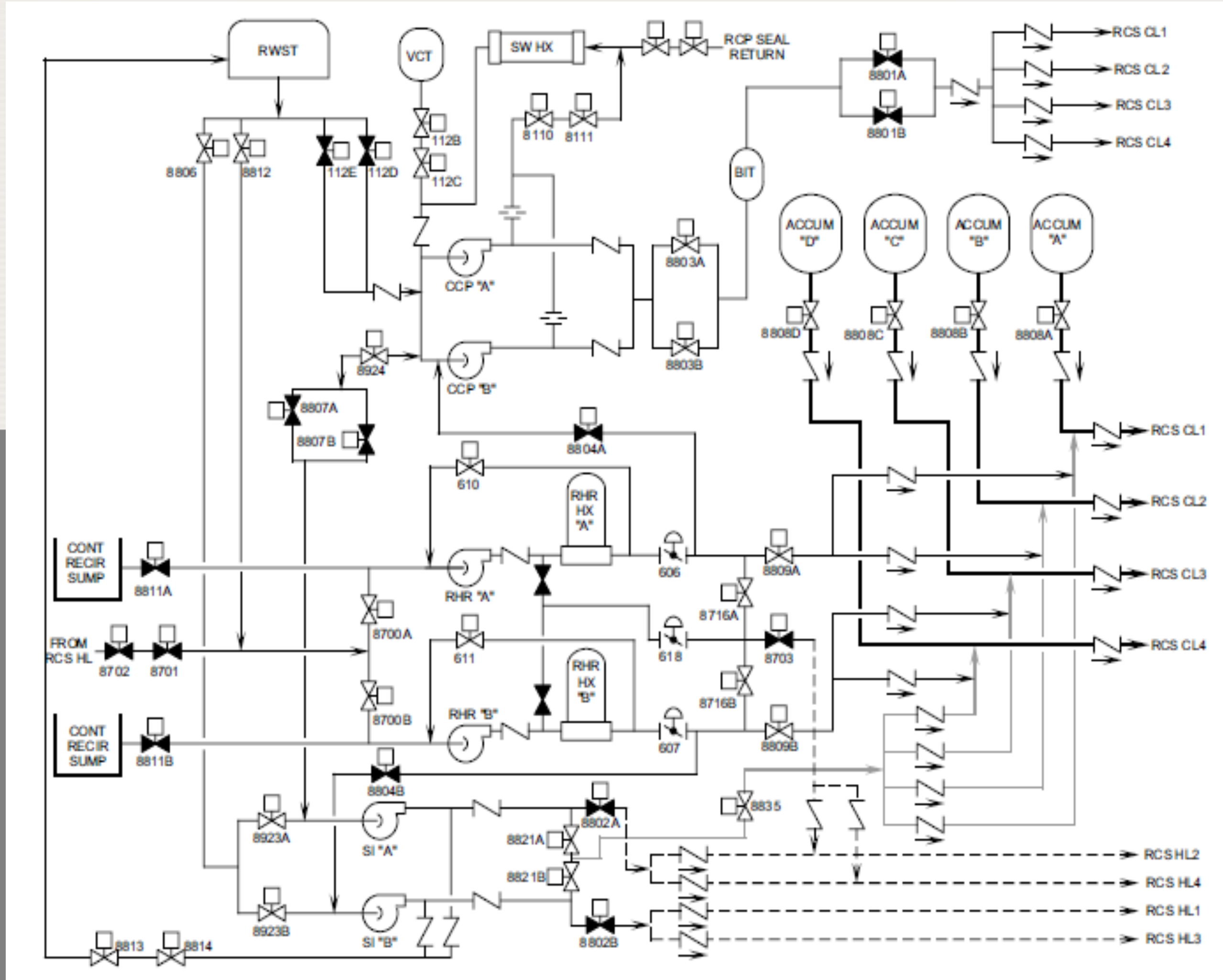


Examples of safety systems

- **Emergency Core Cooling Systems:**
  1. High Pressure Safety Injection (HPIS)
  2. Low Pressure Safety Injection (LPIS) or/and the Residual Heat Removal System (RHR)

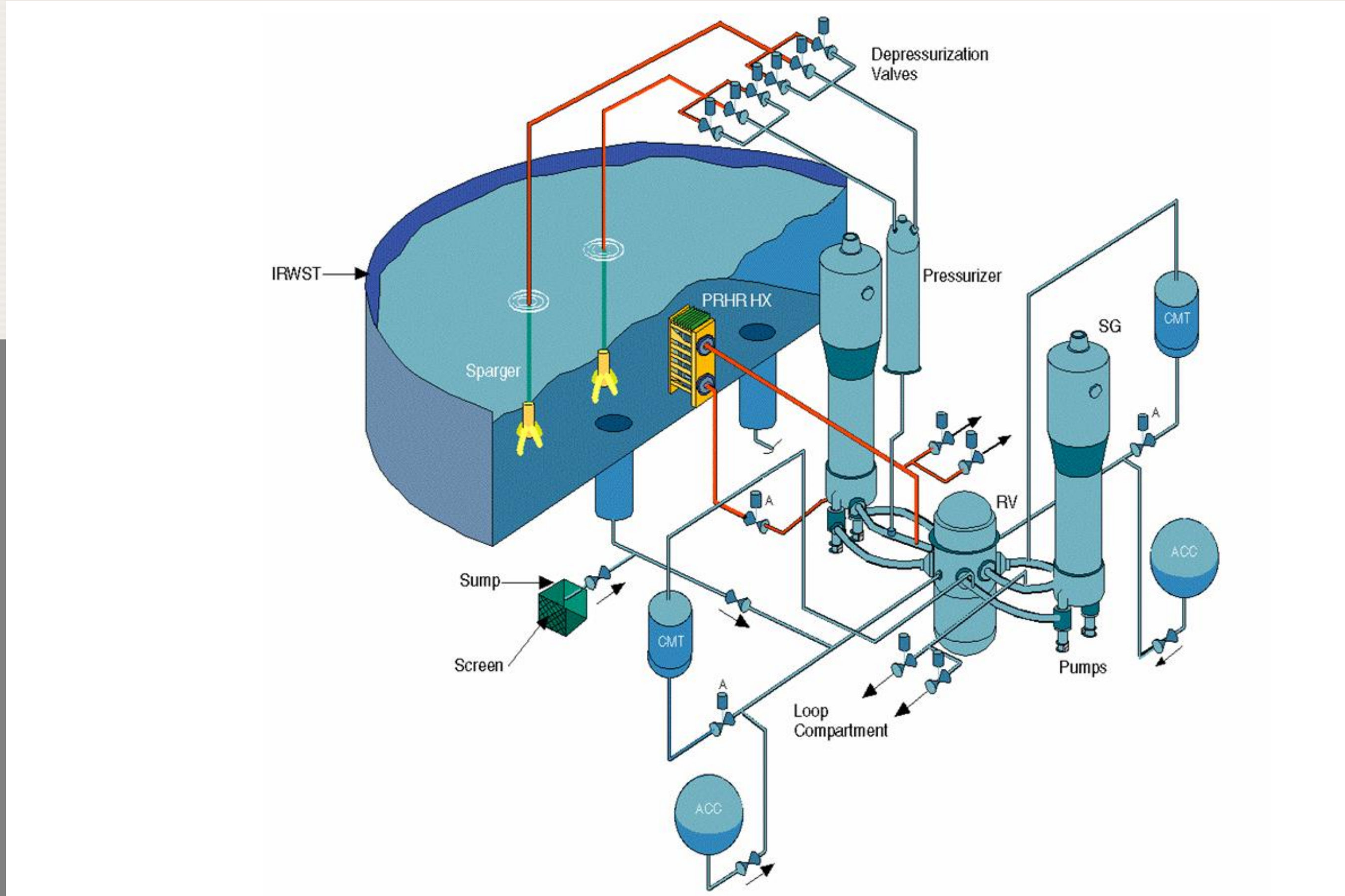


ECCs in PWR



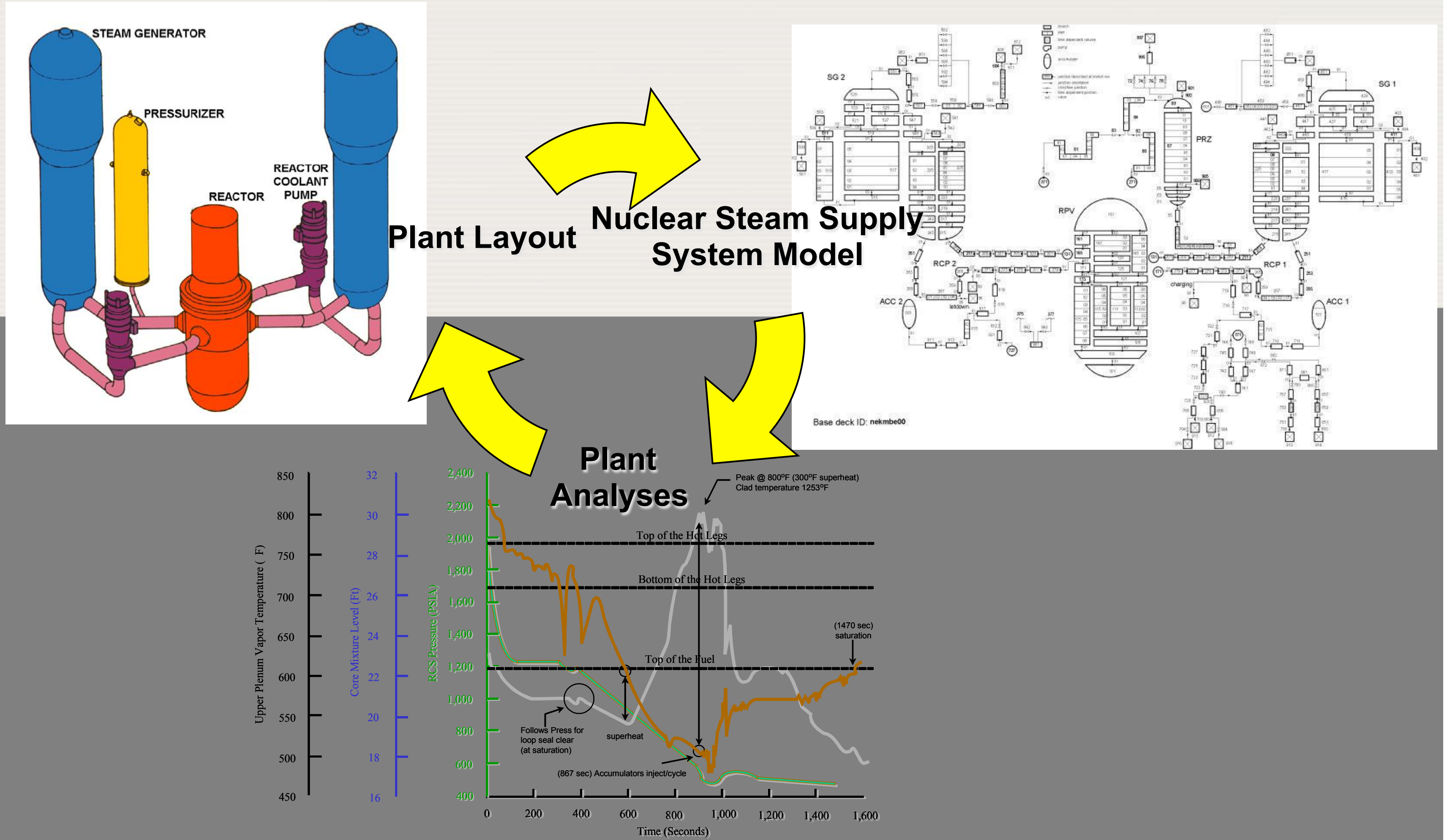
RWST
VCT
SW HX
RCP SEAL RETURN
RCS CL1
RCS CL2
RCS CL3
RCS CL4
8801A
8801B
8806
8812
112E
112D
112B
112C
8110
8111
BIT
CCP "A"
CCP "B"
8803A
8803B
ACCUM "D"
ACCUM "C"
ACCUM "B"
ACCUM "A"
8808D
8808C
8808B
8808A
8924
8807A
8807B
8804A
610
RHR HX "A"
CONT RECIR SUMP
8811A
RHR "A"
606
8809A
8716A
8700A
FROM RCS HL
8702
8701
611
618
8703
8700B
RHR "B"
RHR HX "B"
8716B
607
8809B
8811B
8804B
8923A
SI "A"
8802A
8835
8821A
8821B
RCS HL2
RCS HL4
RCS HL1
RCS HL3
8923B
SI "B"
8802B
8813
8814

ECCS in AP1000



Design and Safety Analysis

ECCS Response Obtained



35

Summary

- The design of the Reactor Coolant System and Associated Systems vary considerably among world's population of nuclear plants
- The results of the safety assessment of the RCSASs are a relevant part of the Safety Analysis Report. There is a strict relation between the accident analysis and the design of the systems.
- The design of the RCSASs of modern reactors is affected by the latest design requirements (independence of levels of defence in depth, design extension conditions) and by the extension of the life of the NPP.

…Thank you for your attention