IAEA
International Atomic Energy Agency
Atoms for Peace

The Abdus Salam
International Centre
for Theoretical Physics

"Physics and Technology of Water-Cooled Reactors through the use of PC-based Simulators"

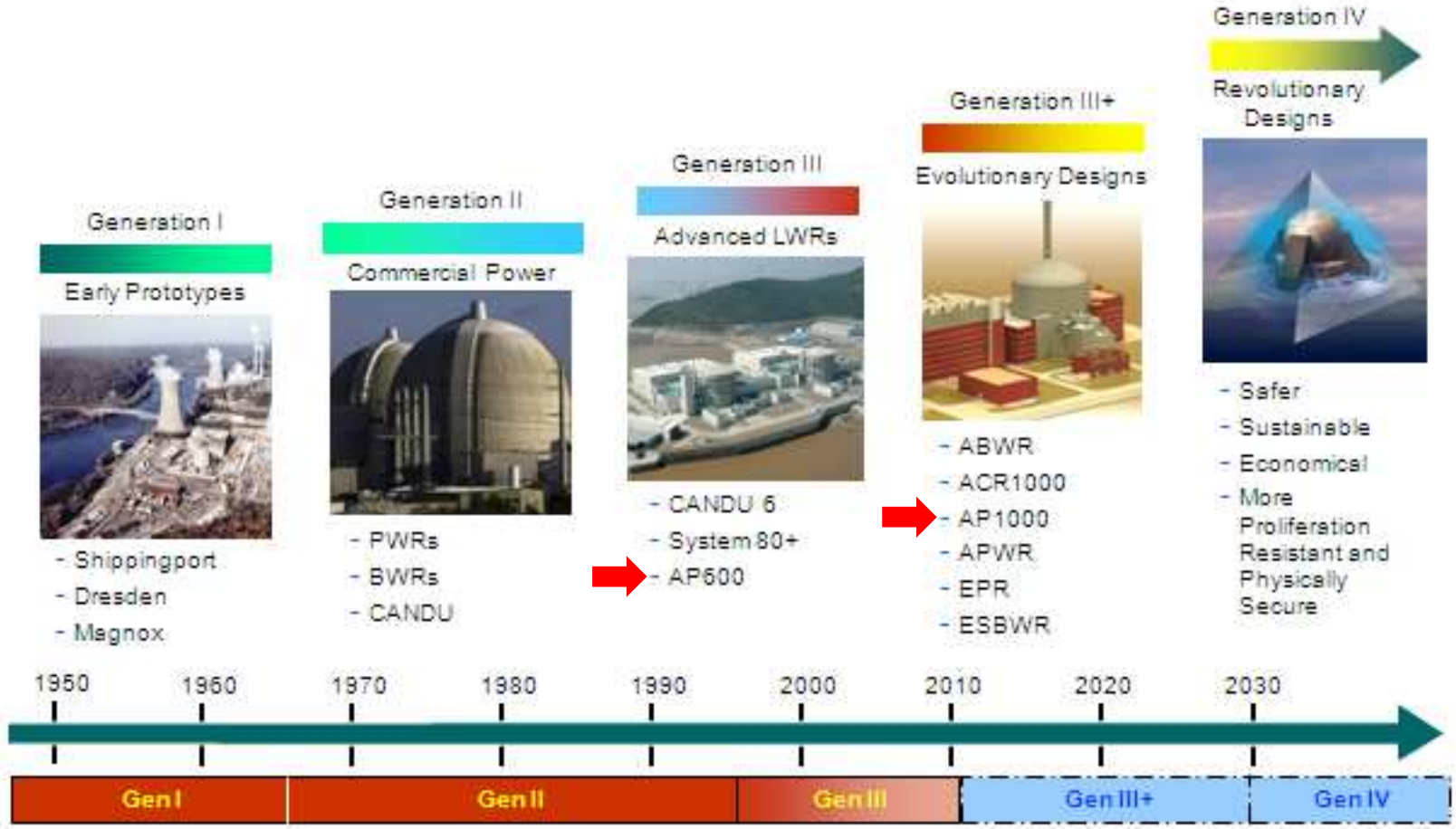
PASSIVE PRESSURIZED WATER REACTOR

International Centre for Theoretical Physics
Trieste
6th – 10th November 2017

tecnatom

Passive PWR Introduction

Evolution of Nuclear Power



Passivity

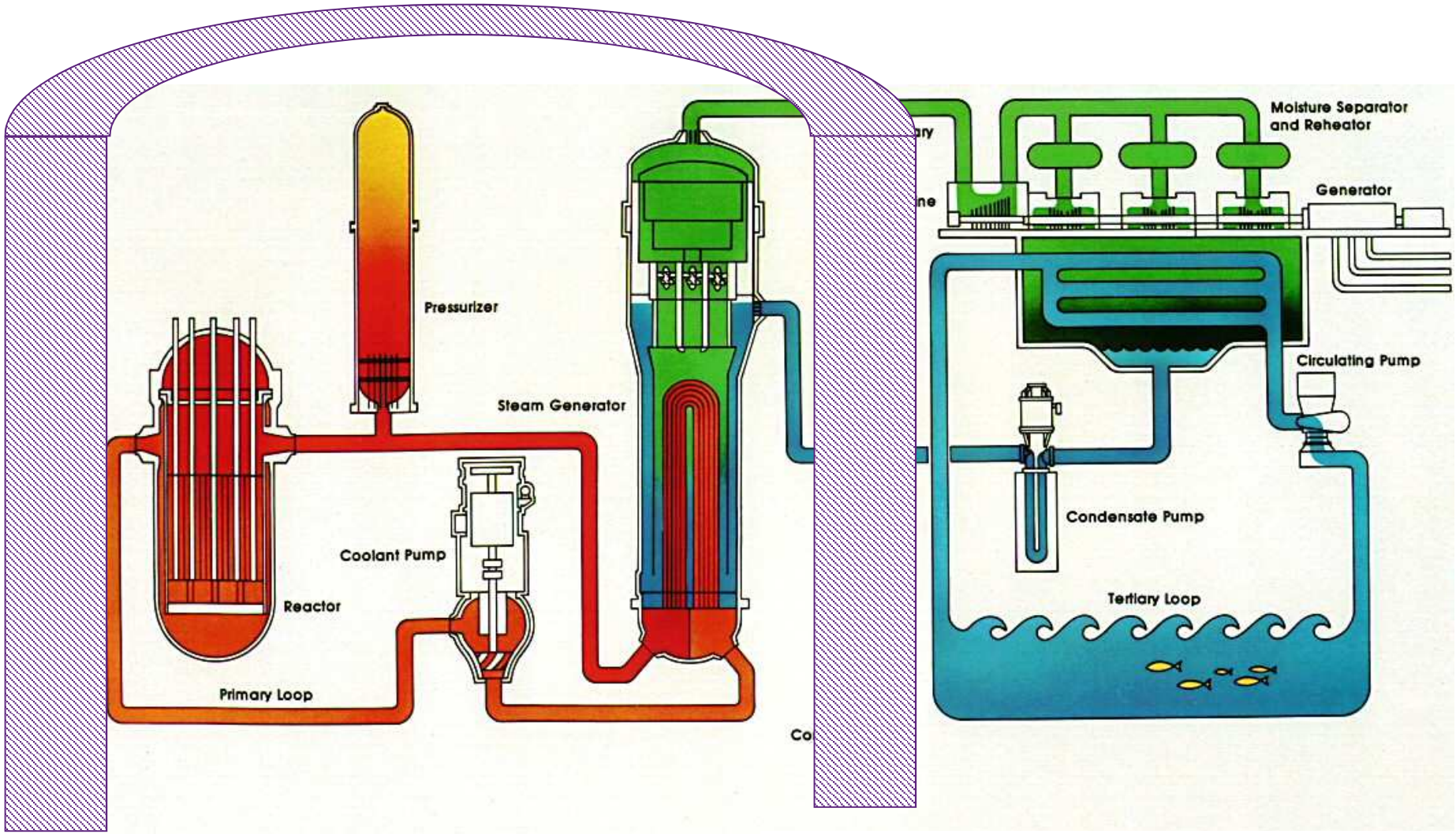
- IAEA set the components degree of passivity based on the following:
  1) **no moving working fluid**
  2) **no moving mechanical part**
  3) **no signal inputs of 'intelligence'**
  4) **no external power input or forces**

- **A:** 1+2+3+4 (fuel rods)
- **B:** 2+3+4 (PZR surge line)
- **C:** 3+4 (ACCs, no intelligence signals, actuation just based on pressure drop instead of situation analysis)
- **D:** 4 (reactor trip: control rods drop by gravity based on signals that analyze plant conditions. Others: CMTs, PRHR, IRWST)

Passive PWR

- Proven components are used.
- Passive means as motive force:
  - Gravity
  - Compressed fluids
  - Natural Circulation
  - Evaporation/Condensation.
- Active non-safety-related components as backup.
- Greatly reduced operator dependency.

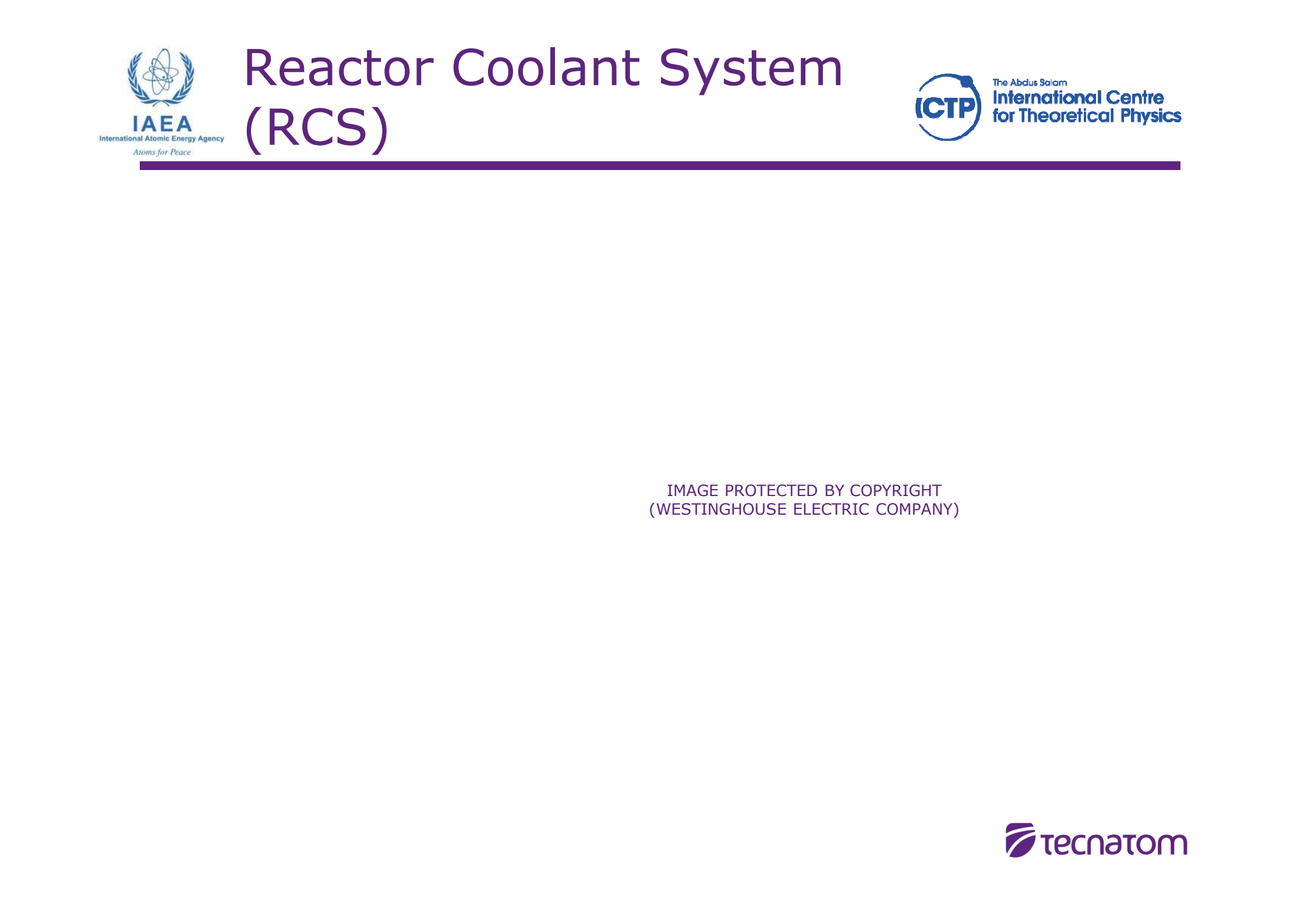
PWR NPP SYSTEMS



PWR NPP SYSTEMS

- Nuclear Steam Supply System (RCS)
- Primary System Auxiliaries (CVS, RNS)
- Engineered Safeguards
- Power Generation (Balance of Plant)
- Control and Protection Systems
- Main Control Room

Reactor Coolant System (RCS)



Reactor Coolant System (RCS)

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See simulator display for reference of RCS layout

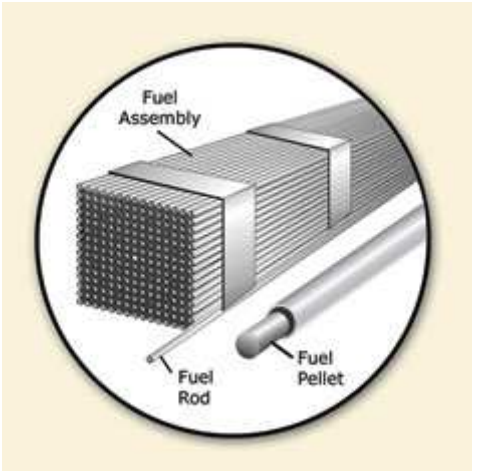
Core Components Arrangement

The core components consist of:

- 157 fuel assemblies
- 53 Rod Cluster Control Assemblies (RCCA) - High rod worth
- 16 Gray Rod Cluster Assemblies (GRCA)- Low Rod worth
- 42 incore detectors

Fuel Assembly

- 157 Fuel assemblies (17x17 configuration)
- A fuel assembly contains 289 cells:
  - 264 individual fuel rods supported by grids.
  - 24 guide thimble tubes.
  - 1 instrumentation thimble tube.
- 14 Feet in length (4.27m)
- The instrumentation thimble tube provides multiple incore discrete neutron flux detectors and core exit thermocouples.



Control Rods

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- Rod Control Cluster Assembly (RCCA)
  - High worth (Ag-In-Cd)
  - Shutdown Margin

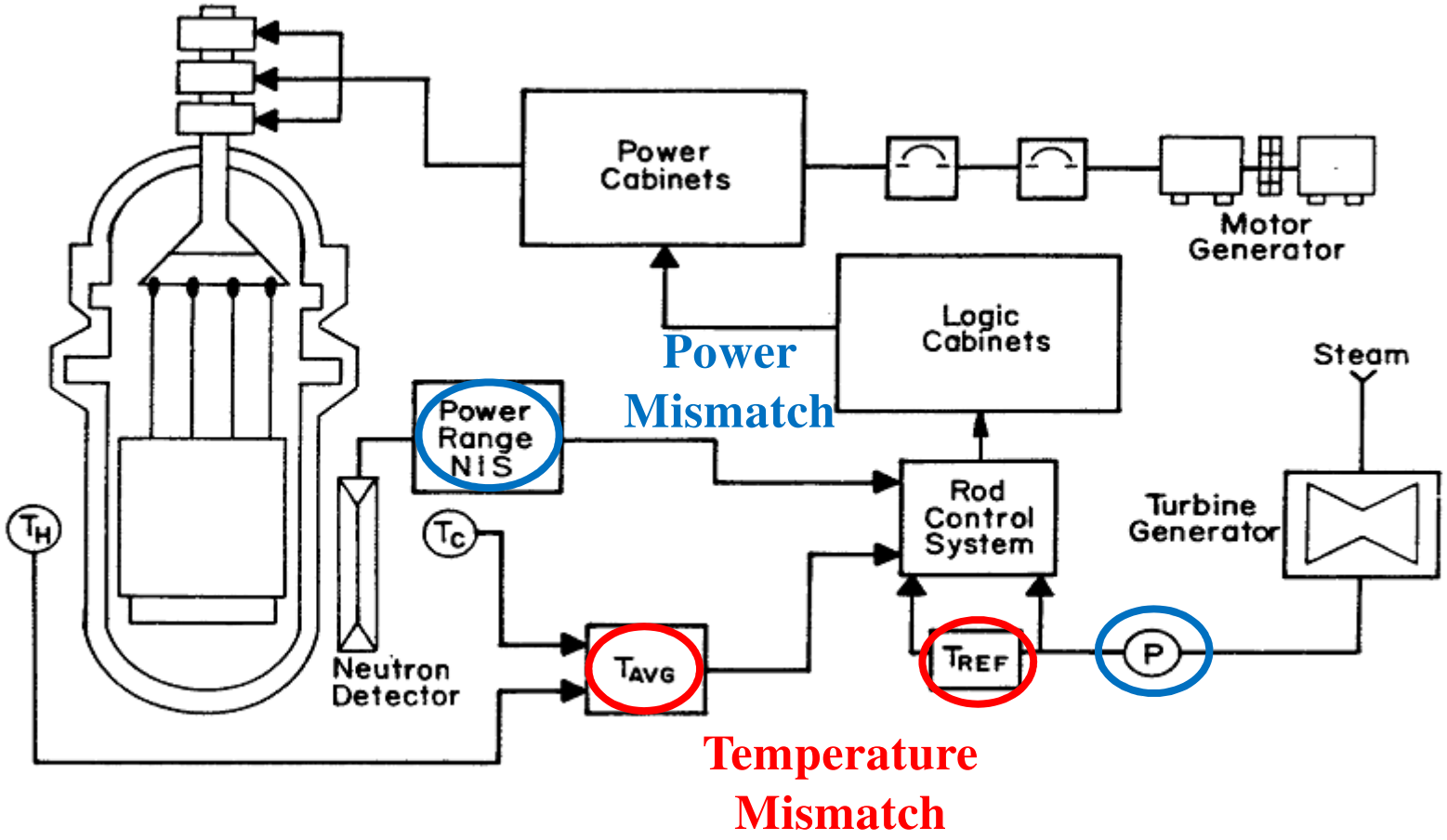
    AND

    Axial Power Control
- Gray Rod Cluster Assembly (GRCA)
  - Low worth (Tg)
  - Power/Reactivity Control

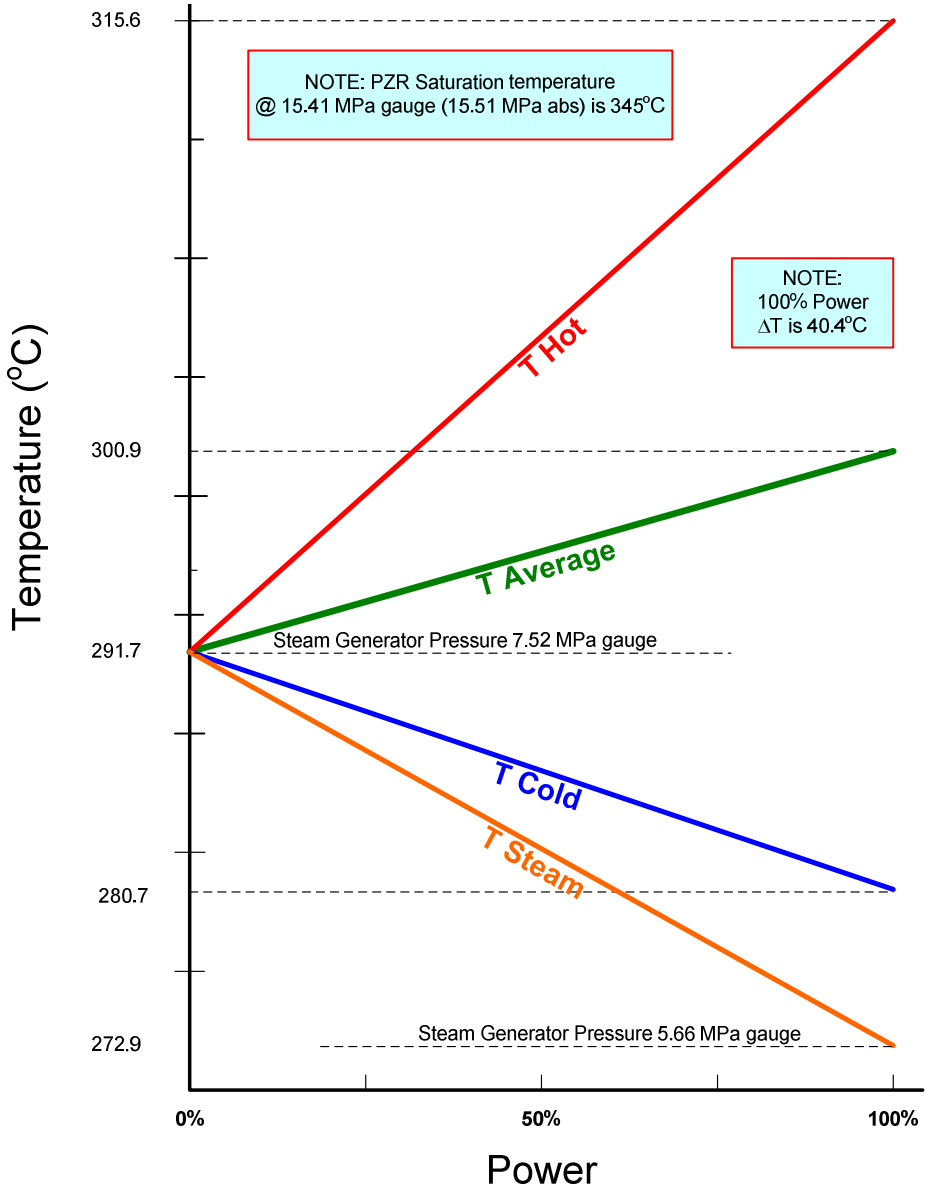
In-Core Instrumentation

- 7 Vanadium Self Powered Neutron Detectors
- 1 *Chromel-Alumel* Core Exit Thermocouple

Rod Control

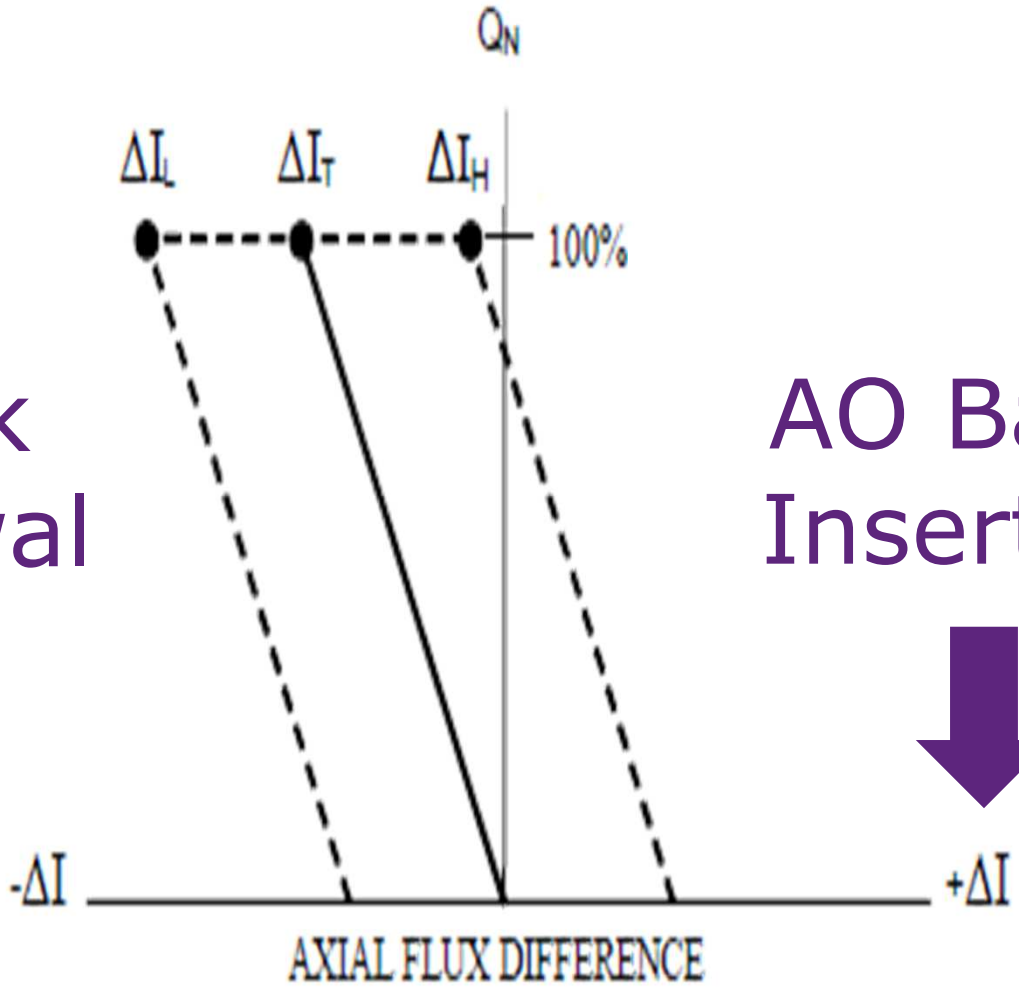

Power Cabinets
Motor Generator
Logic Cabinets
Power Mismatch
Steam
Power Range NIS
Rod Control System
Turbine Generator
T_H
T_C
Neutron Detector
T_{AVG}
T_{REF}
P
Temperature Mismatch

RCS Temperature Program



Axial Offset Control

AO Bank Withdrawal

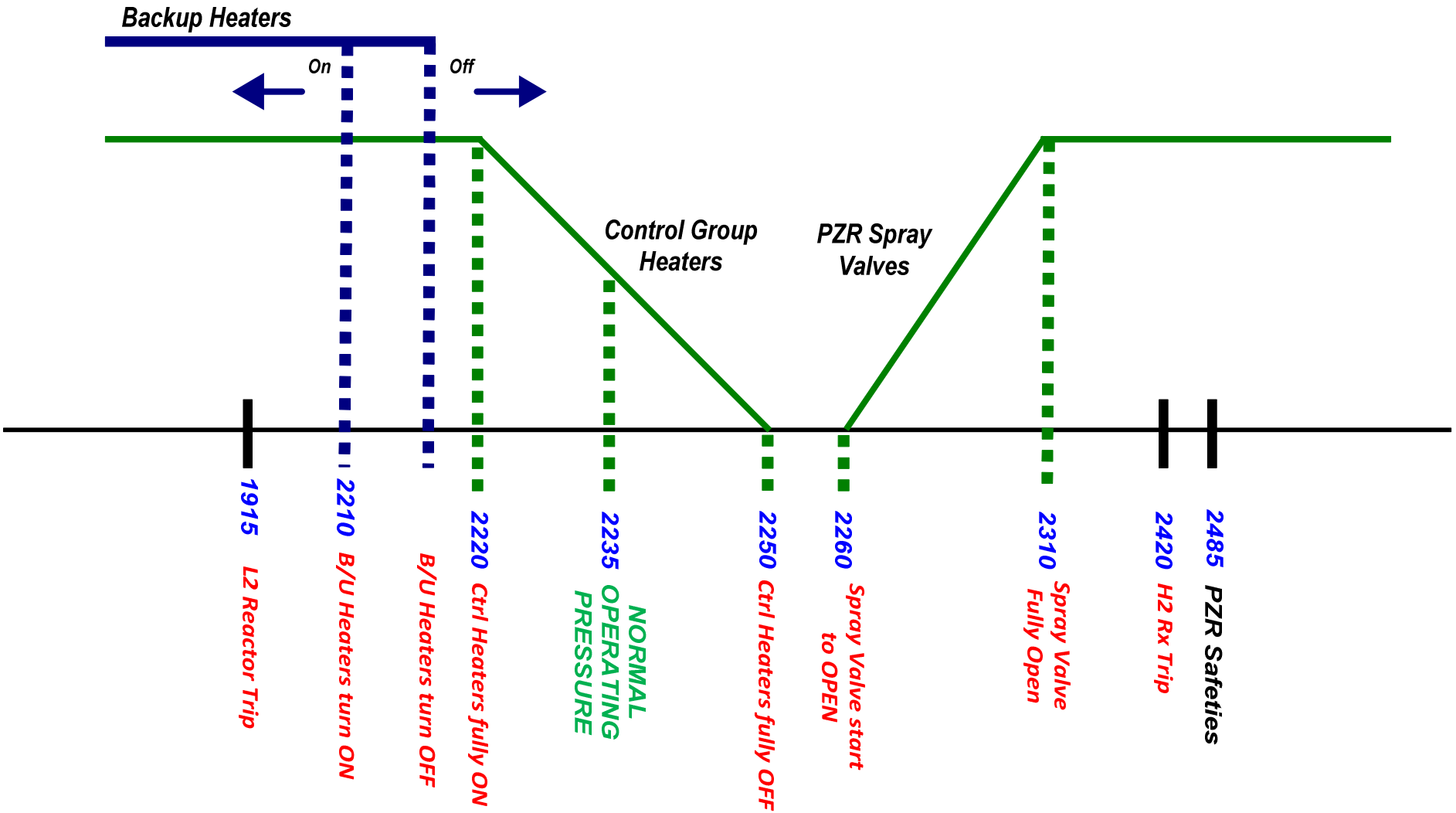


AO Bank Insertion

Pressurizer (PZR)

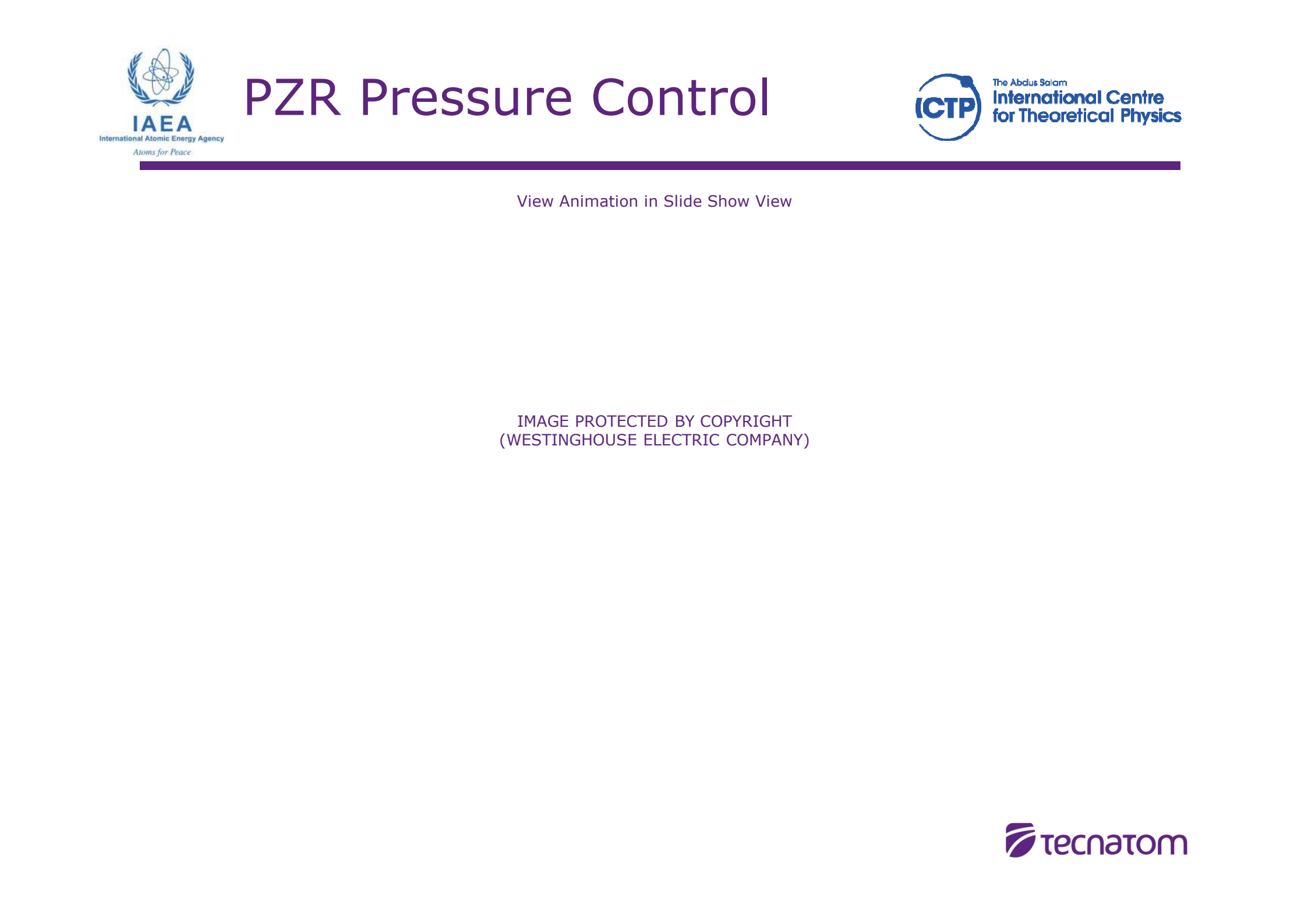
- Maintains RCS pressure
  - Pressure control during normal operation with heaters and spray.
  - Saturated environment.
  - Provides overpressure relief.
  - Pathway for initial ADS pressure reduction.
- Provides surge volume during temperature transients.

PZR Pressure Control



PZR Pressure Control

View Animation in Slide Show View



Chemical and Volume Control System (CVS)

RCPs differential pressure provides driving head for purification flow to CVS

CVS suctions from cold leg 1B.

CVS discharges back to the RCS at SG1 channel head.

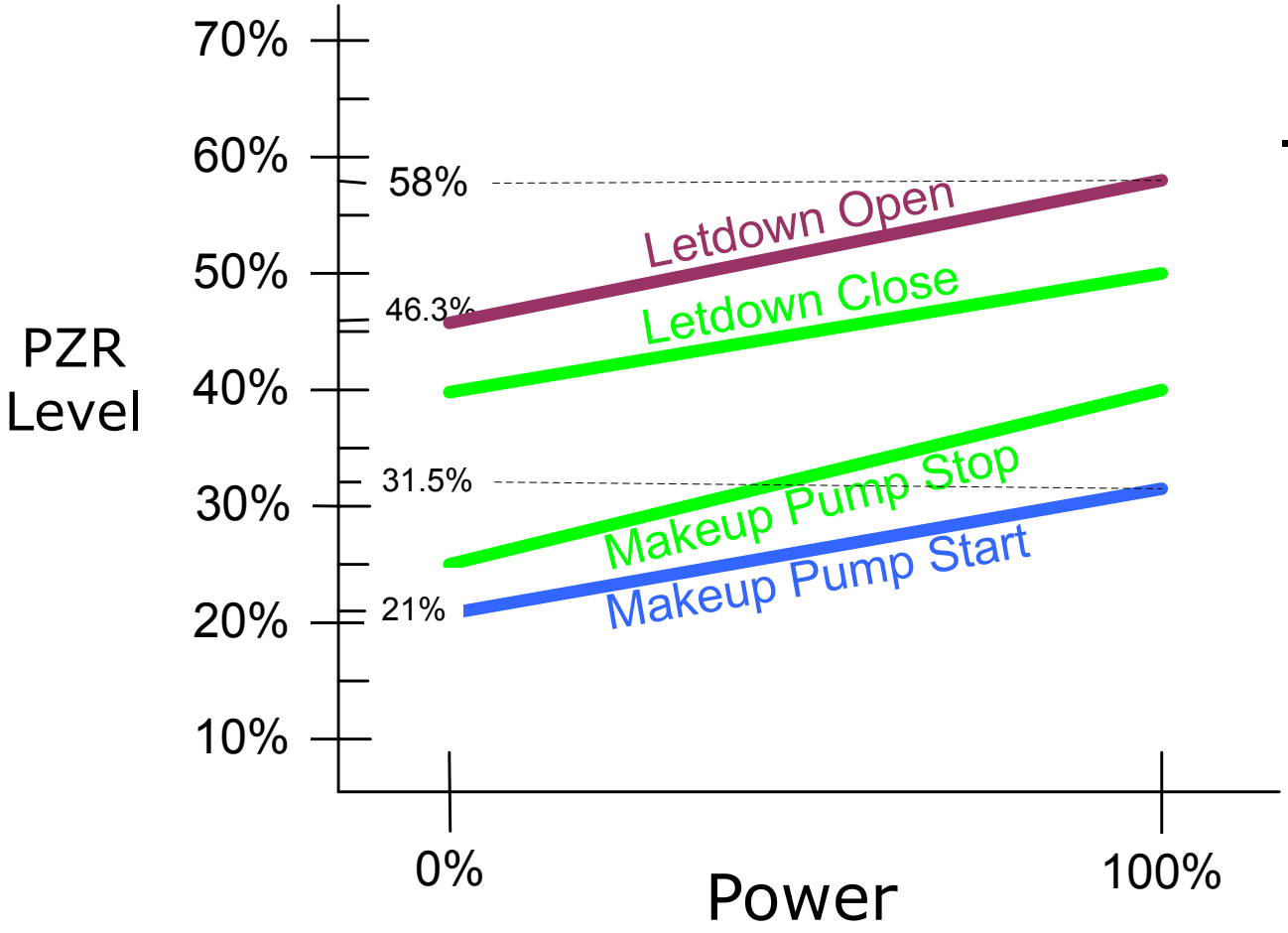
See simulator display for reference of CVS layout

Chemical and Volume Control System (CVS)

CVS functions

- RCS purification
- RCS inventory control
- Chemical shim
- Borated Makeup to Auxiliary Equipment
- pH control
- Oxygen control
- Filling and Pressure Testing the RCS
- Auxiliary Pressurizer Spray

PZR Level Program



100% Power
(31.5 – 58)% level

No-load
(21 – 46.3)% level

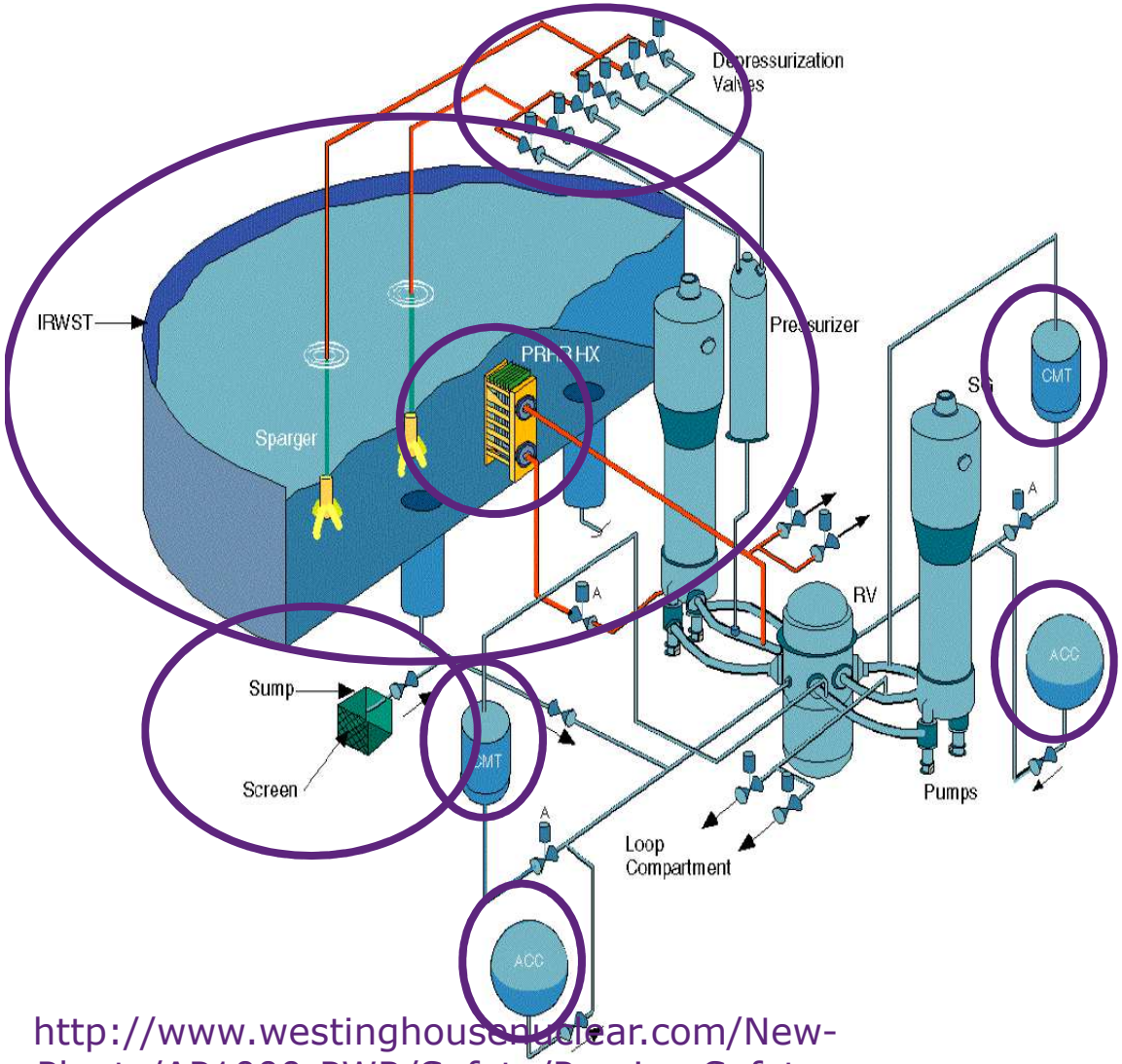
Core Cooling – Heat Sink

- Normal Operation:
  - At power: Steam Generators thru *Turbine*
  - Startup/Shutdown:
    - Steam Generators thru *Steam Bypass / Steam Relief Valves* (>177ºC;>3.1MPag)
    - *Normal Residual Heat Removal System (RNS)* (<177ºC; <3.1MPag)
- Emergency Operation
  - **Passive Core Cooling System (PXS)**
  - **Passive Containment Cooling System (PCS)**

Passive Safety Systems

- **Passive Core Cooling System (PXS)**
  - Passive Residual Heat Removal Subsystem
    - Natural circulation across a HX connected to the RCS
  - Passive Safety Injection Subsystem
    - Core Makeup Tanks (CMTs) injection by natural circulation
    - Nitrogen pressurized Accumulators (ACCs)
    - Gravity drained IRWST
    - Automatic Depressurization System (ADS)
- **Passive Containment Cooling System (PCS)**
  - Water supply by gravity, and heat removal by evaporation and natural circulation

Passive Core Cooling System (PXS)



http://www.westinghousenuclear.com/New-Plants/AP1000-PWR/Safety/Passive-Safety-Systems

Safety Injection Subsystem

- Core Makeup Tanks
- Accumulators
- In-Containment Refueling Water Storage Tank
- Containment Sumps
- Automatic Depressurization Valves

Emergency Core Decay Heat Removal Subsystem

- Passive Residual Heat Removal HX

Automatic Depressurization System (ADS)

- Three stages of ADS valves are connected to the PZR, and discharge through spargers located in the IRWST.
- They are motor operated valves (MOVs).
- The fourth stage ADS valves are connected to the RCS hot legs and discharge directly to the steam generator compartments.
- These are squib valves

See simulator display for reference of ADS layout

Automatic Depressurization System (ADS)

- Reduces the pressure in the RCS during loss-of-coolant accidents (LOCA) in order to permit safety injection.
- The ADS valves are designed to operate in four different stages.
- Automatic signal to open comes from CMT level, but can also be manually actuated.

Passive Core Cooling System (PXS)

View Animation in Slide Show View

Containment Sump Recirculation

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Severe Accident:
In-Vessel Retention of Core Damage

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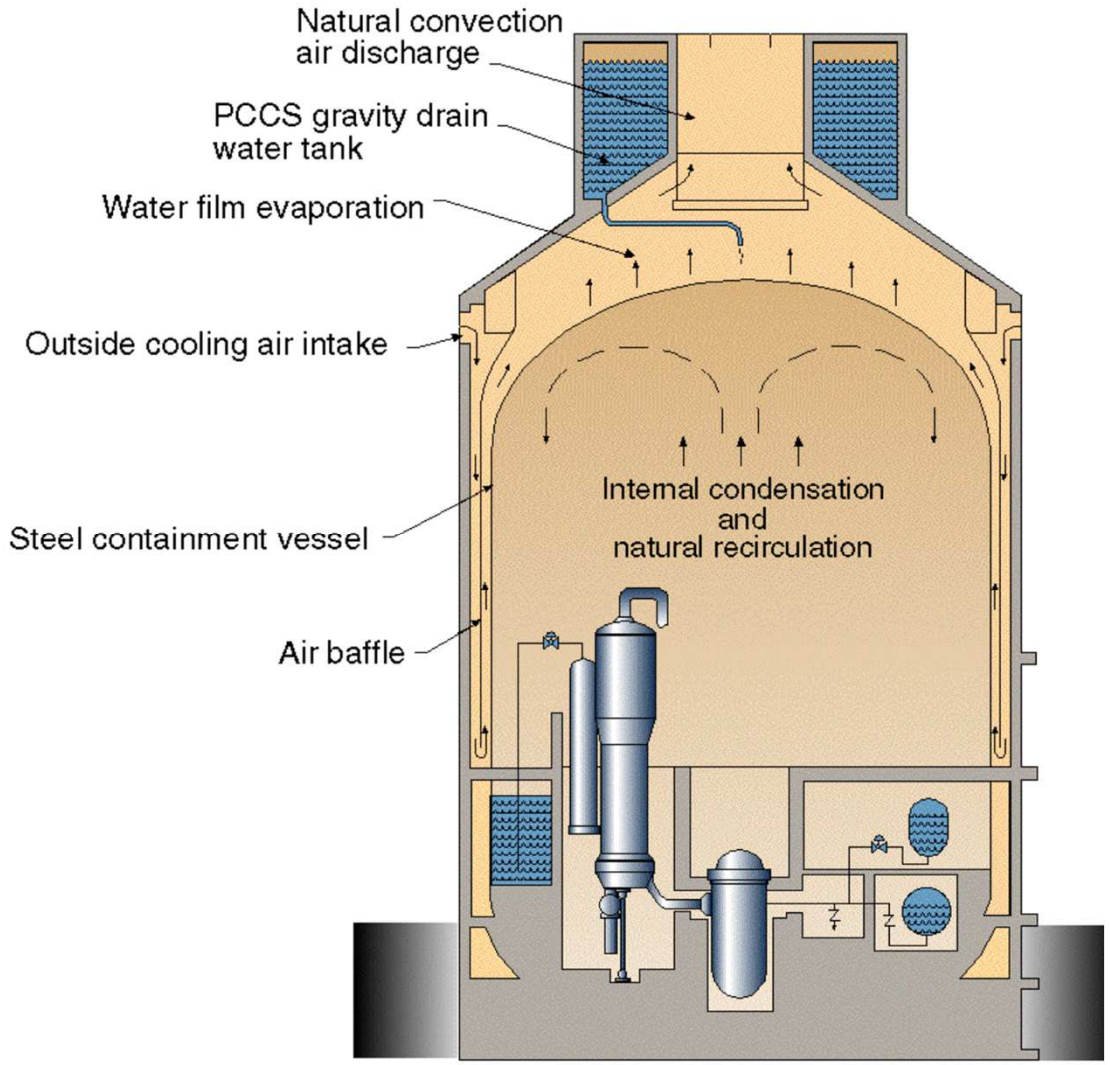
Passive Containment Cooling System (PCS)

Final Heat Sink for

Loss of Coolant Accidents

Or

Steam Line Breaks Inside Containment



https://web.archive.org/web/20140723001334/http://www.westinghousenuclear.com/docs/AP1000_brochure.pdf)

Passive Containment Cooling System (PCS)

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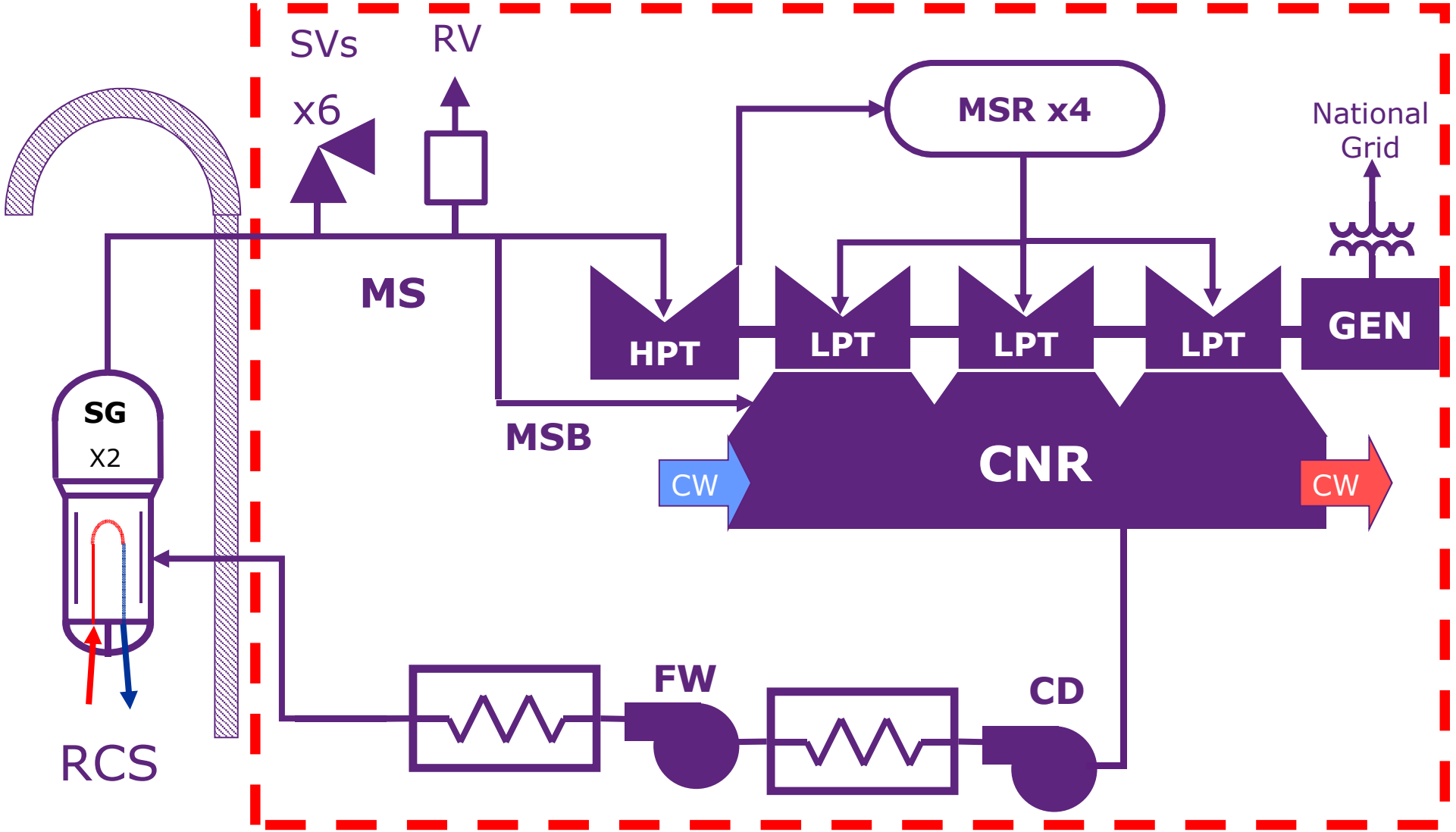
Normal Residual Heat Removal System (RNS)

Normal Residual Heat Removal System (RNS)

- Remove decay heat from the core and reduces the temperature of the RCS during the second phase of plant cooldown (From ~177°C to ~51.6°C)
- Supplement the passive core cooling system (PXS) during emergencies.
- Provide RCS purification motive force when the RCPs are not operating or are operating at reduced speeds.
- IRWST cooling

Balance of Plant



Instrumentation & Control Protection

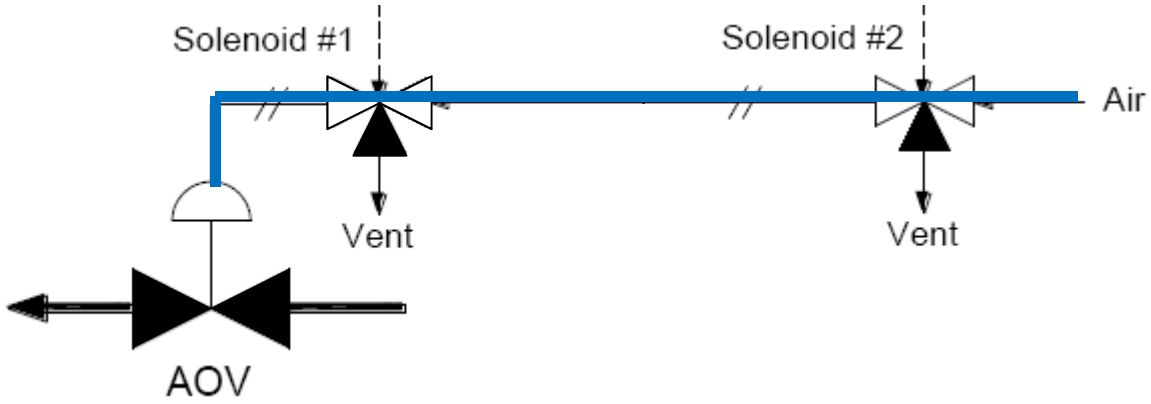
- One **safety-related** protection system:
  - Redundant divisions (Logic 2 out of 4) "de-energize-to-act"
  - Screens and Controls (both hard and soft) in MCR.
  - Backed up by batteries (safety-related) and diesel generators (non-safety-related)
  - Automatic detection of abnormal conditions and **Safety Functions Actuation**.
  - Post-Accident Instrumentation (backed by longer endurance batteries)

Instrumentation & Control Protection

- One **non-safety-related** protection system
  - Back-up where common mode failure is a risk
  - *"Diversity"* (different Hardware & Software architecture)
  - Backed by short endurance batteries and DGs.
  - Automatic detection of abnormal conditions and "reduced" protective functions actuation.
  - Independent instrumentation
  - Logic 2 out of 2, "energize-to-act"
  - Actuates over some equipments as regular protection system
  - Signal isolation between regular protection system

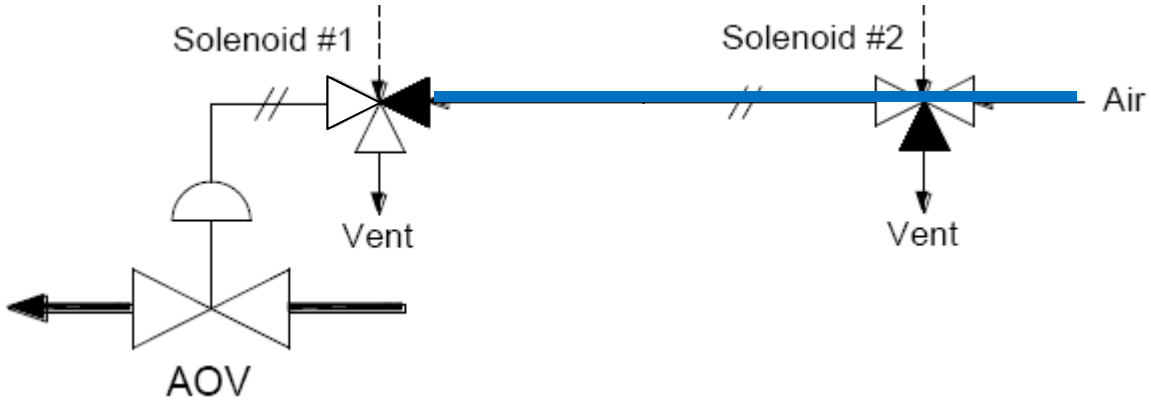
Instrumentation & Control
Diverse Protection

- Non-Actuated
  - Solenoid 1 energized (SR Protection)
  - Solenoid 2 de-energized (NSR Protection)



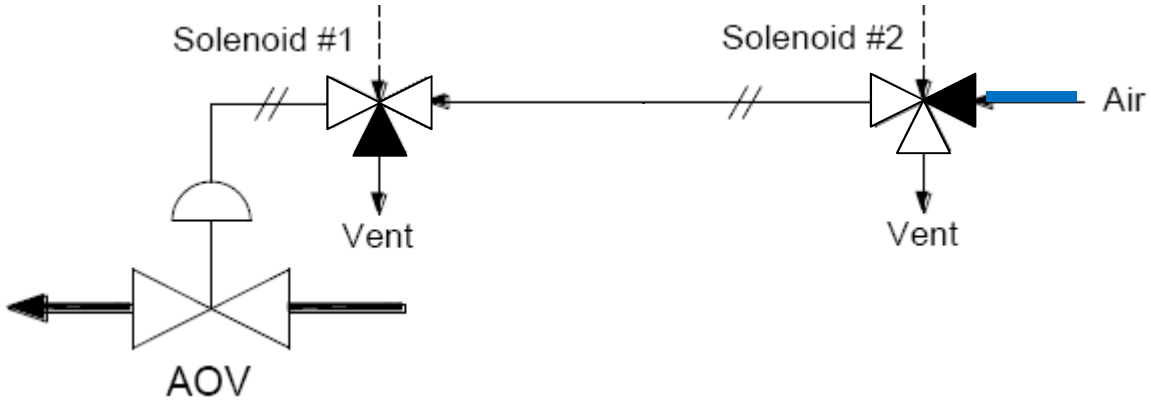
Instrumentation & Control
Diverse Protection

- Actuated by safety-related protection
  - Solenoid 1 de-energized
  - Solenoid 2 de-energized



Instrumentation & Control
Diverse Protection

- Actuated by non-safety-related protection
  - Solenoid 1 energized
  - Solenoid 2 energized



Instrumentation & Control Control

- **Non-safety-related** control system.
- Distributed Control System (modular repaired).
- Two redundant servers.
- Signal Selector Algorithms (single failure criteria).
- Isolation devices with Protection System.
- Alarm Presentation System.
- Computerized Procedures.
- Datalinks for data exchange to external systems (radiation monitors, in-core instrumentation, PLC…).

Advanced Main Control Room

- Compact Control Room
  - Designed to be operated by at least one operator and one supervisor.
- Passive ventilation during accidents:
  - Compressed air to feed the MCR.
  - Ceiling fins acting as passive heat sink.
- Controls
  - Software controls
  - Hardware switches
- Computerized Procedures

Advanced Main Control Room

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PRA Results for a Passive PWR

At Power, Internal Events	Current US	AP600	AP1000	Ratio (Current vs AP600	AP1000)
Transients	1.3E-05 /yr	4.4E-09 /yr	7.3E-09 /yr	2959	1772
Loss Offsite Power	6.6E-06 /yr	1.0E-09 /yr	9.6E-10 /yr	6600	6889
Steam Line / Feed Line Breaks	-- /yr	6.1E-10 /yr	7.5E-10 /yr	na	na
SG Tube Rupture	1.7E-06 /yr	6.1E-09 /yr	6.8E-09 /yr	279	250
RCS Leak	-- /yr	2.3E-09 /yr	1.7E-09 /yr	na	na
Small LOCA	8.0E-06 /yr	4.7E-09 /yr	1.9E-08 /yr	1717	430
Medium LOCA	5.0E-06 /yr	8.0E-08 /yr	1.1E-07 /yr	63	44
Large LOCA	8.0E-07 /yr	5.0E-08 /yr	7.5E-08 /yr	16	11
ATWS	2.2E-06 /yr	1.0E-08 /yr	4.4E-09 /yr	218	496
Loss Support Sys (CCW/SW, ...)	-- /yr	2.9E-10 /yr	1.0E-09 /yr	na	na
Inter-System LOCA	1.0E-06 /yr	5.0E-11 /yr	5.0E-11 /yr	20000	20000
Vessel Rupture	3.0E-07 /yr	1.0E-08 /yr	1.0E-08 /yr	30	30
Total	**3.9E-05** /yr	**1.7E-07** /yr	**2.4E-07** /yr	228	160
Total without Operator Actions	**~ 2 E-03** /yr	**1.8E-05** /yr	**1.4E-05** /yr	111	146
Total without Nonsafety Systems	**~ 2 E-03** /yr	**7.7E-06** /yr	**7.4E-06** /yr	260	270

QUESTIONS?