The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
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IAEA
International Atomic Energy Agency

1879-2

Nuclear Power Plant Simulators for Education

29 October - 9 November, 2007

APWR Material

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Cassiopeia Technologies Inc., Toronto, Canada

NPP Simulators Workshop for Education - Passive PWR NPP & Simulator Overview

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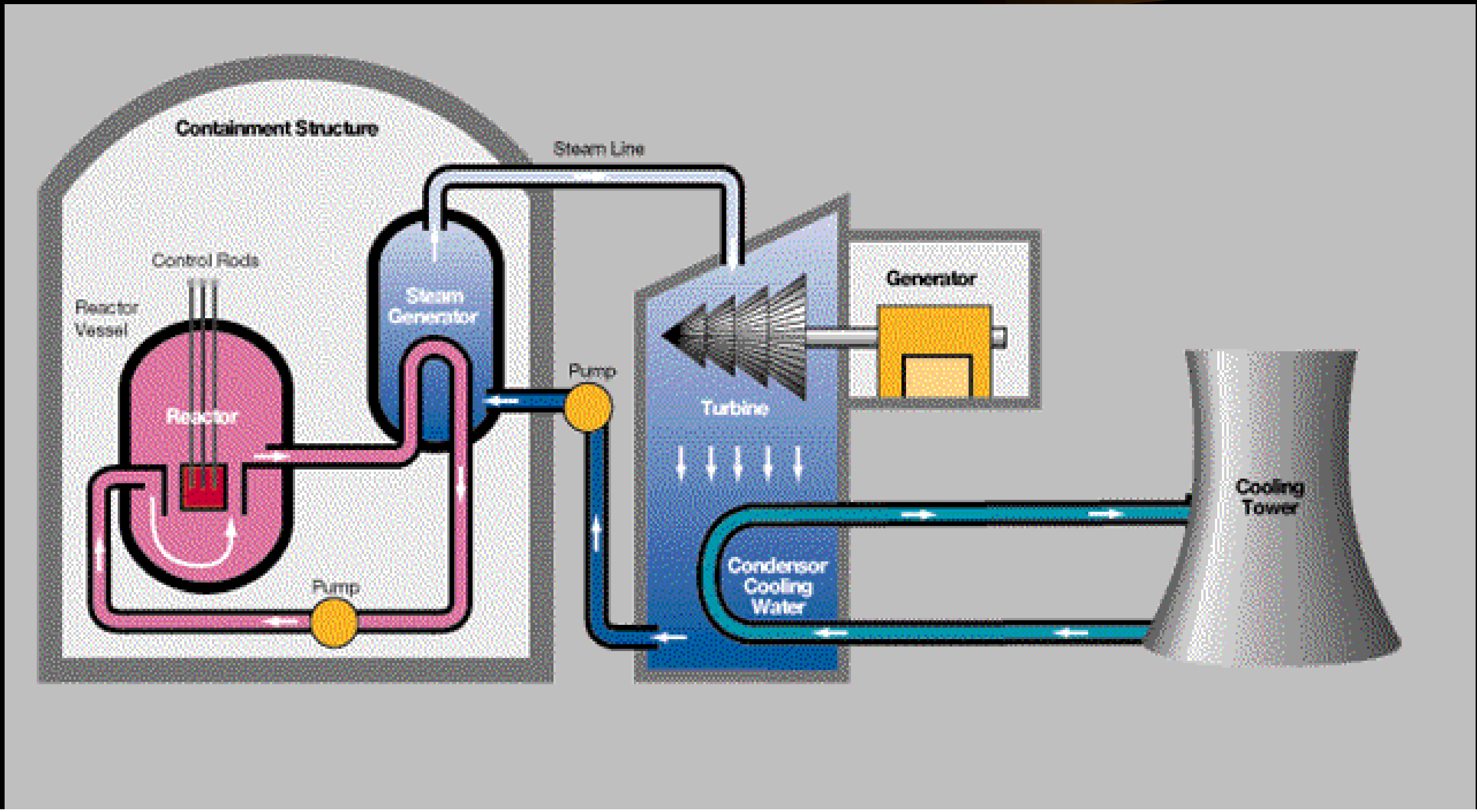
Sponsored by IAEA

Pressurized Light Water Reactor

- Reactor heats water from 279 to 315 deg. C
- Pressurizer keeps coolant pressure 15.5 MPa; boiling is not allowed. Thermal efficiency ~ 32 %.
- Use Gen III+ Passive PWR AP-1000 & EPR as examples



Background

- 1980 - Westinghouse started AP600 D & D
- AP600 - 600 MWe 2 loops PWR ; hallmark : passive safeguard systems & plant simplification.
- URD - ALWR Utility Requirements Document via EPRI effort - large experience base from LWR to minimize risks, etc. (208 reactors in operation - 4351 reactor operation years).

AP600 Design Objectives

- Greatly simplified Plant to meet or exceed NRC safety goals, as well as ALWR Utility Requirements.
- Principal features: use experience-based components; plant systems simplification; increased operating margin; reduced operator actions; passive safety features; modularity.
- NRC Design Certification in 1999

Why Was Advanced Passive AP1000 Design Developed?

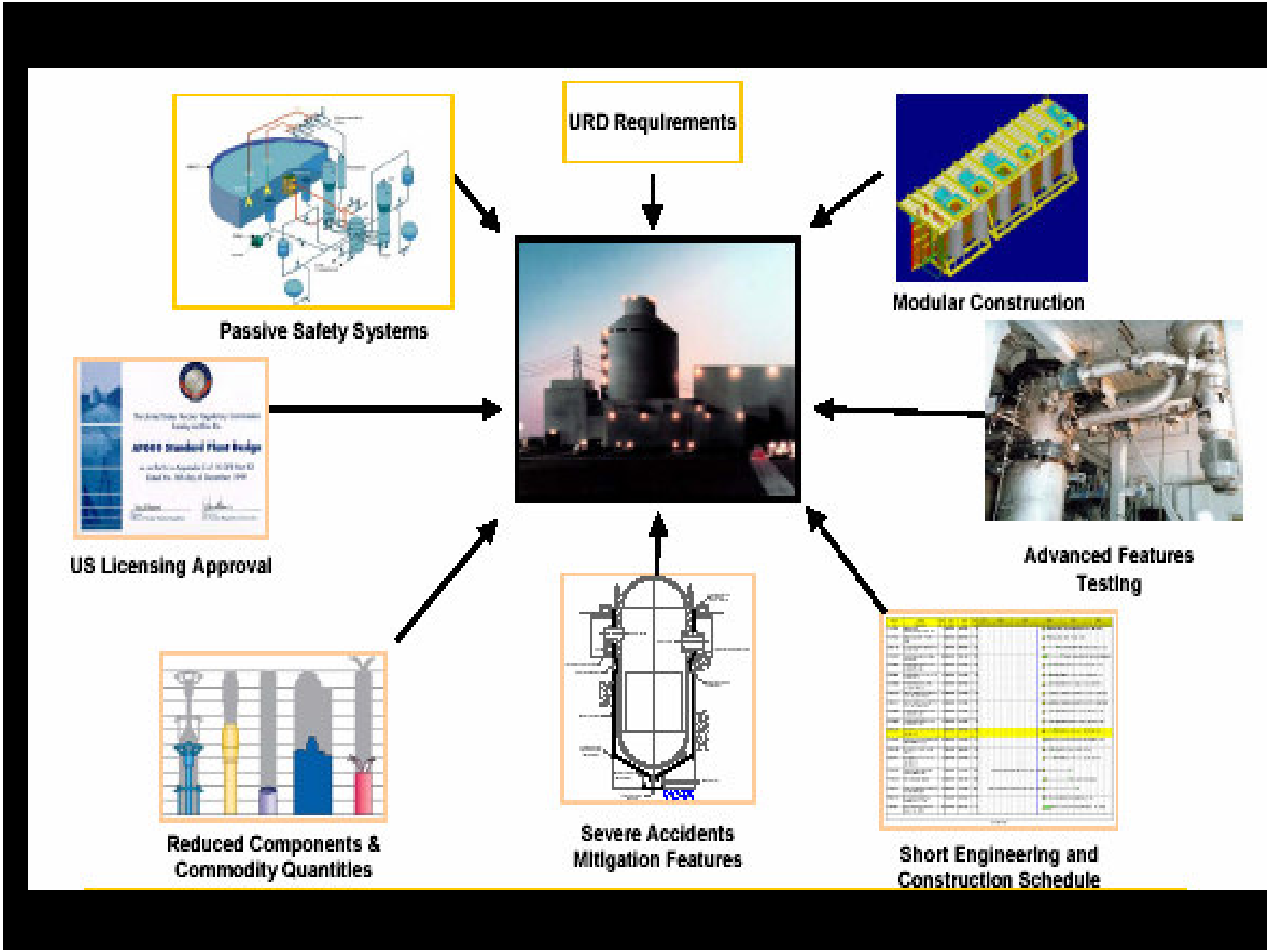
- Existing designs with incremental improvements could not meet the deregulated electricity generation cost target 3 to 3.5¢/kWh
- Westinghouse Passive Plant Technology was mature and licensed in US
- Large investment in Passive Plant Technology development could be leveraged to provide a cost competitive design in a relatively short time

AP1000 NRC certification in 2004

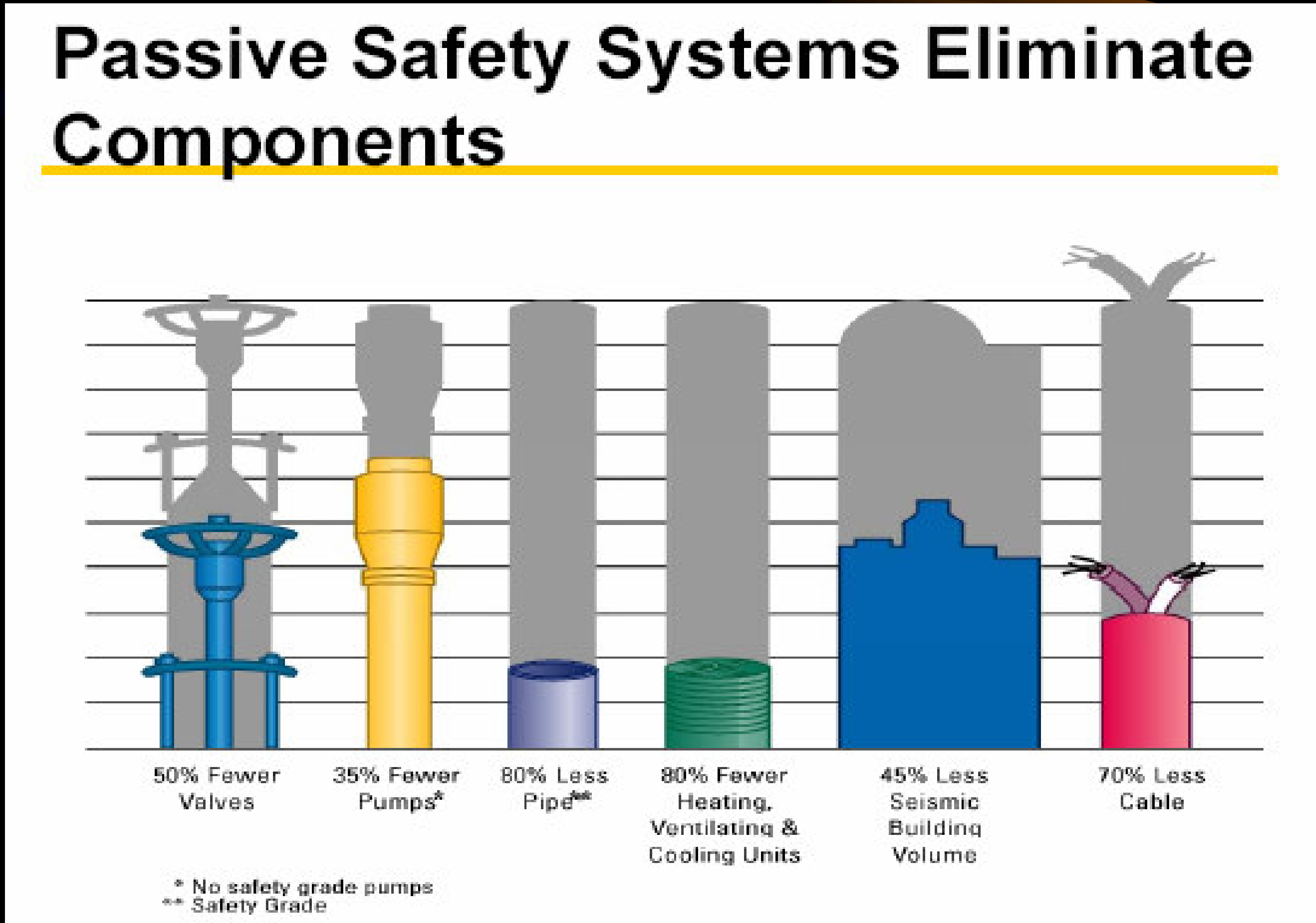
Conventional PWR, AP600, AP1000

Parameter	Doel 4/Tihange 3	AP600	AP1000
Net Electric Output, MWe	985	610	1117
Reactor Power, MWt	2988	1933	3400
Hot Leg Temperature, ^{o}C (^{o}F)	330 (626)	316 (600)	321 (610)
Number of Fuel Assemblies	157	145	157
Type of Fuel Assembly	17x17	17x17	17x17
Active Fuel Length, m (ft)	4.3 (14)	3.7 (12)	4.3 (14)
Linear Hear Rating, kw/ft	5.02	4.1	5.71
Control Rods / Gray Rods	52 / 0	45 / 16	53 / 16
R/V I.D., cm (inch)	399 (157)	399 (157)	399 (157)
Vessel flow (Thermal) 10^3 m3/hr (10^3 gpm)	67.1 (295)	44.1 (194)	68.1 (300)
Steam Generator Surface Area, m2 (ft2)	6320 (68,000)	6970 (75,000)	11,600 (125,000)
Pressurizer Volume, m3 (ft3)	39.6 (1400)	45.3 (1600)	59.5 (2100)

Table 1 - Selected AP1000 RCS Parameters

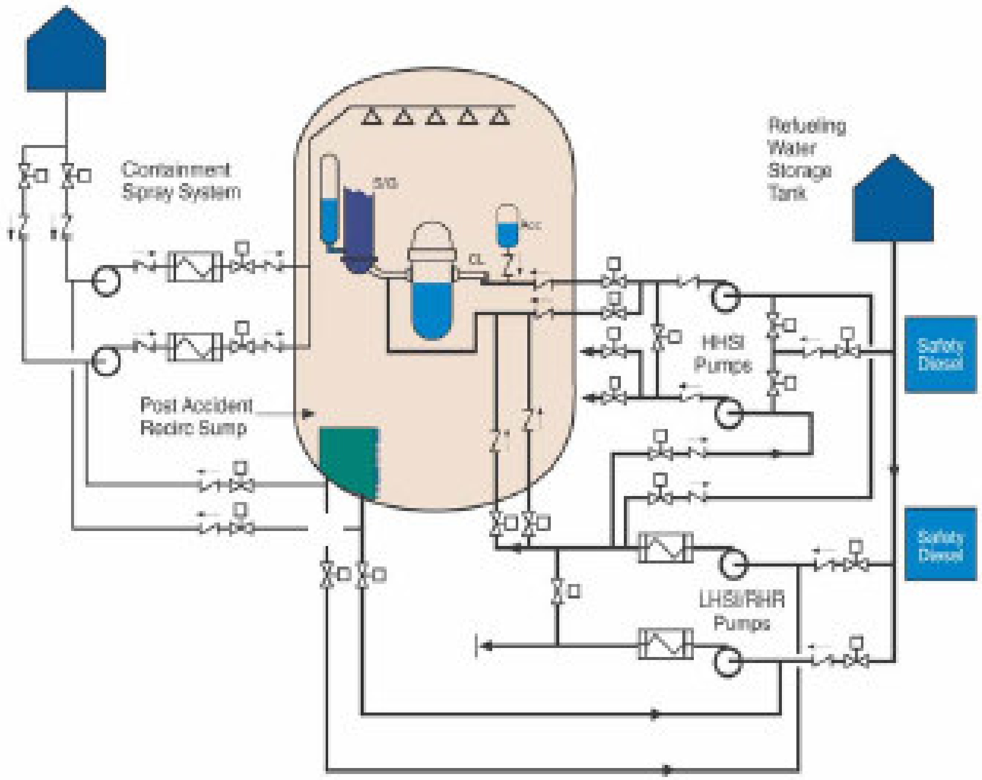

URD Requirements
Passive Safety Systems
Modular Construction
US Licensing Approval
Advanced Features Testing
Reduced Components & Commodity Quantities
Severe Accidents Mitigation Features
Short Engineering and Construction Schedule

Less Components in AP1000

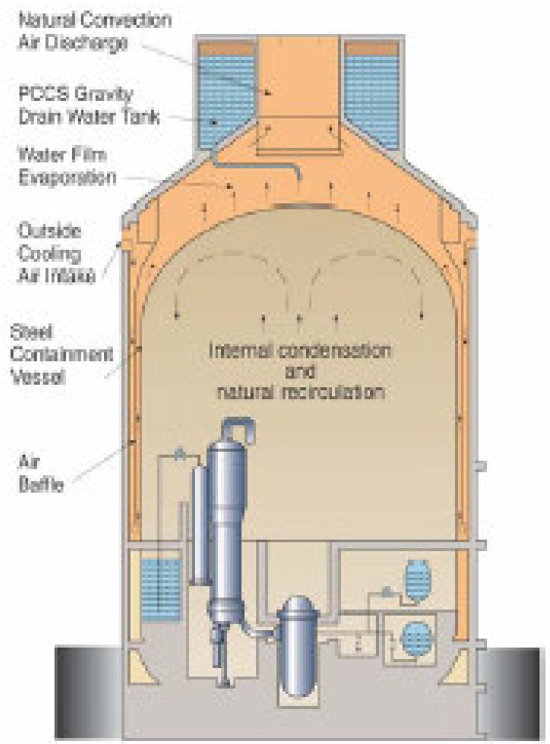


Simplification of Safety Systems Dramatically Reduces Building Volumes

Standard PWR



AP1000



AP1000 Approach to Safety

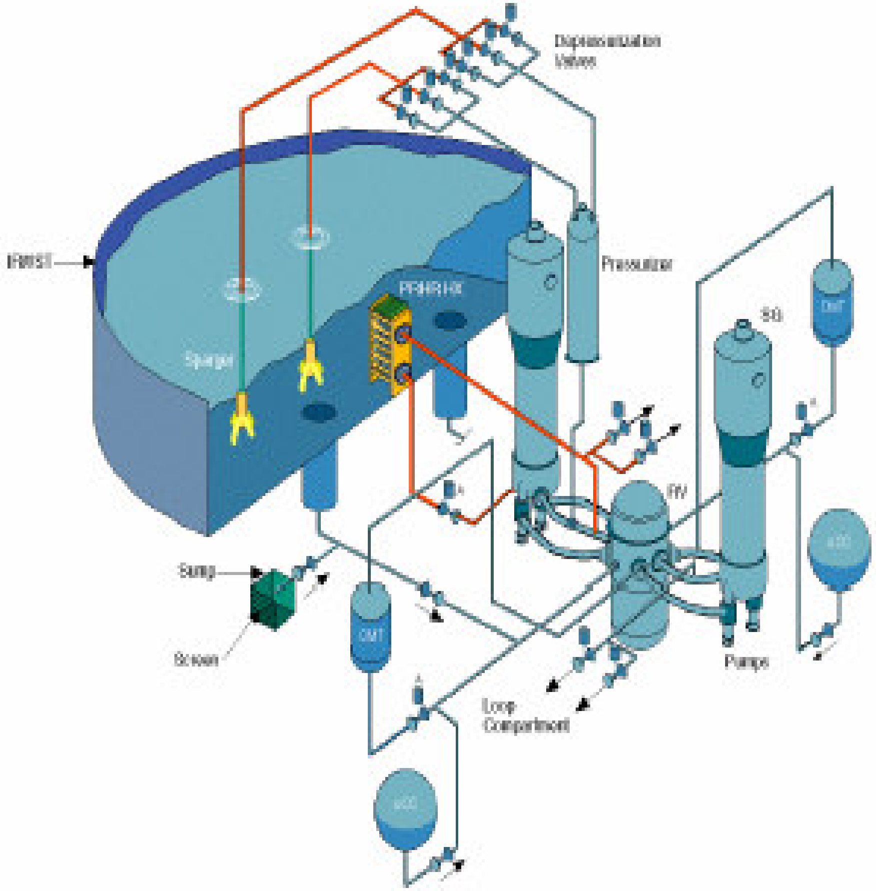
- Passive Safety Systems
  - Use “passive” processes only; no safety-grade active pumps, diesels….
  - Dedicated systems; not used for normal operations
  - Reduced dependency on operator actions
  - Mitigate design basis accidents
  - Meet regulatory safety goals
- Active Non-Safety Systems
  - Reliably support normal operation
  - Minimize challenges to passive safety systems
  - Not required to mitigate design basis accidents or meet safety goals
  - Provide plant investment protection

Passive Safety Advantages

- No reliance on AC power
- Automatic response to accident condition assures safety
- Long term plant safety assured without active components (natural forces only)
- Containment reliability greatly increased by passive cooling
- In severe accidents, reactor vessel cooling keeps core debris in vessel
- Large margin to safety limits
- Defense in depth - active non-safety systems provide additional first line of defense

Passive Core Cooling System

- AP1000 has no reliance on AC power
  - Passive Decay Heat Removal
  - Passive Safety Injection
  - Passive Containment Cooling
- Long term safe shutdown state > 72 hours without operator action

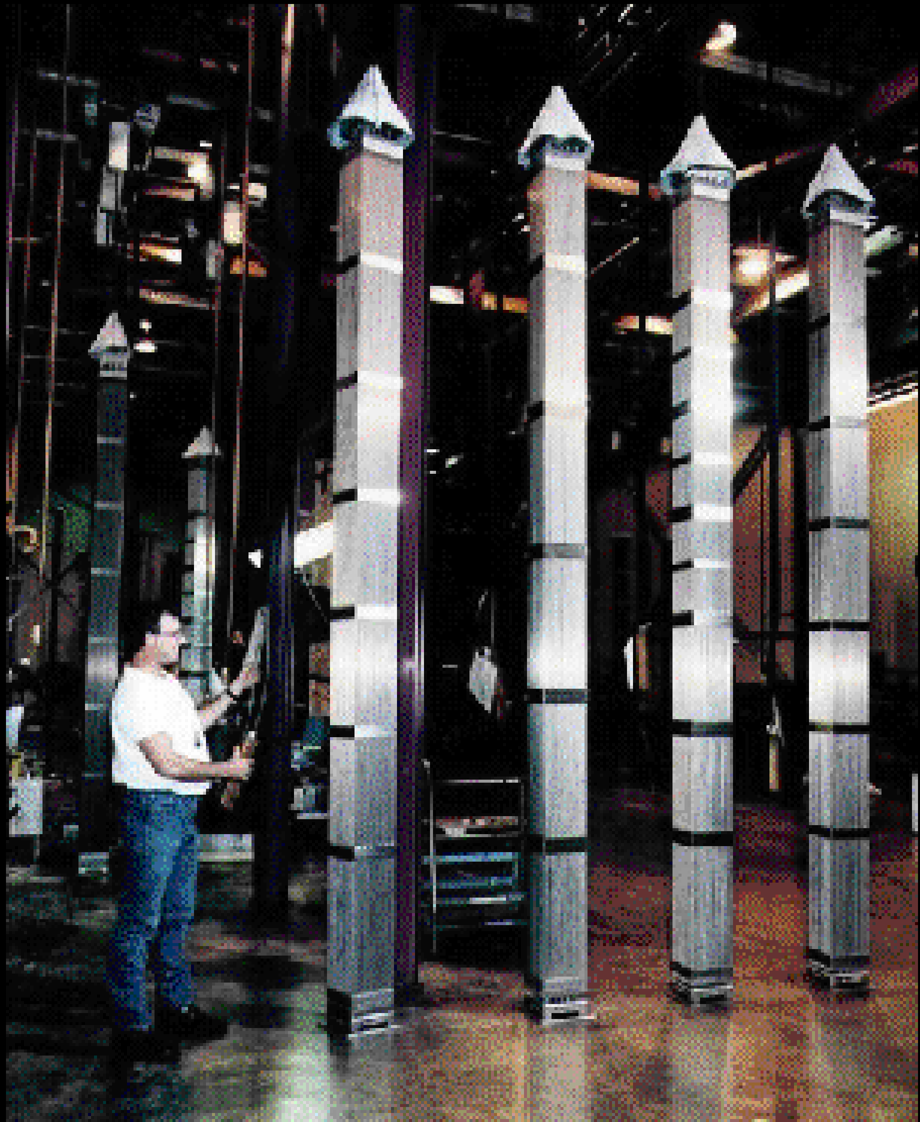


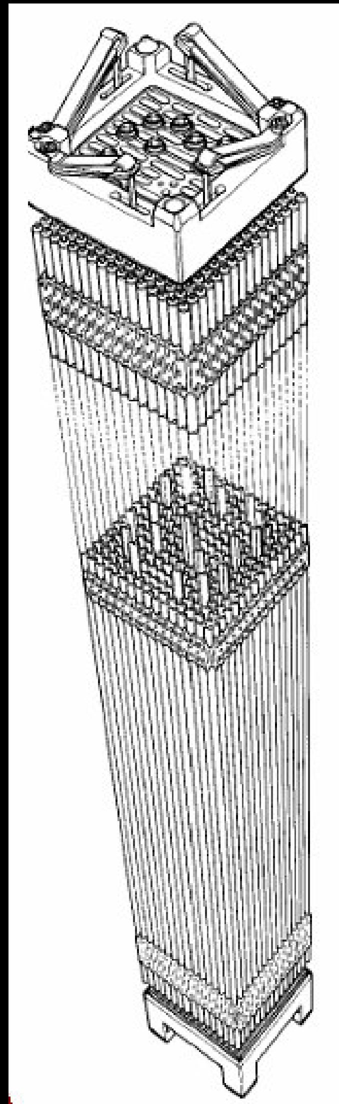
AP1000 Provides Multiple Levels of System Defense In Depth

- First action is usually by non-safety grade active system
    - High quality industrial grade equipment
- Second action is by safety grade passive system
    - Provides safety case for SAR
    - Highest quality nuclear grade equipment
- Other passive systems provide additional defense-in-depth
    - Example; passive feed/bleed backs up PRHR HX
- Available for all shutdown conditions as well as at power
- More likely events have more levels of defense

AP1000 Reactor Core & Fuel Design

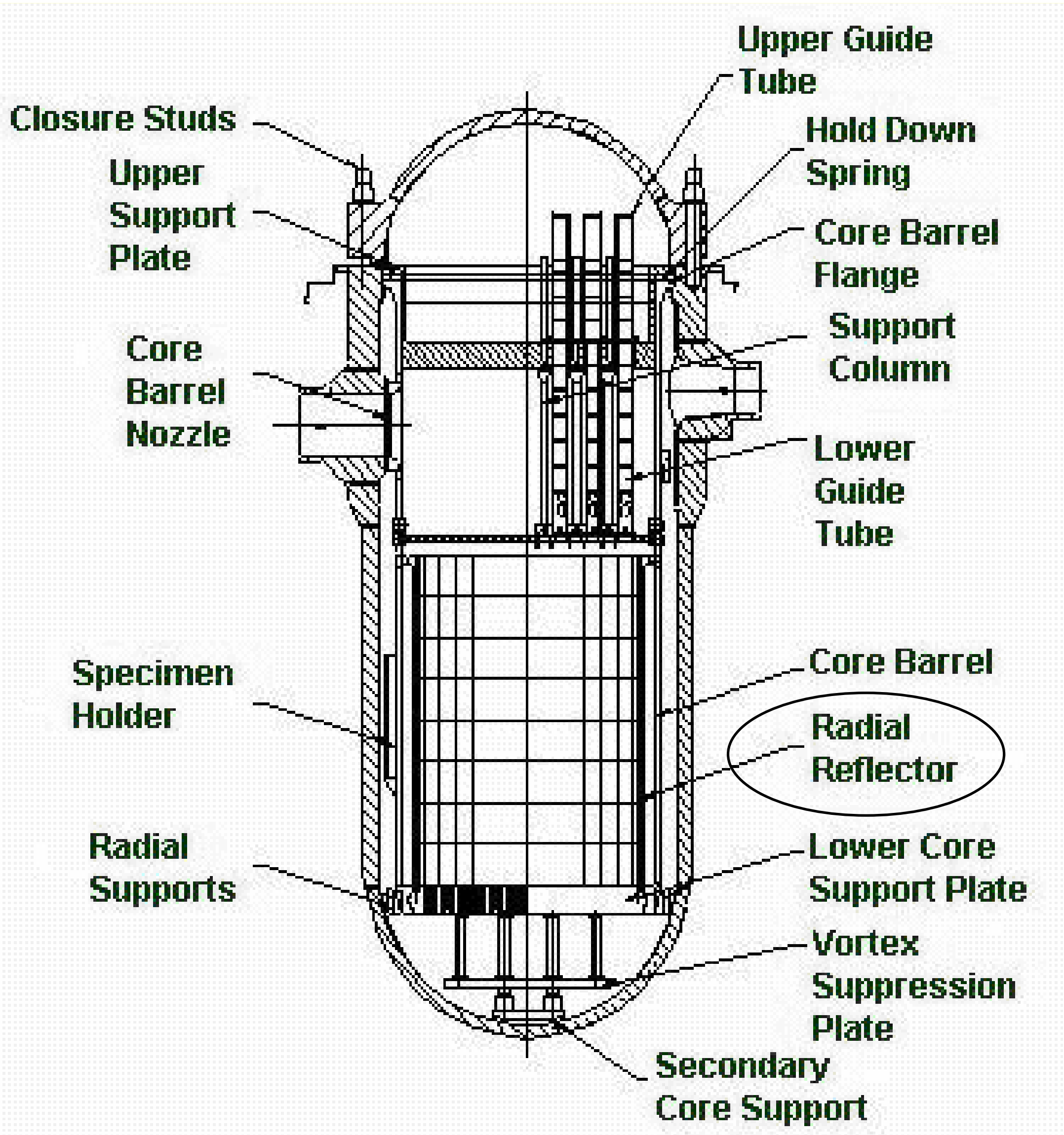
- Rod array - standard 14 ft, 17x17 fuel assemblies.
- Larger core + reflector - result in Lower (25% less) Power Density Core - average fuel power density 28.89 kW/kg U; average core power density (vol) 78.82 kW/L
- # of assemblies increased from 145 to 157.
- 264 rods per assembly.
- Lower fuel enrichment (2 - 4 % in three radial region); less reliance on burnable absorbers; longer fuel cycle - 24 months; 15 % more in safety margin for DNB, and LOCA.

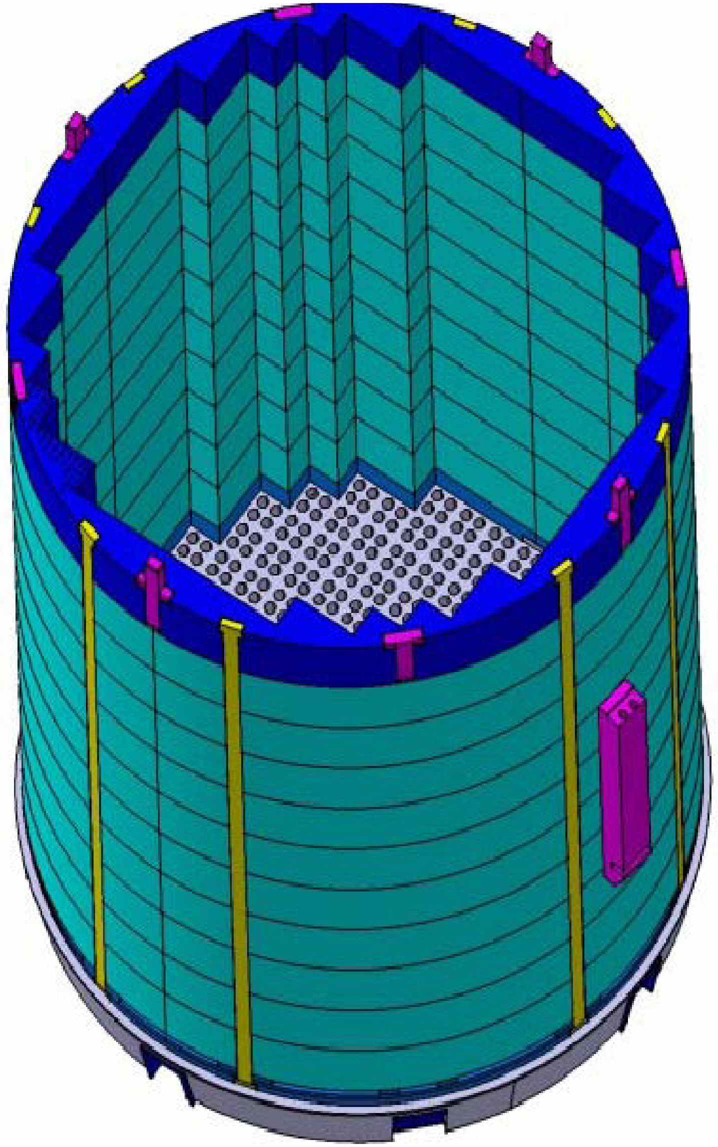




Reactor Core & Fuel Design

- Stainless steel radial reflector - reduces neutron leakage - improve core neutron utilization, hence reduced fuel enrichment. Added benefit - reduce radiation damage on reactor vessel, extending design life.


Closure Studs
Upper Support Plate
Core Barrel Nozzle
Specimen Holder
Radial Supports
Upper Guide Tube
Hold Down Spring
Core Barrel Flange
Support Column
Lower Guide Tube
Core Barrel
Radial Reflector
Lower Core Support Plate
Vortex Suppression Plate
Secondary Core Support



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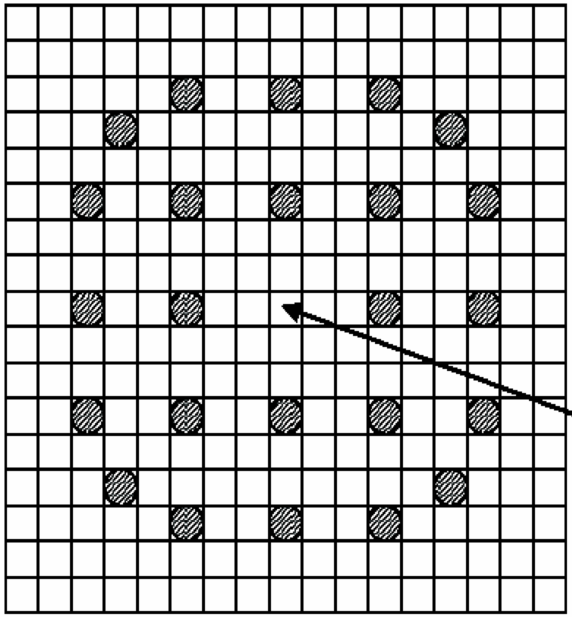
Rod Cluster Control Assembly RCCAs

- 53 RCCAs
- Very high thermal neutron absorber silver-indium-cadmium alloy

Gray Rod Cluster Assembly GRCAs

- 16 GRCAs
- Reduced-worth control rods (“gray” rods) - to achieve load following capability without substantial use of soluble boron - eliminate the need of heavy duty water purification system.

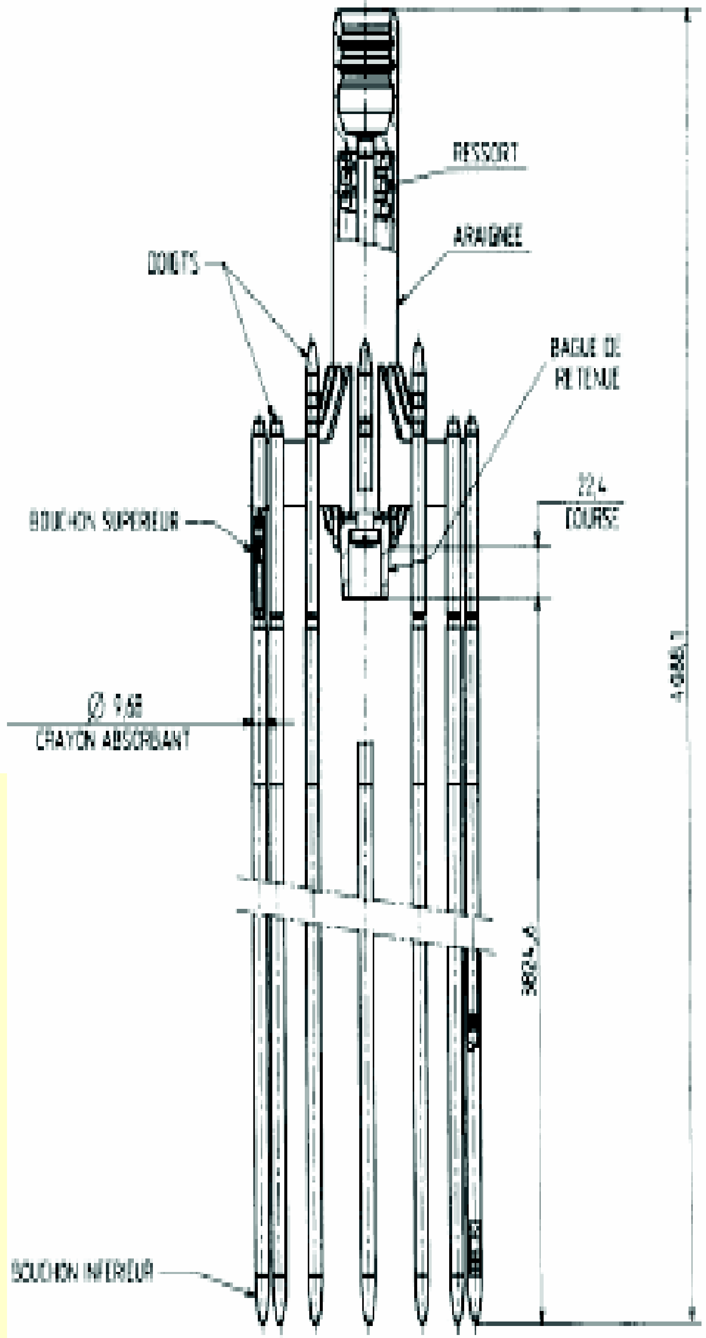
17x17 ASSEMBLY



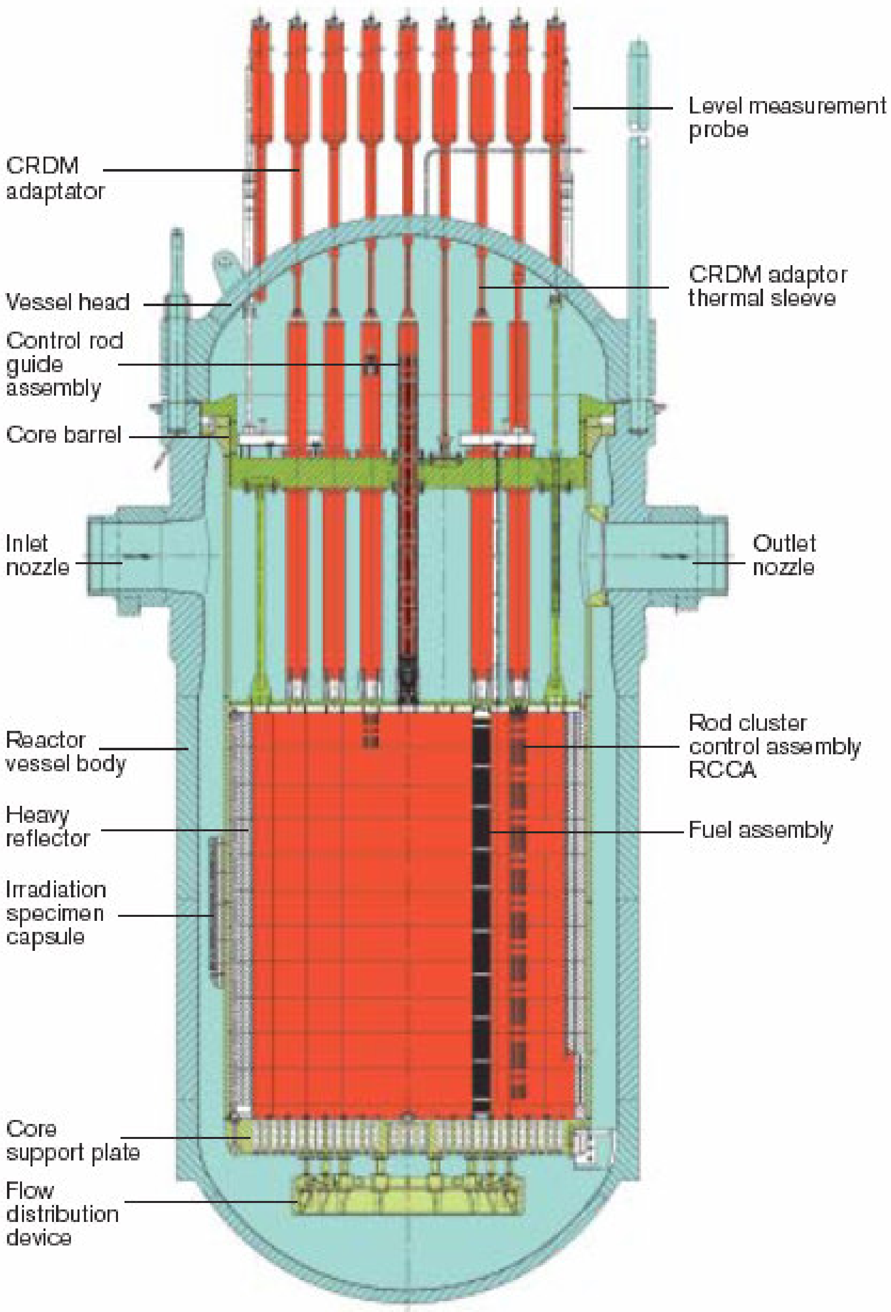
Fuel Rod

Guide Tube
for RCCA absorber rod or
instrumentation thimble

No central
instrumentation
guide tube

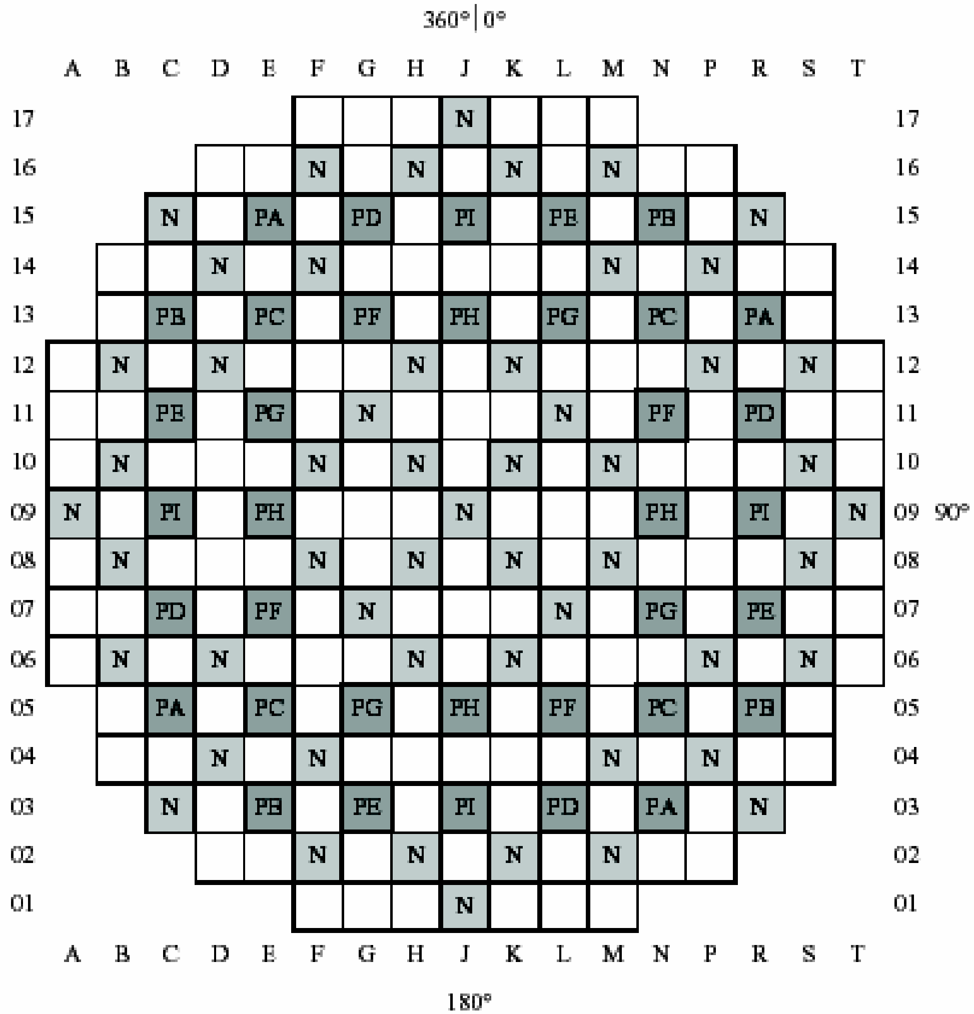


Reactor pressure vessel and internals cutaway



RCCA Pattern

- 89 RCCA for maximizing the shutdown margin
- 53 for shutdown (N)
- 36 for control
  - 9 banks of 4 rods symmetrically located (PA to PI)
  - The 4 rods move at the same time with the same signal
- Assignment of bank to control groups can be changed during the fuel cycle



EPR

Core Reactivity

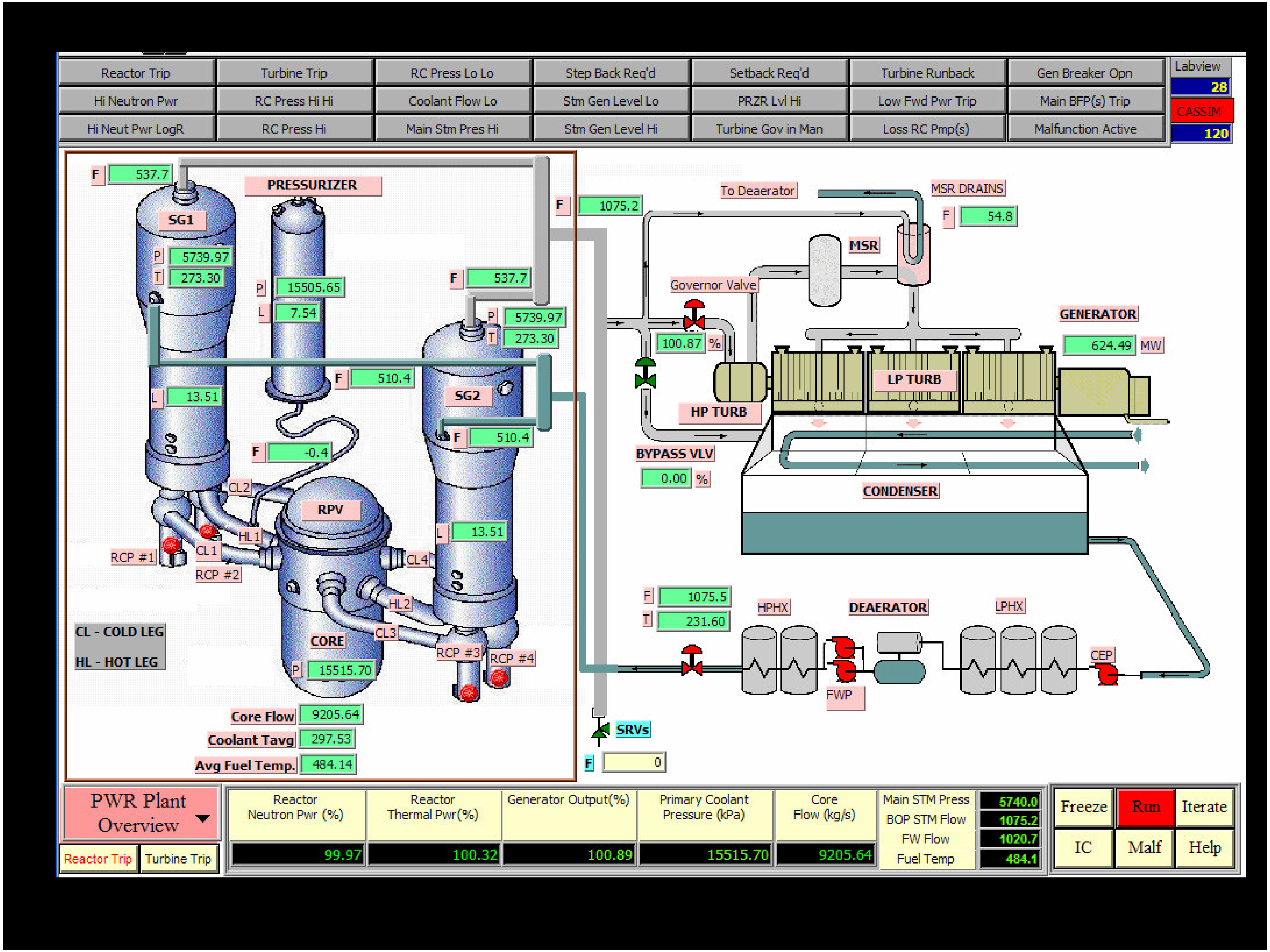
- Temperature coef of core reactivity is highly negative.

EPR **Core Reactivity Control Principles**

Soluble Boron - CVCS - EBS	Fuel burnup compensation Xenon compensation Ensure subcriticality at cold state	Enriched B_{10} keeps C_B < 1400 ppm (HFP, BOC)
Control rods 89 black rods	Control - Reactor coolant T°avg - Axial Offset Ensure subcriticality for core safe shutdown (260 °C)	Control of rod bank insertion Partial trip Reactor trip
Burnable absorbers (Gd_2O_3)	Reduce boron conc at BOC Limit radial power peaking factor	Moderator T° coef < 0 $F\Delta h$ < $F\Delta h$ limit

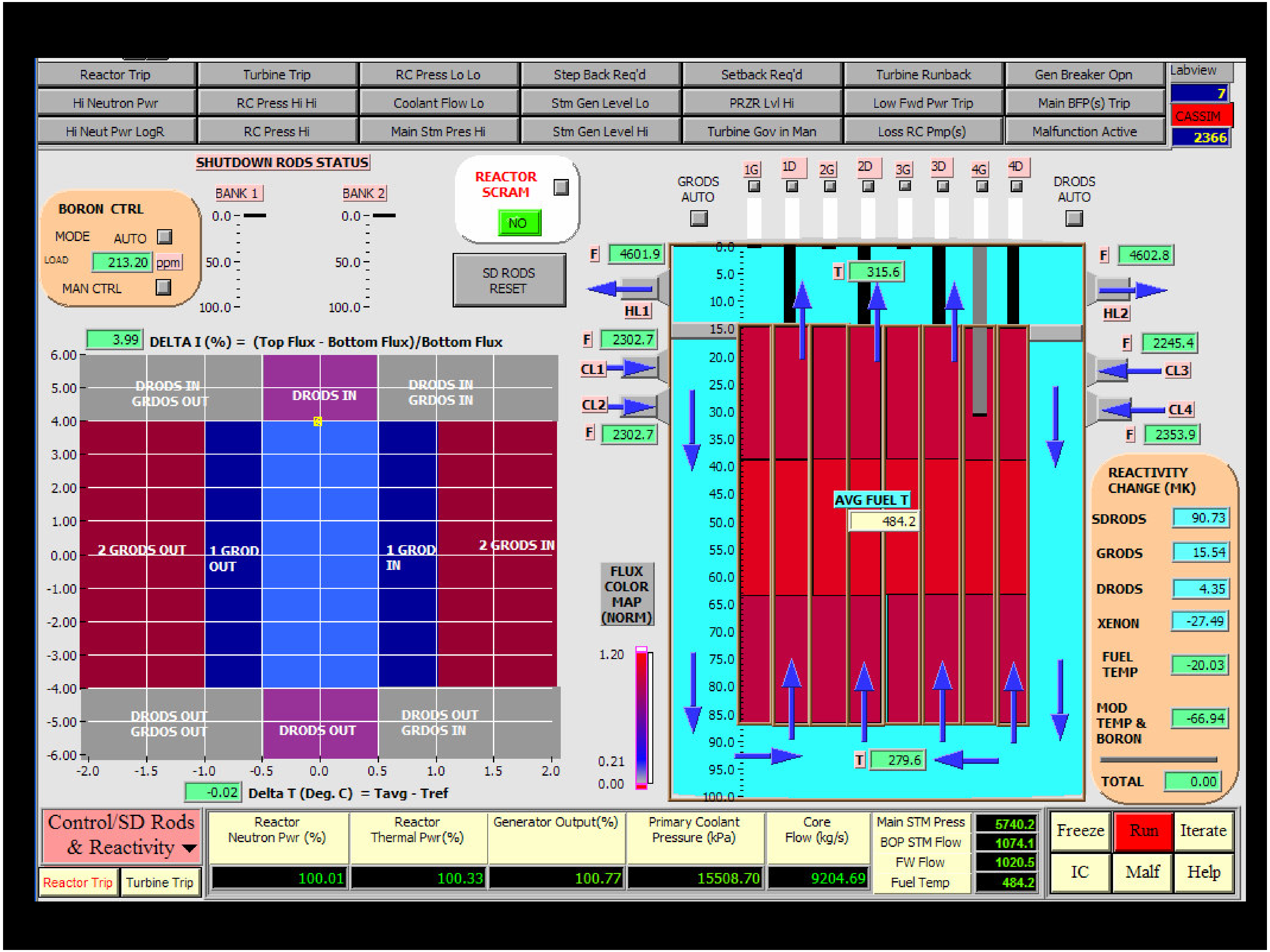
Passive PWR Simulator

- AP-1000 process design is used as a reference.
- Reactor Controls based on Korean Standardized 1000 MW PWR Design –Mode K
- SG pressure control to maintain setpoint at 5.7 KPa
- Overall Unit Control allows Reactor-Leading or Turbine-Leading Mode
- Passive Systems modeled to demonstrate LOCA mitigation

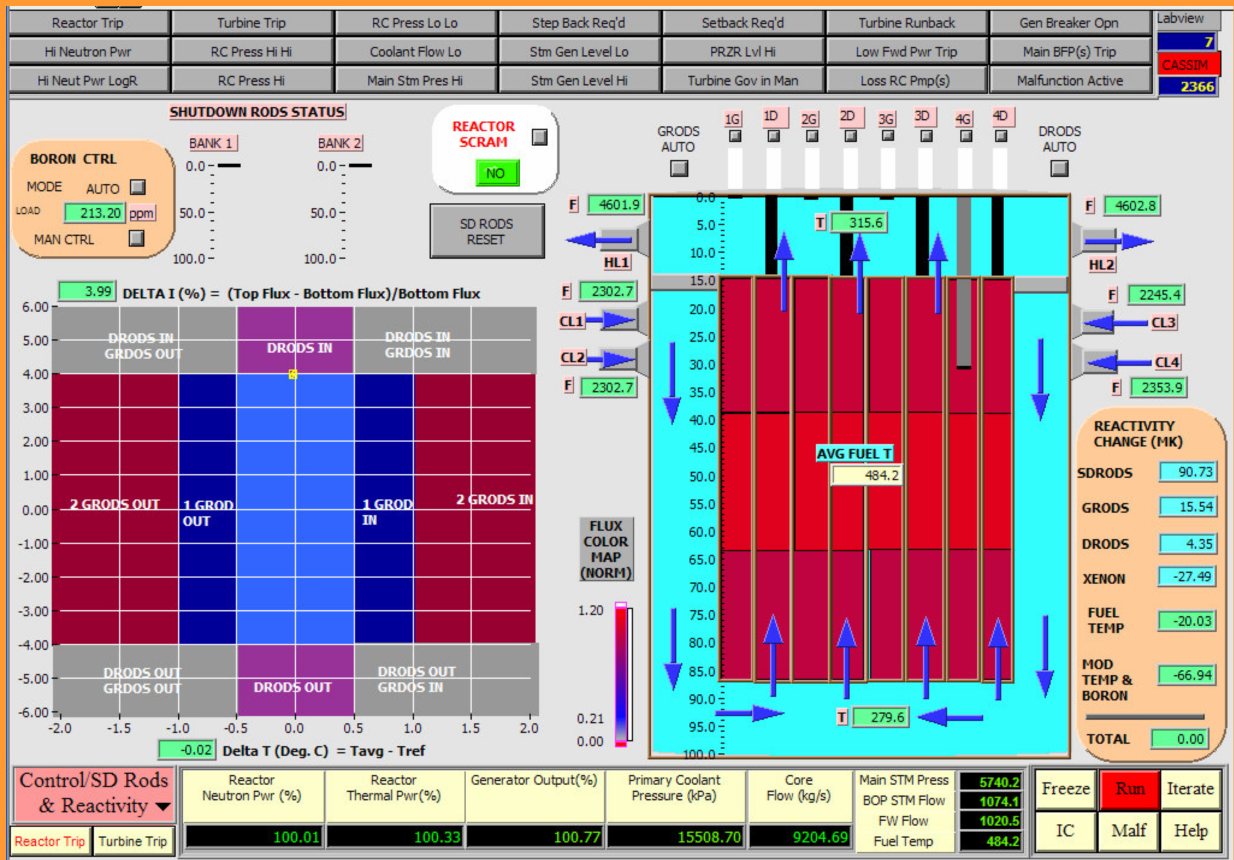

Reactor Trip
Turbine Trip
RC Press Lo Lo
Step Back Req'd
Setback Req'd
Turbine Runback
Gen Breaker Opn
Hi Neutron Pwr
RC Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR Lvl Hi
Low Fwd Pwr Trip
Main BFP(s) Trip
Hi Neut Pwr LogR
RC Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
Turbine Gov in Man
Loss RC Pmp(s)
Malfunction Active
Labview
28
CASSIM
120
F 537.7
PRESSURIZER
SG1
P 5739.97
T 273.30
P 15505.65
L 7.54
F 537.7
P 5739.97
T 273.30
F 510.4
L 13.51
SG2
F 510.4
F -0.4
CL2
RPV
HL1
CL1
RCP #1
RCP #2
CL4
L 13.51
HL2
CL3
CORE
P 15515.70
RCP #3
RCP #4
CL - COLD LEG
HL - HOT LEG
Core Flow 9205.64
Coolant Tavg 297.53
Avg Fuel Temp. 484.14
F 1075.2
To Deaerator
MSR DRAINS
F 54.8
MSR
Governor Valve
100.87 %
GENERATOR
624.49 MW
LP TURB
HP TURB
BYPASS VLV
0.00 %
CONDENSER
F 1075.5
T 231.60
HPHX
DEAERATOR
LPHX
CEP
FWP
SRVs
F 0
PWR Plant Overview
Reactor Trip
Turbine Trip
Reactor Neutron Pwr (%)
99.97
Reactor Thermal Pwr(%)
100.32
Generator Output(%)
100.89
Primary Coolant Pressure (kPa)
15515.70
Core Flow (kg/s)
9205.64
Main STM Press 5740.0
BOP STM Flow 1075.2
FW Flow 1020.7
Fuel Temp 484.1
Freeze
Run
Iterate
IC
Malf
Help

Reactor Model

SYSTEM	SIMULATION SCOPE	DISPLAY PAGES	OPERATOR CONTROLS	MALFUNCTIONS
REACTOR	• neutron flux levels over a range of 0.001 to 110% full power, 6 delayed neutron groups • decay heat (3 groups) • all reactivity control devices - “dark” rods; “gray” rods; boron control. • Xenon/Iodine poison • reactor power control system • reactor shutdown system	• PWR power control • PWR control rods & SD rods • PWR trip parameters	• reactor power and rate of change (input to control computer) • manual control of reactivity devices - control rods and boron addition/removal • reactor trip • reactor setback • reactor stepback	• reactor setback and stepback fail • one bank of Dark control rods drop into the reactor core
SAFETY SYSTEM		• PWR passive core cooling		



Reactor Trip
Turbine Trip
RC Press Lo Lo
Step Back Req'd
Setback Req'd
Turbine Runback
Gen Breaker Opn
Labview
Hi Neutron Pwr
RC Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR Lvl Hi
Low Fwd Pwr Trip
Main BFP(s) Trip
CASSIM
Hi Neut Pwr LogR
RC Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
Turbine Gov in Man
Loss RC Pmp(s)
Malfunction Active
SHUTDOWN RODS STATUS
BANK 1
BANK 2
BORON CTRL
MODE AUTO
LOAD 213.20 ppm
MAN CTRL
REACTOR SCRAM
NO
SD RODS RESET
GRODS AUTO
DRODS AUTO
1G 1D 2G 2D 3G 3D 4G 4D
HL1
HL2
CL1
CL2
CL3
CL4
AVG FUEL T
484.2
DELTA I (%) = (Top Flux - Bottom Flux)/Bottom Flux
DRODS IN GRDOS OUT
DRODS IN
DRODS IN GRDOS IN
2 GRODS OUT
1 GROD OUT
1 GROD IN
2 GRODS IN
DRODS OUT GRDOS OUT
DRODS OUT
DRODS OUT GRDOS IN
FLUX COLOR MAP (NORM)
Delta T (Deg. C) = Tavg - Tref
REACTIVITY CHANGE (MK)
SDRODS 90.73
GRODS 15.54
DRODS 4.35
XENON -27.49
FUEL TEMP -20.03
MOD TEMP & BORON -66.94
TOTAL 0.00
Control/SD Rods & Reactivity
Reactor Trip
Turbine Trip
Reactor Neutron Pwr (%) 100.01
Reactor Thermal Pwr(%) 100.33
Generator Output(%) 100.77
Primary Coolant Pressure (kPa) 15508.70
Core Flow (kg/s) 9204.69
Main STM Press 5740.2
BOP STM Flow 1074.1
FW Flow 1020.5
Fuel Temp 484.2
Freeze
Run
Iterate
IC
Malf
Help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RC Press Lo Lo
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Setback Req'd
Turbine Runback
Gen Breaker Opn
Labview
Hi Neutron Pwr
RC Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR Lvl Hi
Low Fwd Pwr Trip
Main BFP(s) Trip
CASSIM
Hi Neut Pwr LogR
RC Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
Turbine Gov in Man
Loss RC Pmp(s)
Malfunction Active
2366
SHUTDOWN RODS STATUS
BANK 1
BANK 2
BORON CTRL
MODE
AUTO
LOAD
213.20
ppm
MAN CTRL
REACTOR SCRAM
NO
SD RODS RESET
GRODS AUTO
DRODS AUTO
1G 1D 2G 2D 3G 3D 4G 4D
4601.9
4602.8
HL1
HL2
315.6
2302.7
2245.4
CL1
CL2
CL3
CL4
2353.9
AVG FUEL T
484.2
279.6
3.99
DELTA I (%) = (Top Flux - Bottom Flux)/Bottom Flux
DRODS IN GRDOS OUT
DRODS IN
DRODS IN GRDOS IN
2 GRODS OUT
1 GROD OUT
1 GROD IN
2 GRODS IN
DRODS OUT GRDOS OUT
DRODS OUT
DRODS OUT GRDOS IN
-0.02
Delta T (Deg. C) = Tavg - Tref
FLUX COLOR MAP (NORM)
REACTIVITY CHANGE (MK)
SDRODS 90.73
GRODS 15.54
DRODS 4.35
XENON -27.49
FUEL TEMP -20.03
MOD TEMP & BORON -66.94
TOTAL 0.00
Control/SD Rods & Reactivity
Reactor Neutron Pwr (%) 100.01
Reactor Thermal Pwr(%) 100.33
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Main STM Press 5740.2
BOP STM Flow 1074.1
FW Flow 1020.5
Fuel Temp 484.2
Freeze
Run
Iterate
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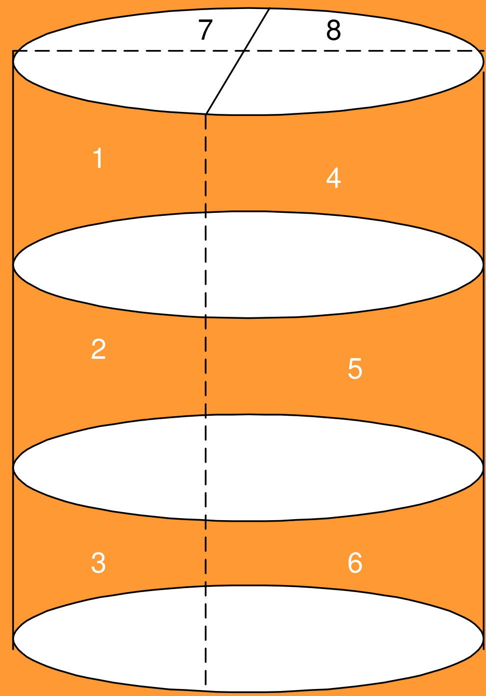
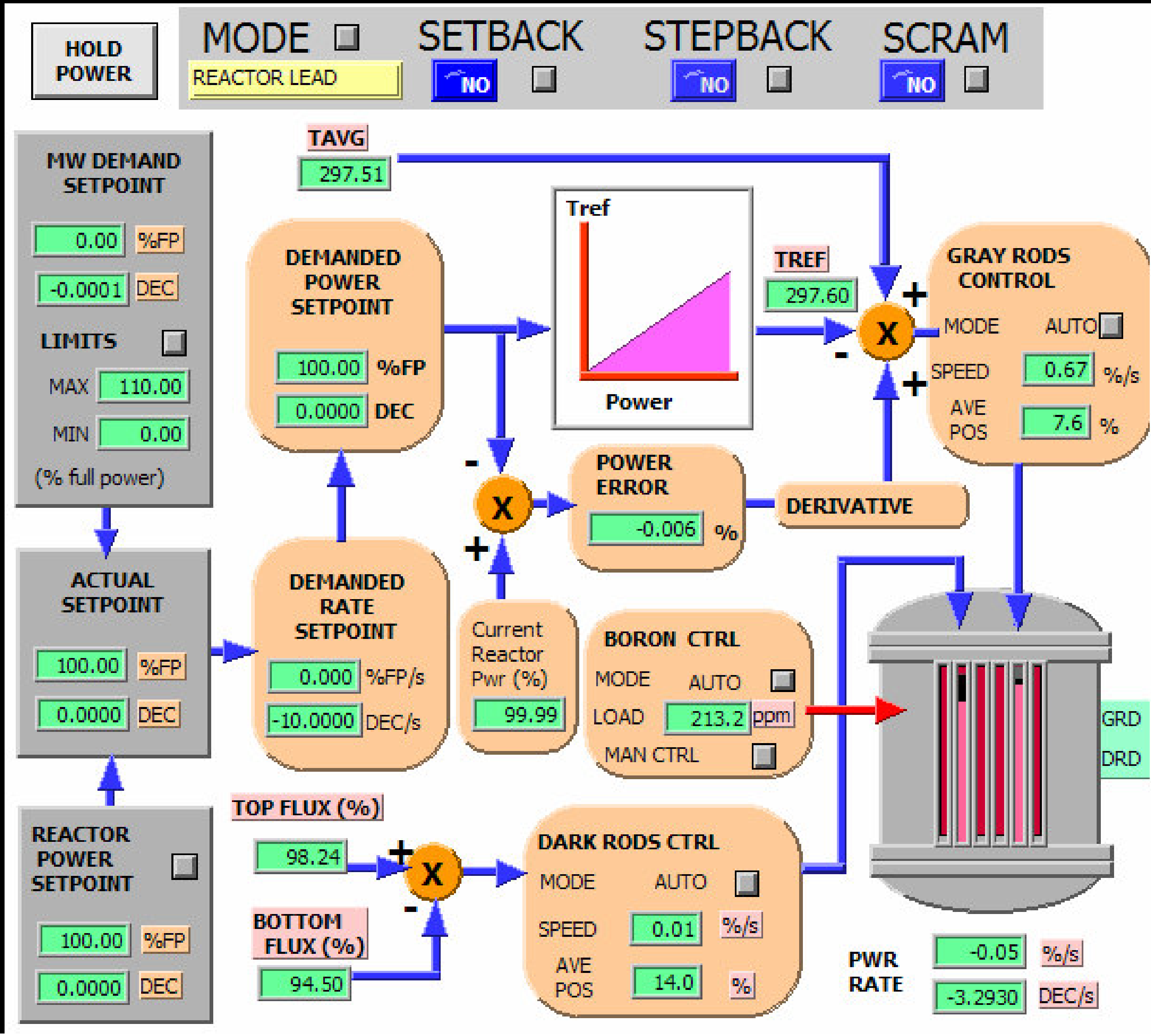
Malf
Help


7
8
1
4
2
5
3
6

Advanced PWR Reactor Control

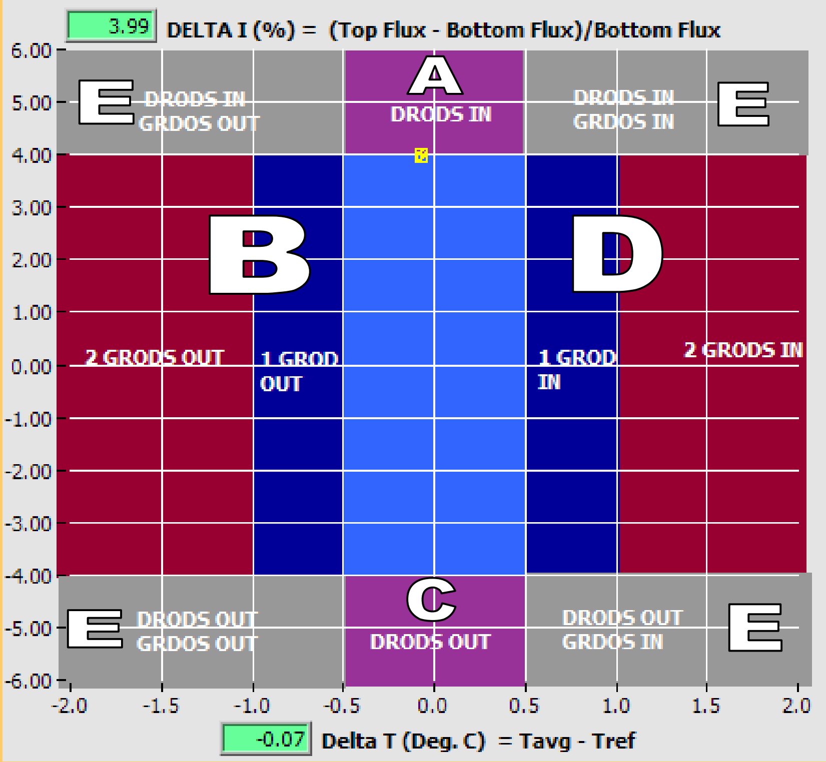


Mode K Reactor Control Strategy

- Double closed loop control of (1) reactor coolant temp (2) axial power difference.
- Heavy-worth control rods bank dedicated to axial shape control.
- Light-worth control rods bank for controlling coolant temp at setpoint.
- Auto regulation of both the reactivity and power distribution - permits load-follow operations (frequency control) to respond to grid conditions, with minimum use of Boron.

Reference Paper for Mode K Reactor Controls

- Korean Standardized 1000 MW PWR Design - YGN-3 NSSS Design
- Paper - “Automatic Reactor Power Control for a Pressurized Water Reactor “ by Jung-In Choi et al, Kyungwon University, Korea (August 27, 1992) - Nuclear Technology, Volume 102, May 1993, p.277



Limit control diagram.

Designating Flux Tilt error as FT (%) Average Coolant Temperature error as DT (deg. C)

Region A: FT > 4; -0.5 < DT < 0.5

Region C: FT < -4; -0.5 < DT < 0.5

Region B: -4 < FT < 4; DT < -0.5

Region D: -4 < FT < 4; DT > 0.5

Region E: the four corners

FT > 4; DT < -0.5;

FT > 4; DT > 0.5;

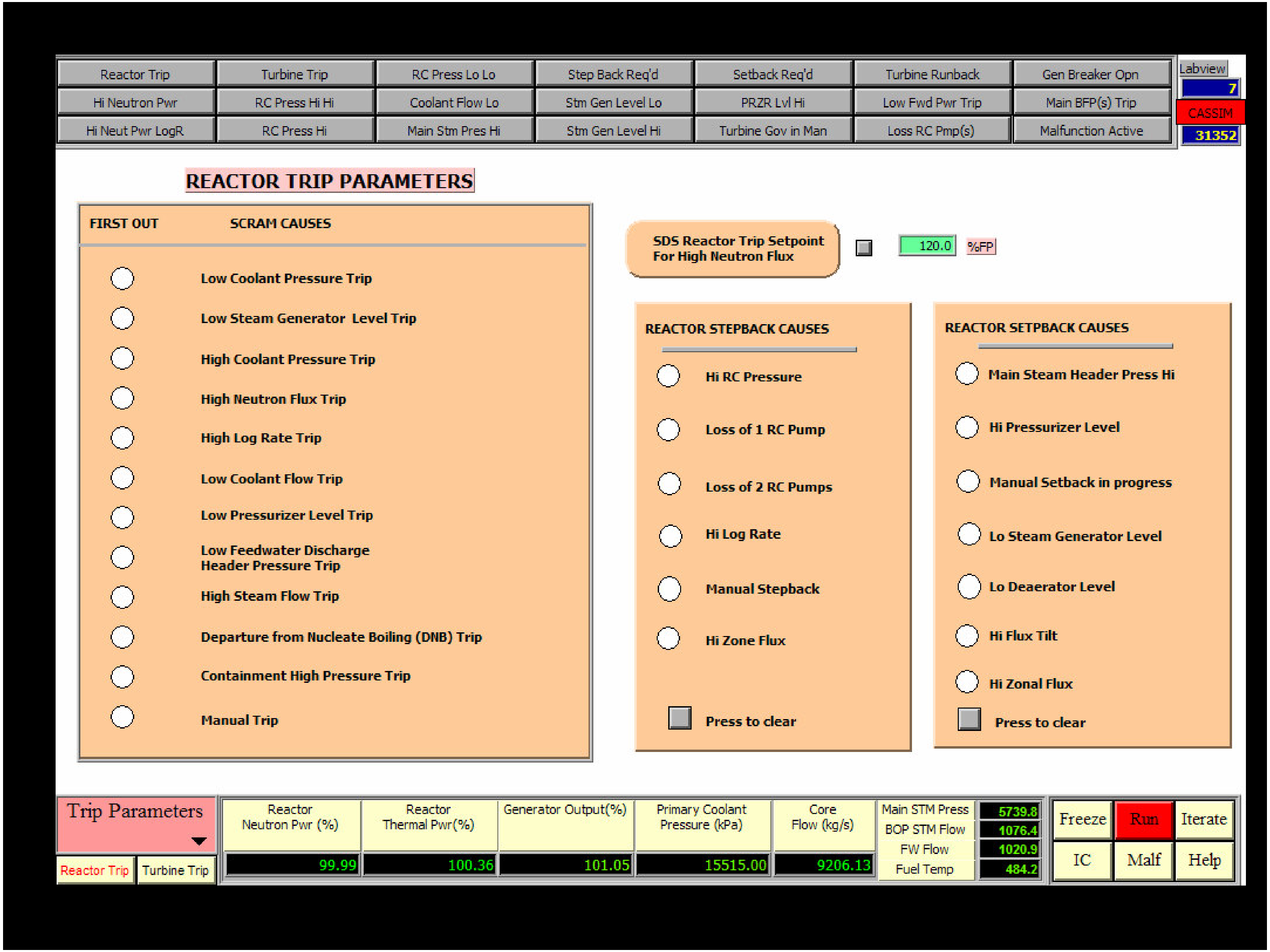
FT < -4; DT < -0.5;

FT < -4; DT > 0.5

Mode K Reactor Control Scheme

Reactor Power (%)	Average Gray Rods Position (average of the rod positions for the individual four banks)
0 – 10 %	93 % - 87 % in core
10 – 20 %	87 % - 83 % in core
20 – 30 %	83 % - 70 % in core
30 – 40%	70 % - 60 % in core
40 – 50 %	60 % - 53 % in core
50 – 60 %	53 % - 48 % in core
60 – 70 %	48 % - 44 % in core
70 – 80%	44 % - 40 % in core
80 – 90 %	40 % - 35 % in core
90 – 100 %	35 % - 30 % in core

Boron will be used if Gray rods limiting position has been reached

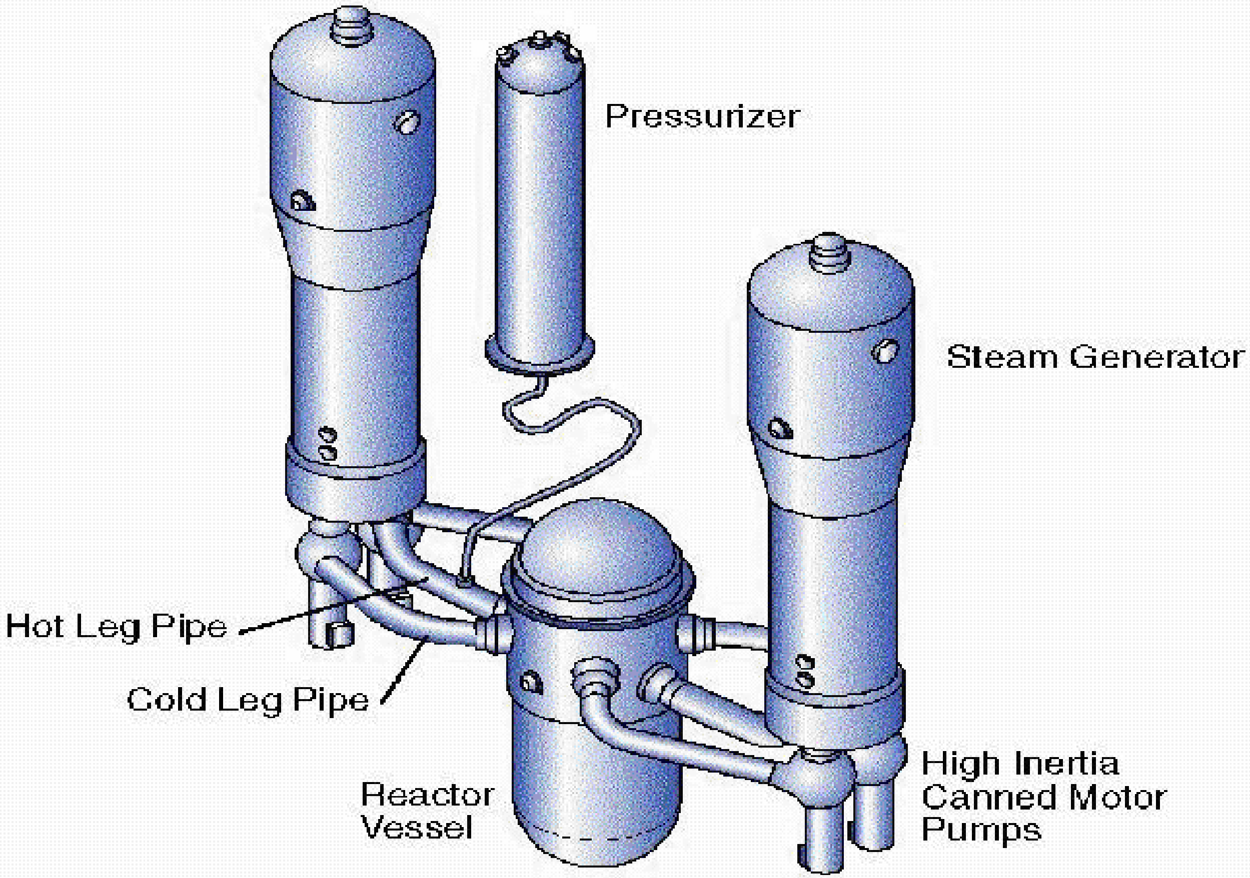


Reactor Trip
Turbine Trip
RC Press Lo Lo
Step Back Req'd
Setback Req'd
Turbine Runback
Gen Breaker Opn
Hi Neutron Pwr
RC Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR Lvl Hi
Low Fwd Pwr Trip
Main BFP(s) Trip
Hi Neut Pwr LogR
RC Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
Turbine Gov in Man
Loss RC Pmp(s)
Malfunction Active
Labview
7
CASSIM
31352
REACTOR TRIP PARAMETERS
FIRST OUT
SCRAM CAUSES
Low Coolant Pressure Trip
Low Steam Generator Level Trip
High Coolant Pressure Trip
High Neutron Flux Trip
High Log Rate Trip
Low Coolant Flow Trip
Low Pressurizer Level Trip
Low Feedwater Discharge Header Pressure Trip
High Steam Flow Trip
Departure from Nucleate Boiling (DNB) Trip
Containment High Pressure Trip
Manual Trip
SDS Reactor Trip Setpoint For High Neutron Flux
120.0
%FP
REACTOR STEPBACK CAUSES
Hi RC Pressure
Loss of 1 RC Pump
Loss of 2 RC Pumps
Hi Log Rate
Manual Stepback
Hi Zone Flux
Press to clear
REACTOR SETPBACK CAUSES
Main Steam Header Press Hi
Hi Pressurizer Level
Manual Setback in progress
Lo Steam Generator Level
Lo Deaerator Level
Hi Flux Tilt
Hi Zonal Flux
Press to clear
Trip Parameters
Reactor Trip
Turbine Trip
Reactor Neutron Pwr (%)
99.99
Reactor Thermal Pwr(%)
100.36
Generator Output(%)
101.05
Primary Coolant Pressure (kPa)
15515.00
Core Flow (kg/s)
9206.13
Main STM Press
5739.8
BOP STM Flow
1076.4
FW Flow
1020.9
Fuel Temp
484.2
Freeze
Run
Iterate
IC
Malf
Help

Reactor Coolant System

- 2 heat transfer circuits, or 2 loops.
- Each loop has one Steam Generator, one hot leg(31-inch inside diameter), and two cold legs (22-inch inside diameter) for circulating reactor coolant for primary heat transport.
- One Pressurizer in one of the loops

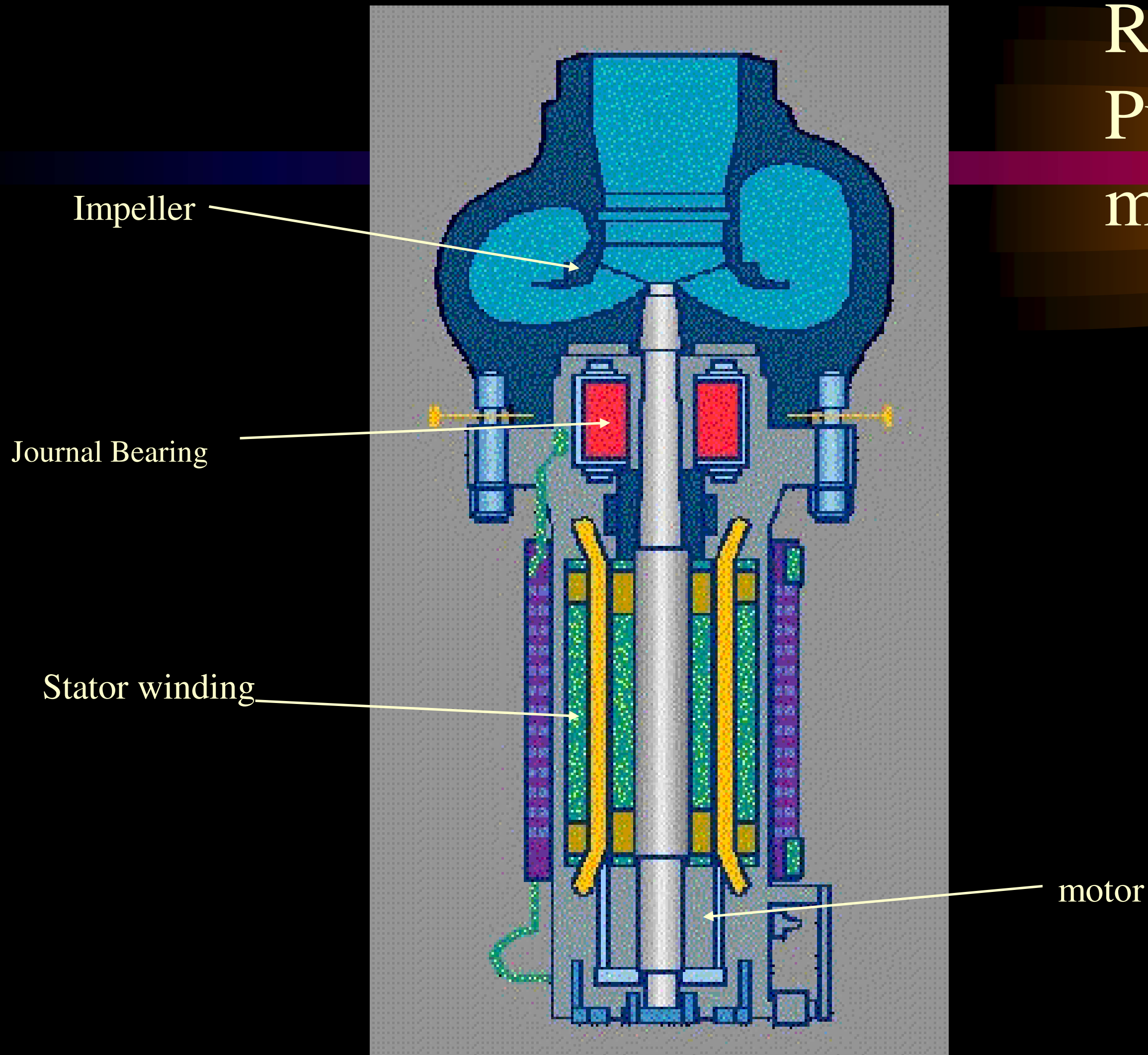
The AP600 Uses a Nuclear Steam Supply System Proven in the Field



Reactor Coolant Pump

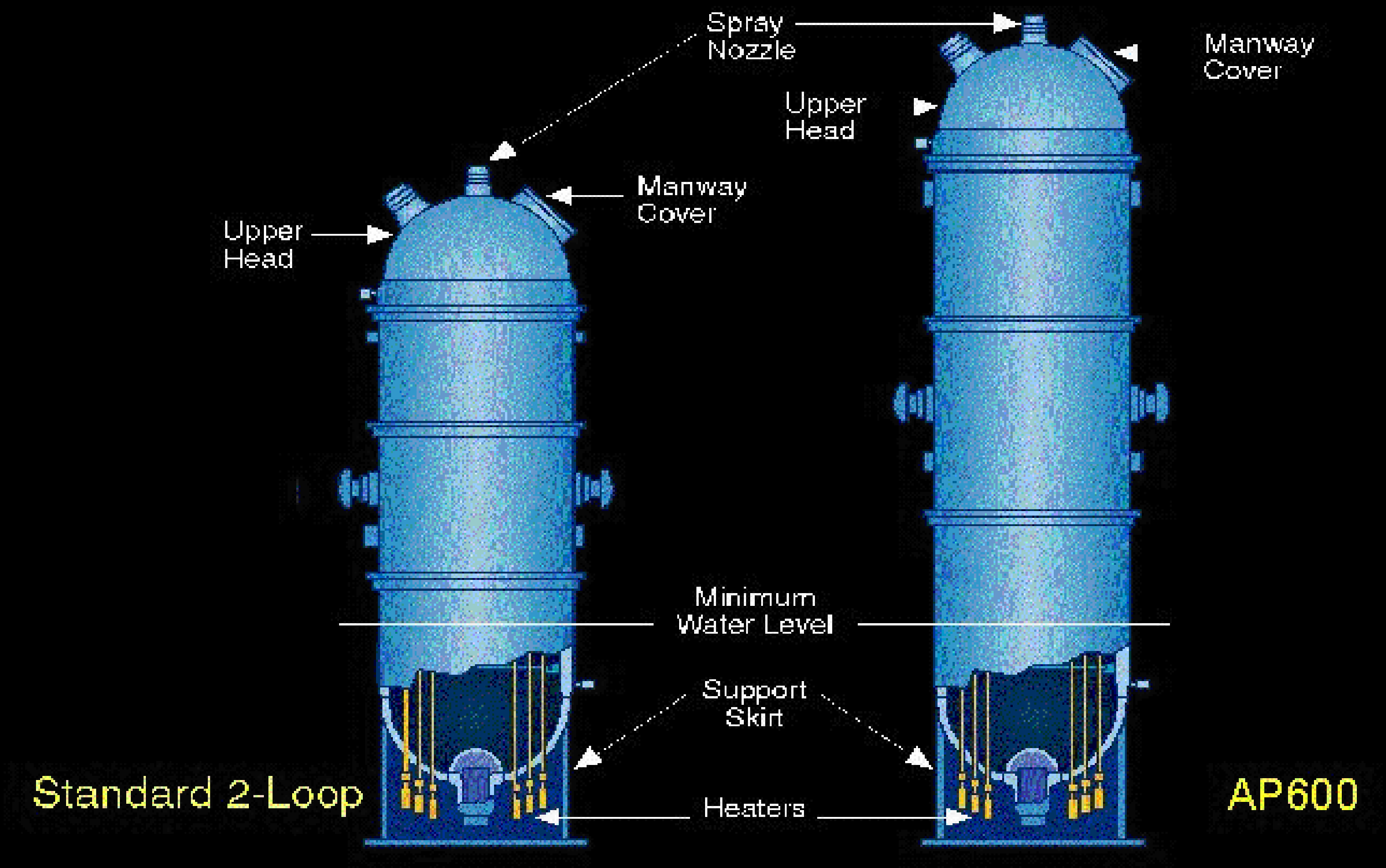
- Two canned motor pumps mounted directly in the channel head of each Steam Generator.
- No seals - cannot cause seal failure LOCA.
- Allows pumps and SG to use the same structural support; eliminates the crossover leg of coolant loop piping; reduces loop pressure drop; eliminates a potential of core uncovery due to loop seal venting during small LOCA.

Reactor Coolant Pump (canned motor)



Pressurizer

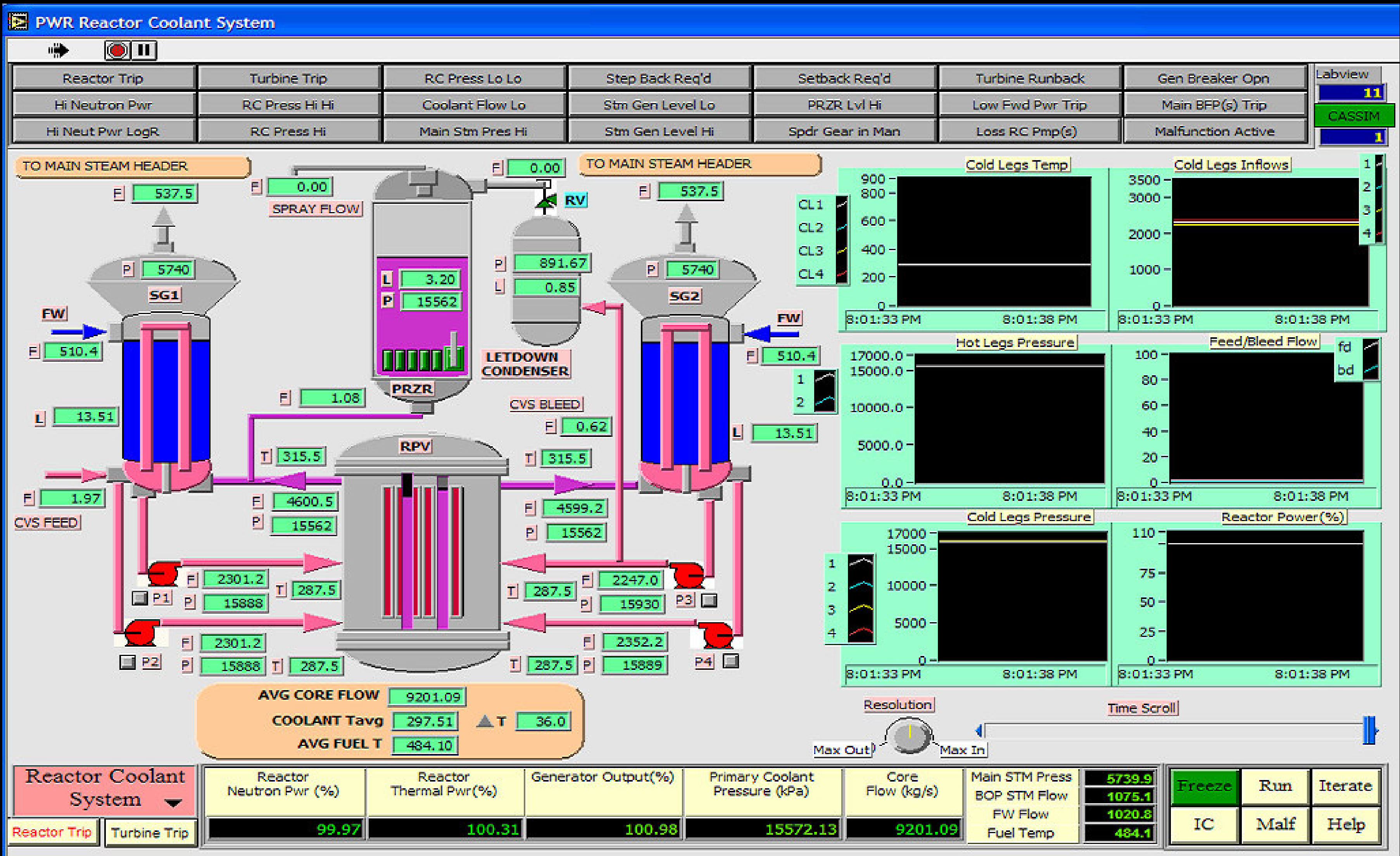
- Standard Westinghouse Design used in existing PWRs.
- 1600 cubic feet; 30 % larger - increases transient margin and eliminates the need for relief valve actuation - eliminates one possible source of RCS leakage and maintenance.

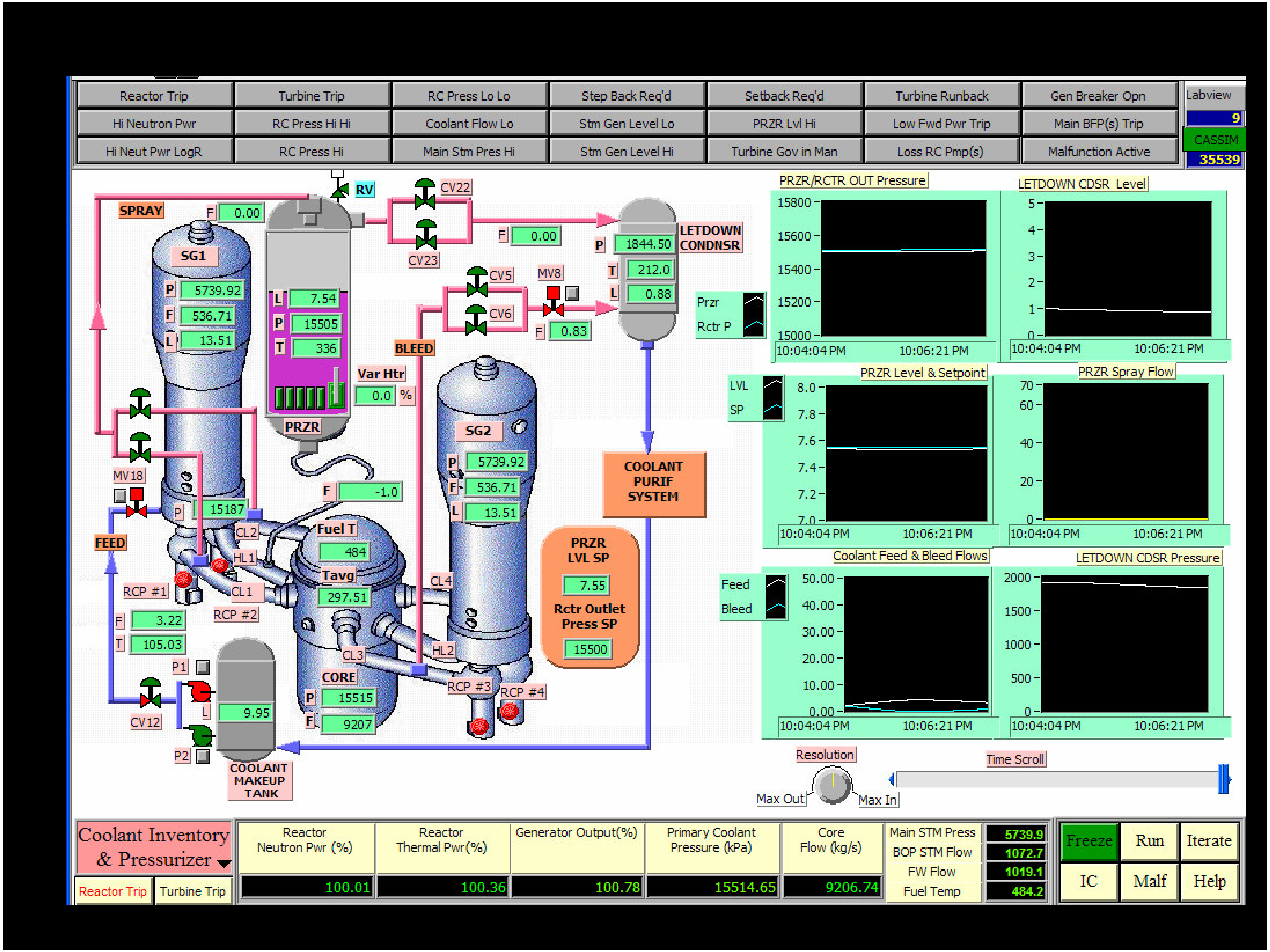


Pressurizer

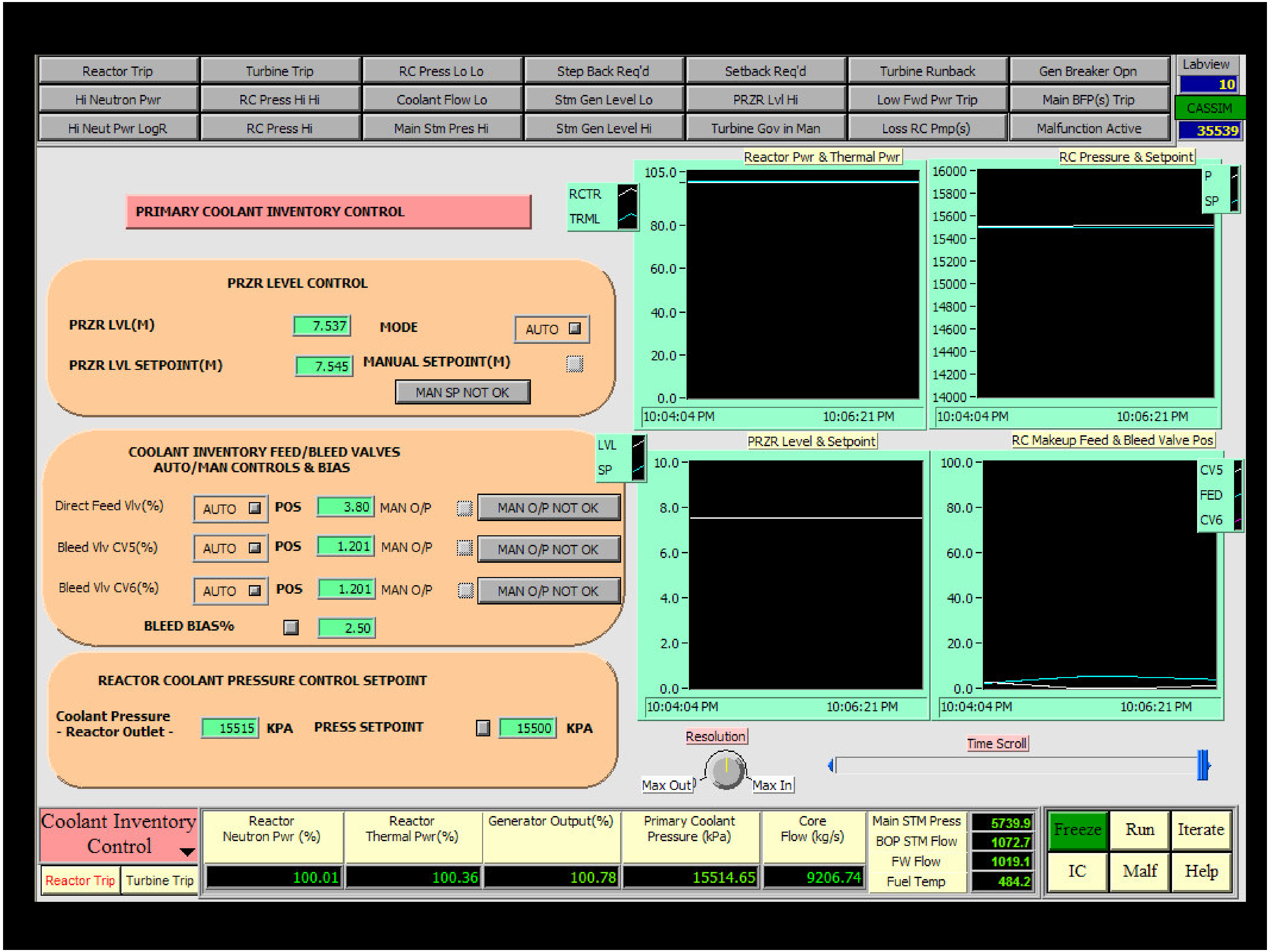
Reactor Coolant Model

SYSTEM	SIMULATION SCOPE	DISPLAY PAGES	OPERATOR CONTROLS	MALFUNCTIONS
REACTOR COOLANT	• main circuit coolant loop with four pumps, two steam generators, four equivalent “lumped” reactor coolant channels • pressure and inventory control which includes pressurizer, coolant letdown condenser, charge & letdown control, and pressure relief • operating range is from zero power hot to full power	• PWR reactor coolant system • PWR coolant inventory & pressurizer • PWR inventory control • PWR pressure control	• reactor coolant pumps • coolant makeup pumps • pressurizer pressure control: heaters; spray; pressure relief valve • pressurizer level control by regulating coolant feed & bleed flow • isolation valves for: coolant feed and bleed	• Pressurizer pressure relief valve fails open • charging (feed) valve fails open • letdown (bleed) valve fails open • pressurizer heaters #2 to # 6 turned "ON" by malfunction • reactor header break

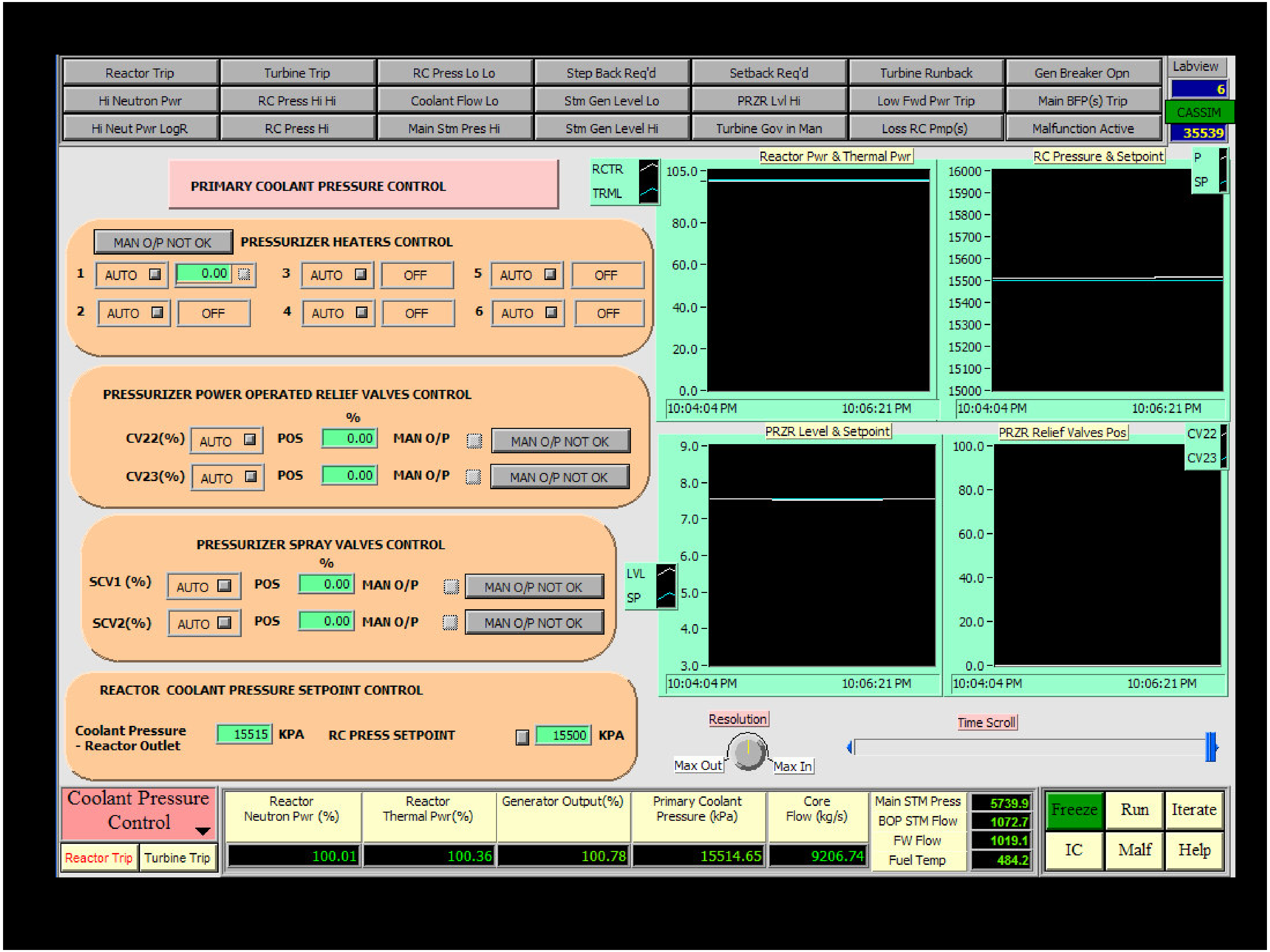

PWR Reactor Coolant System
Reactor Trip
Turbine Trip
RC Press Lo Lo
Step Back Req'd
Setback Req'd
Turbine Runback
Gen Breaker Opn
Hi Neutron Pwr
RC Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR Lvl Hi
Low Fwd Pwr Trip
Main BFP(s) Trip
Hi Neut Pwr LogR
RC Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
Spdr Gear in Man
Loss RC Pmp(s)
Malfunction Active
Labview
CASSIM
TO MAIN STEAM HEADER
SPRAY FLOW
RV
SG1
SG2
PRZR
LETDOWN CONDENSER
CVS BLEED
CVS FEED
RPV
FW
Cold Legs Temp
Cold Legs Inflows
Hot Legs Pressure
Feed/Bleed Flow
Cold Legs Pressure
Reactor Power(%)
AVG CORE FLOW 9201.09
COOLANT Tavg 297.51
AVG FUEL T 484.10
Resolution
Time Scroll
Max Out
Max In
Reactor Coolant System
Reactor Trip
Turbine Trip
Reactor Neutron Pwr (%) 99.97
Reactor Thermal Pwr(%) 100.31
Generator Output(%) 100.98
Primary Coolant Pressure (kPa) 15572.13
Core Flow (kg/s) 9201.09
Main STM Press 5739.9
BOP STM Flow 1075.1
FW Flow 1020.8
Fuel Temp 484.1
Freeze
Run
Iterate
IC
Malf
Help



Reactor Trip
Turbine Trip
RC Press Lo Lo
Step Back Req'd
Setback Req'd
Turbine Runback
Gen Breaker Opn
Hi Neutron Pwr
RC Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR Lvl Hi
Low Fwd Pwr Trip
Main BFP(s) Trip
Hi Neut Pwr LogR
RC Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
Turbine Gov in Man
Loss RC Pmp(s)
Malfunction Active
Labview
9
CASSIM
35539
SPRAY
F 0.00
RV
CV22
CV23
F 0.00
P 1844.50
LETDOWN CONDNSR
T 212.0
L 0.88
SG1
P 5739.92
F 536.71
L 13.51
L 7.54
P 15505
T 336
PRZR
CV5
CV6
MV8
F 0.83
BLEED
Var Htr
0.0 %
SG2
P 5739.92
F 536.71
L 13.51
MV18
P 15187
F -1.0
CL2
HL1
CL1
Fuel T
484
Tavg
297.51
CL4
FEED
RCP #1
RCP #2
F 3.22
T 105.03
CL3
HL2
CORE
P 15515
F 9207
RCP #3
RCP #4
P1
L
9.95
CV12
P2
COOLANT MAKEUP TANK
COOLANT PURIF SYSTEM
PRZR LVL SP
7.55
Rctr Outlet Press SP
15500
PRZR/RCTR OUT Pressure
Przr
Rctr P
15800
15600
15400
15200
15000
10:04:04 PM
10:06:21 PM
LETDOWN CDSR Level
5
4
3
2
1
0
10:04:04 PM
10:06:21 PM
PRZR Level & Setpoint
LVL
SP
8.0
7.8
7.6
7.4
7.2
7.0
10:04:04 PM
10:06:21 PM
PRZR Spray Flow
70
60
40
20
0
10:04:04 PM
10:06:21 PM
Coolant Feed & Bleed Flows
Feed
Bleed
50.00
40.00
30.00
20.00
10.00
0.00
10:04:04 PM
10:06:21 PM
LETDOWN CDSR Pressure
2000
1500
1000
500
0
10:04:04 PM
10:06:21 PM
Resolution
Max Out
Max In
Time Scroll
Coolant Inventory & Pressurizer
Reactor Trip
Turbine Trip
Reactor Neutron Pwr (%)
100.01
Reactor Thermal Pwr(%)
100.36
Generator Output(%)
100.78
Primary Coolant Pressure (kPa)
15514.65
Core Flow (kg/s)
9206.74
Main STM Press 5739.9
BOP STM Flow 1072.7
FW Flow 1019.1
Fuel Temp 484.2
Freeze
Run
Iterate
IC
Malf
Help



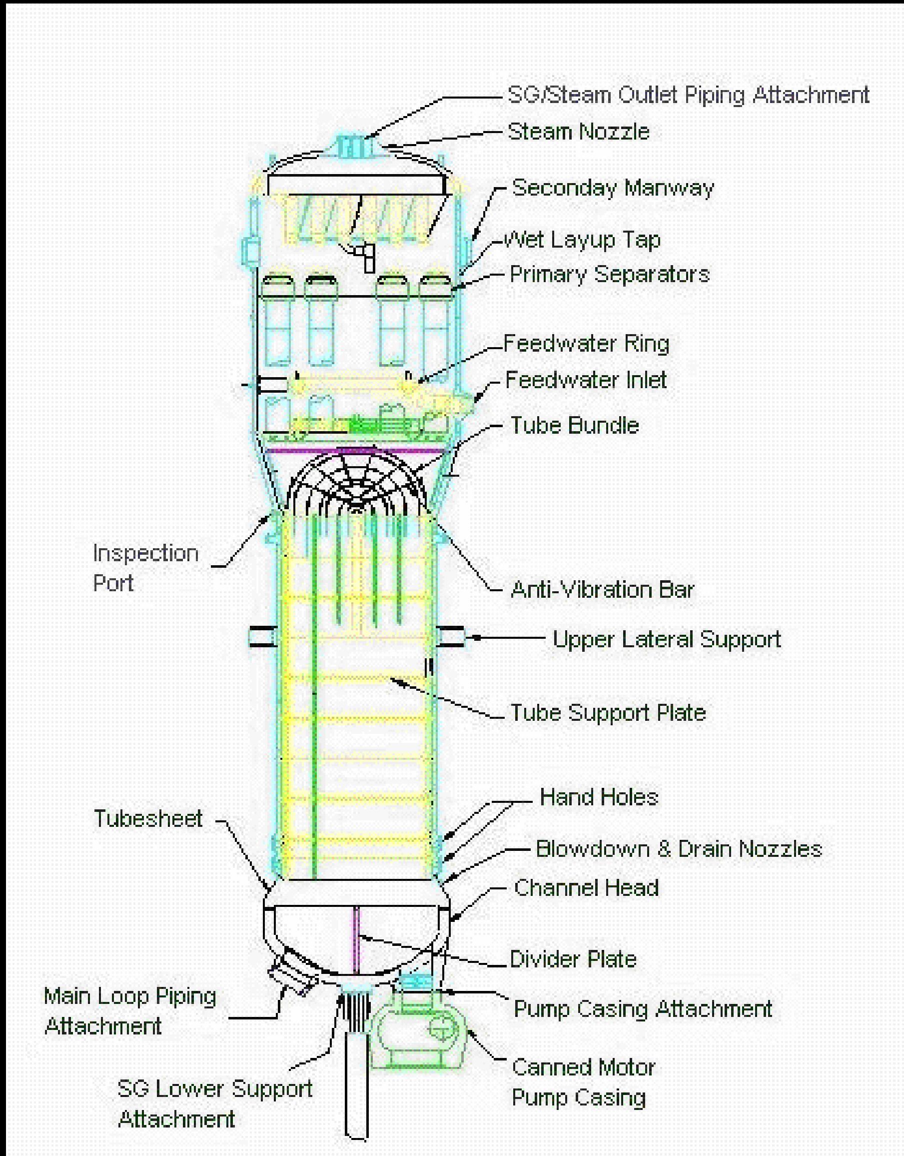
Reactor Trip
Turbine Trip
RC Press Lo Lo
Step Back Req'd
Setback Req'd
Turbine Runback
Gen Breaker Opn
Labview
10
Hi Neutron Pwr
RC Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR Lvl Hi
Low Fwd Pwr Trip
Main BFP(s) Trip
CASSIM
Hi Neut Pwr LogR
RC Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
Turbine Gov in Man
Loss RC Pmp(s)
Malfunction Active
35539
PRIMARY COOLANT INVENTORY CONTROL
PRZR LEVEL CONTROL
PRZR LVL(M) 7.537
MODE AUTO
PRZR LVL SETPOINT(M) 7.545
MANUAL SETPOINT(M)
MAN SP NOT OK
COOLANT INVENTORY FEED/BLEED VALVES
AUTO/MAN CONTROLS & BIAS
Direct Feed Vlv(%) AUTO POS 3.80 MAN O/P MAN O/P NOT OK
Bleed Vlv CV5(%) AUTO POS 1.201 MAN O/P MAN O/P NOT OK
Bleed Vlv CV6(%) AUTO POS 1.201 MAN O/P MAN O/P NOT OK
BLEED BIAS% 2.50
REACTOR COOLANT PRESSURE CONTROL SETPOINT
Coolant Pressure
- Reactor Outlet - 15515 KPA
PRESS SETPOINT 15500 KPA
Reactor Pwr & Thermal Pwr
RCTR
TRML
105.0
80.0
60.0
40.0
20.0
0.0
10:04:04 PM
10:06:21 PM
RC Pressure & Setpoint
P
SP
16000
15800
15600
15400
15200
15000
14800
14600
14400
14200
14000
10:04:04 PM
10:06:21 PM
PRZR Level & Setpoint
LVL
SP
10.0
8.0
6.0
4.0
2.0
0.0
10:04:04 PM
10:06:21 PM
RC Makeup Feed & Bleed Valve Pos
CV5
FED
CV6
100.0
80.0
60.0
40.0
20.0
0.0
10:04:04 PM
10:06:21 PM
Resolution
Max Out
Max In
Time Scroll
Coolant Inventory Control
Reactor Trip
Turbine Trip
Reactor Neutron Pwr (%) 100.01
Reactor Thermal Pwr(%) 100.36
Generator Output(%) 100.78
Primary Coolant Pressure (kPa) 15514.65
Core Flow (kg/s) 9206.74
Main STM Press 5739.9
BOP STM Flow 1072.7
FW Flow 1019.1
Fuel Temp 484.2
Freeze
Run
Iterate
IC
Malf
Help


Reactor Trip
Turbine Trip
RC Press Lo Lo
Step Back Req'd
Setback Req'd
Turbine Runback
Gen Breaker Opn
Labview
6
Hi Neutron Pwr
RC Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR Lvl Hi
Low Fwd Pwr Trip
Main BFP(s) Trip
CASSIM
Hi Neut Pwr LogR
RC Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
Turbine Gov in Man
Loss RC Pmp(s)
Malfunction Active
35539
PRIMARY COOLANT PRESSURE CONTROL
MAN O/P NOT OK
PRESSURIZER HEATERS CONTROL
1 AUTO 0.00
2 AUTO OFF
3 AUTO OFF
4 AUTO OFF
5 AUTO OFF
6 AUTO OFF
PRESSURIZER POWER OPERATED RELIEF VALVES CONTROL
%
CV22(%) AUTO POS 0.00 MAN O/P MAN O/P NOT OK
CV23(%) AUTO POS 0.00 MAN O/P MAN O/P NOT OK
PRESSURIZER SPRAY VALVES CONTROL
%
SCV1 (%) AUTO POS 0.00 MAN O/P MAN O/P NOT OK
SCV2(%) AUTO POS 0.00 MAN O/P MAN O/P NOT OK
REACTOR COOLANT PRESSURE SETPOINT CONTROL
Coolant Pressure - Reactor Outlet 15515 KPA
RC PRESS SETPOINT 15500 KPA
Reactor Pwr & Thermal Pwr
RCTR
TRML
10:04:04 PM
10:06:21 PM
RC Pressure & Setpoint
P
SP
PRZR Level & Setpoint
LVL
SP
PRZR Relief Valves Pos
CV22
CV23
Resolution
Max Out
Max In
Time Scroll
Coolant Pressure Control
Reactor Trip
Turbine Trip
Reactor Neutron Pwr (%) 100.01
Reactor Thermal Pwr(%) 100.36
Generator Output(%) 100.78
Primary Coolant Pressure (kPa) 15514.65
Core Flow (kg/s) 9206.74
Main STM Press 5739.9
BOP STM Flow 1072.7
FW Flow 1019.1
Fuel Temp 484.2
Freeze
Run
Iterate
IC
Malf
Help

Steam Generators

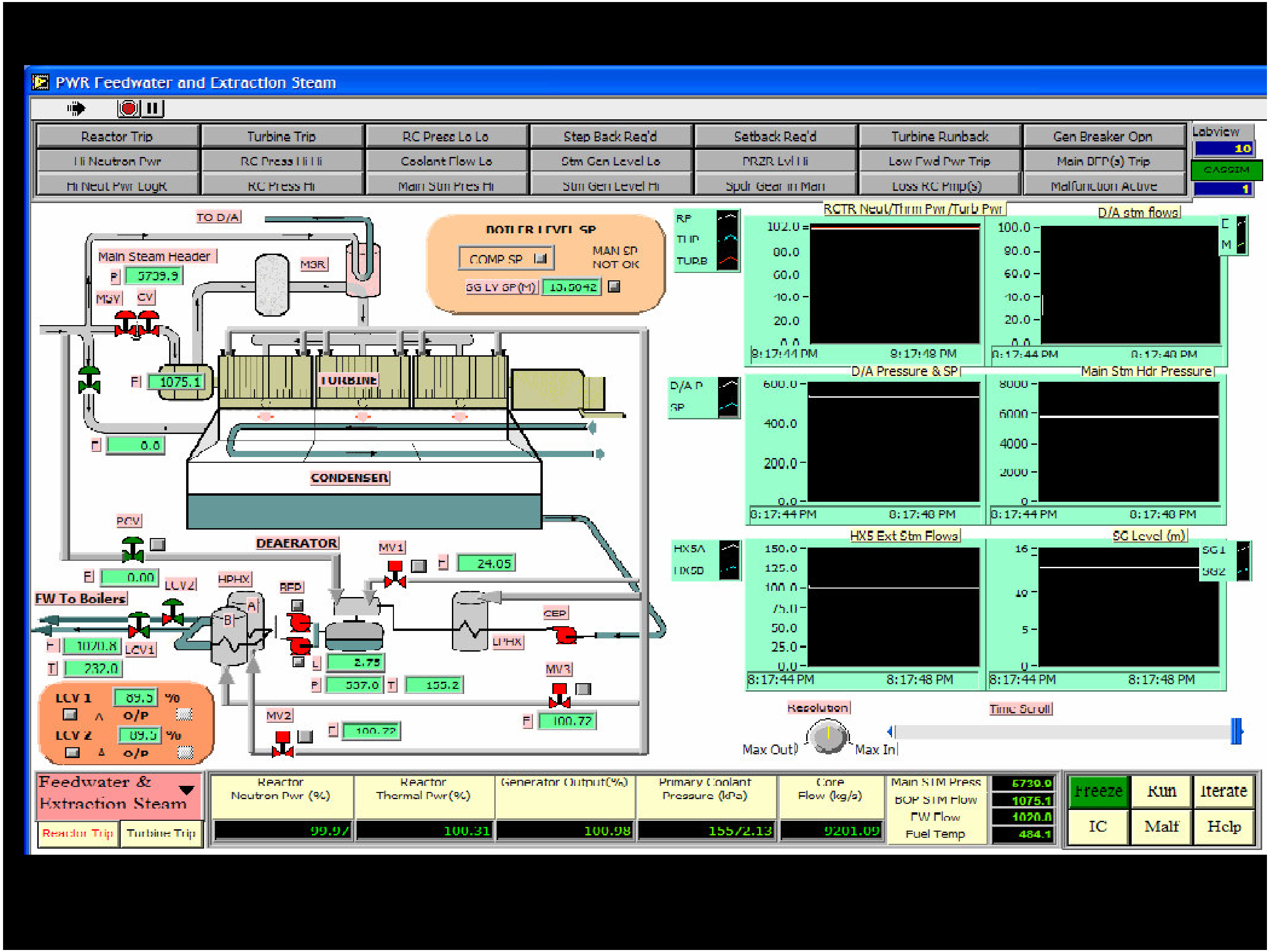
- Based on standard Westinghouse Model F technology.
- U-tube SG design, using Inconel 690 for tube material - enhanced reliability - Westinghouse claims less than 1 tube plugged per SG per four years of operation.

Steam Generator

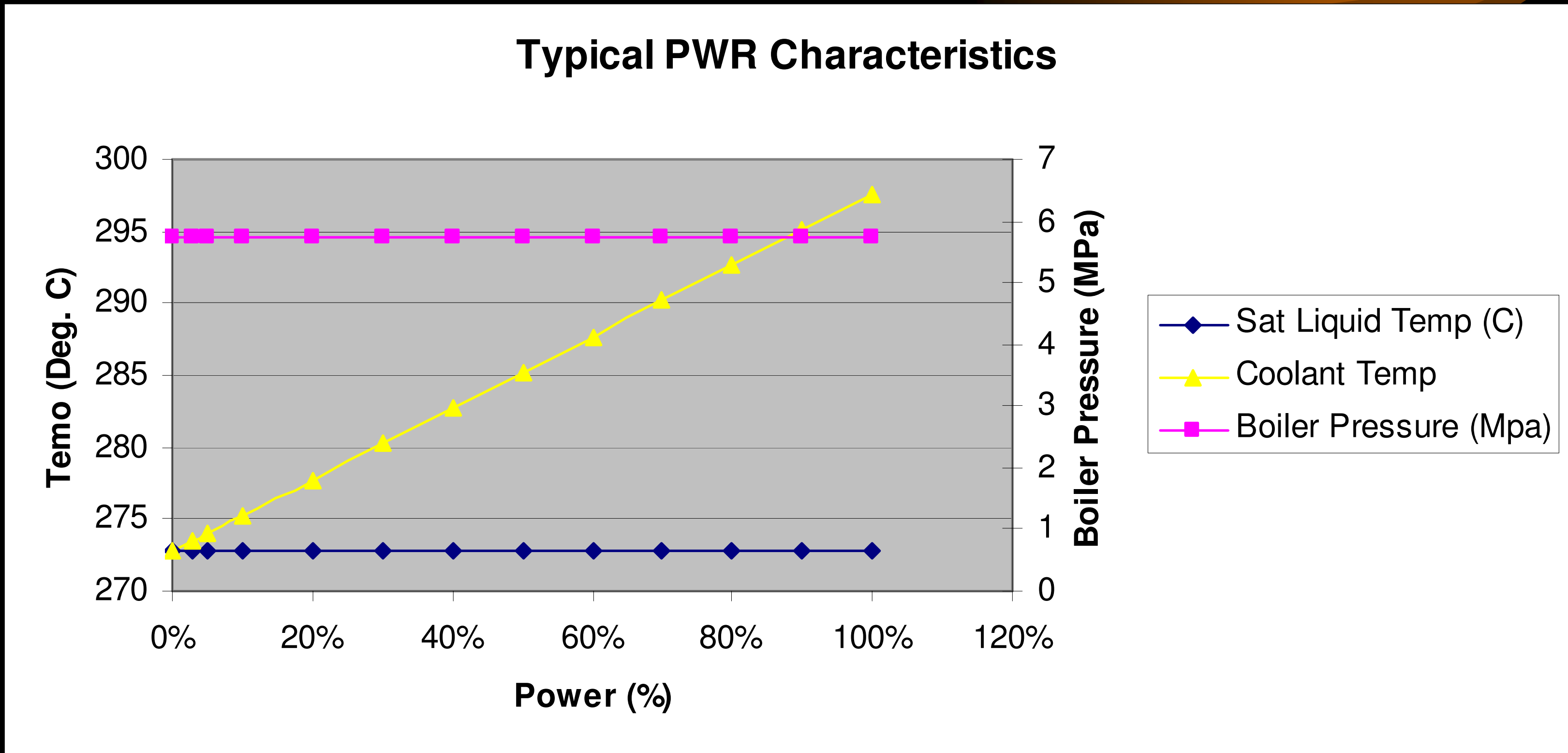


Steam & Feedwater

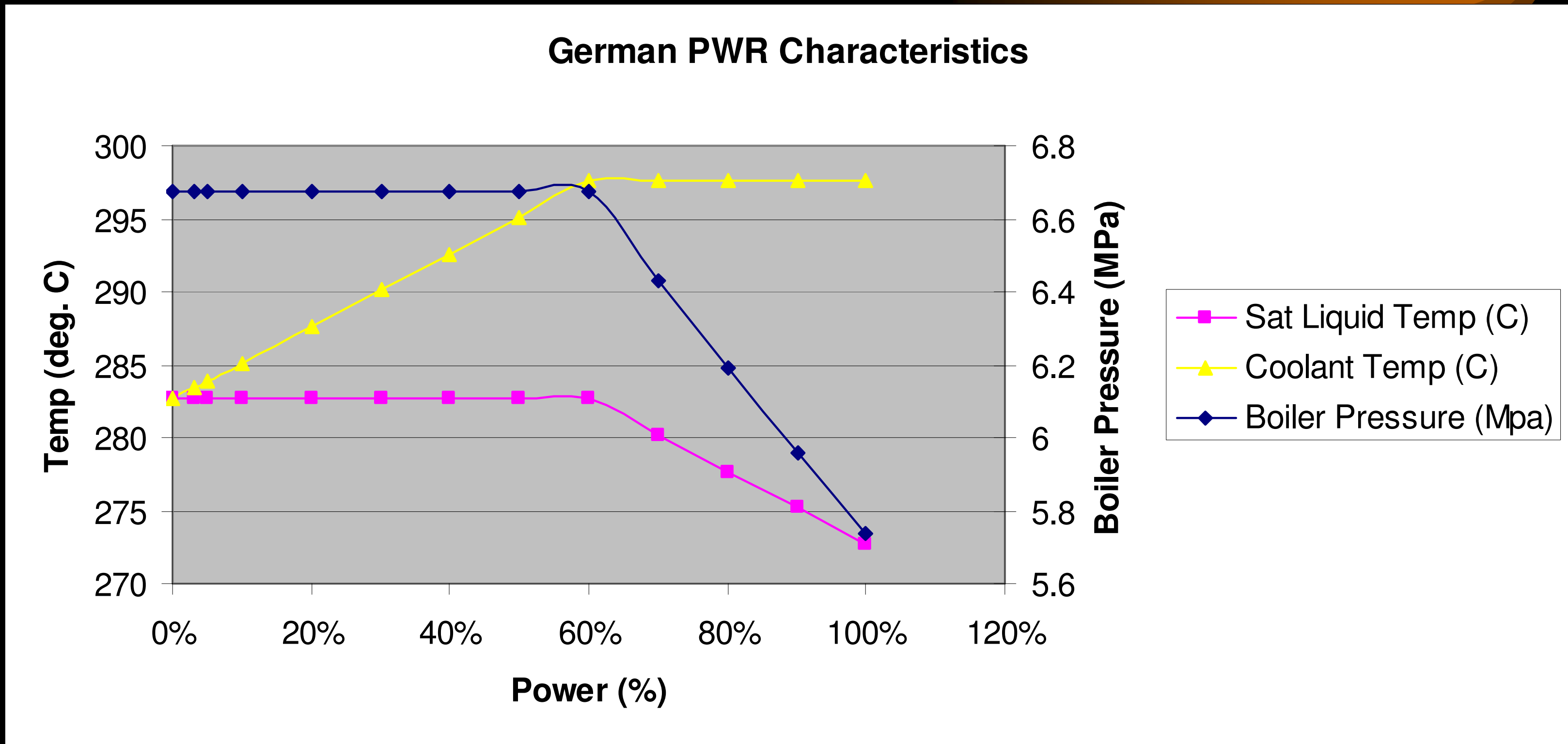
SYSTEM	SIMULATION SCOPE	DISPLAY PAGES	OPERATOR CONTROLS	MALFUNCTIONS
STEAM & FEEDWATER	• boiler dynamics, including shrink and swell effects • steam supply to turbine and reheater • turbine by-pass to condenser • extraction steam to feed heating • steam generator pressure control • steam generator level control • boiler feed system	• PWR feedwater & extraction steam	• feed pump on/off operation • boiler level controller mode: Auto or manual • level control setpoint during Auto operation • level control valve opening during manual operation • extraction steam valves opening	• all level control isolation valves fail closed • one level control valve fails open • one level control valve fails closed • all feed pumps trip • all steam safety valves open • steam header break • steam flow transmitter fails


PWR Feedwater and Extraction Steam
Reactor Trip
Turbine Trip
RC Press Lo Lo
Step Back Req'd
Setback Req'd
Turbine Runback
Gen Breaker Opn
Hi Neutron Pwr
RC Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR Lvl Hi
Low Fwd Pwr Trip
Main BFP(s) Trip
Hi Neut Pwr LogR
RC Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
Spdr Gear in Man
Loss RC Pmp(s)
Malfunction Active
Labview
CASSIM
TO D/A
Main Steam Header
MSR
MSV
CV
BOILER LEVEL SP
COMP SP
MAN SP
NOT OK
SG LV SP(M)
TURBINE
CONDENSER
DEARATOR
PCV
MV1
MV2
MV3
FW To Boilers
LCV1
LCV2
HPHX
BFP
CEP
LPHX
LCV 1
LCV 2
O/P
Feedwater &
Extraction Steam
RCTR Neut/Thrm Pwr/Turb Pwr
D/A stm flows
D/A Pressure & SP
Main Stm Hdr Pressure
HX5 Ext Stm Flows
SG Level (m)
Resolution
Time Scroll
Max Out
Max In
Reactor Neutron Pwr (%)
Reactor Thermal Pwr(%)
Generator Output(%)
Primary Coolant Pressure (kPa)
Core Flow (kg/s)
Main STM Press
BOP STM Flow
FW Flow
Fuel Temp
Freeze
Run
Iterate
IC
Malf
Help

PWR Characteristics with constant SG pressure – This Simulator



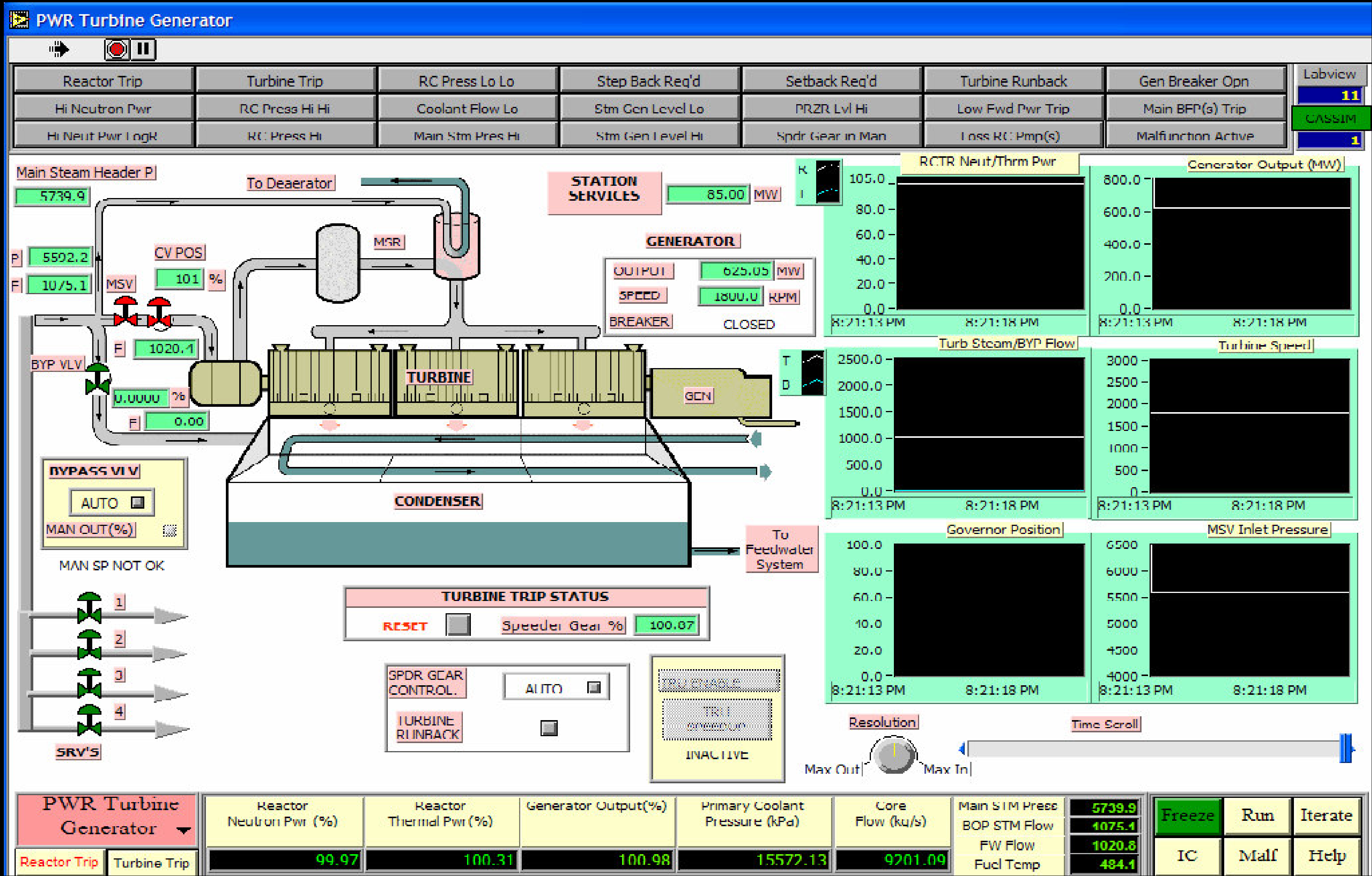
German PWR Design



Reference: Features of KWU Type NPPs and their Leittechnik System - IAEA Technical Reports Series 387, 1999

Turbine Generator

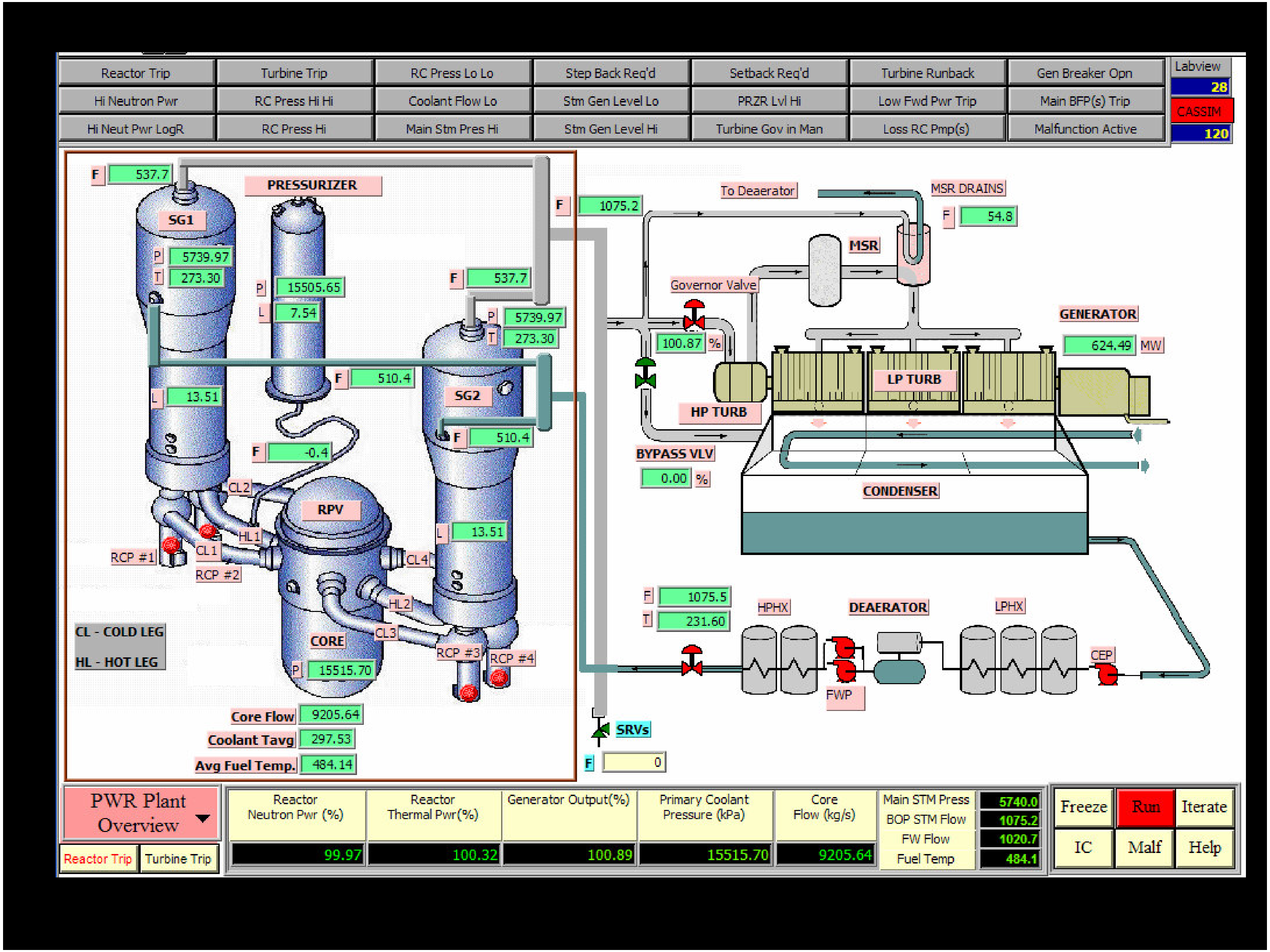
SYSTEM	SIMULATION SCOPE	DISPLAY PAGES	OPERATOR CONTROLS	MALFUNCTIONS
TURBINE-GENERATOR	• simple turbine model • mechanical power and generator output are proportional to steam flow • speeder gear and governor valve allow synchronized and non-synchronized operation	• PWR turbine generator	• turbine trip • turbine run-back • turbine run-up and synchronization • condenser steam discharge valves	• turbine spurious trip • turbine spurious run-back



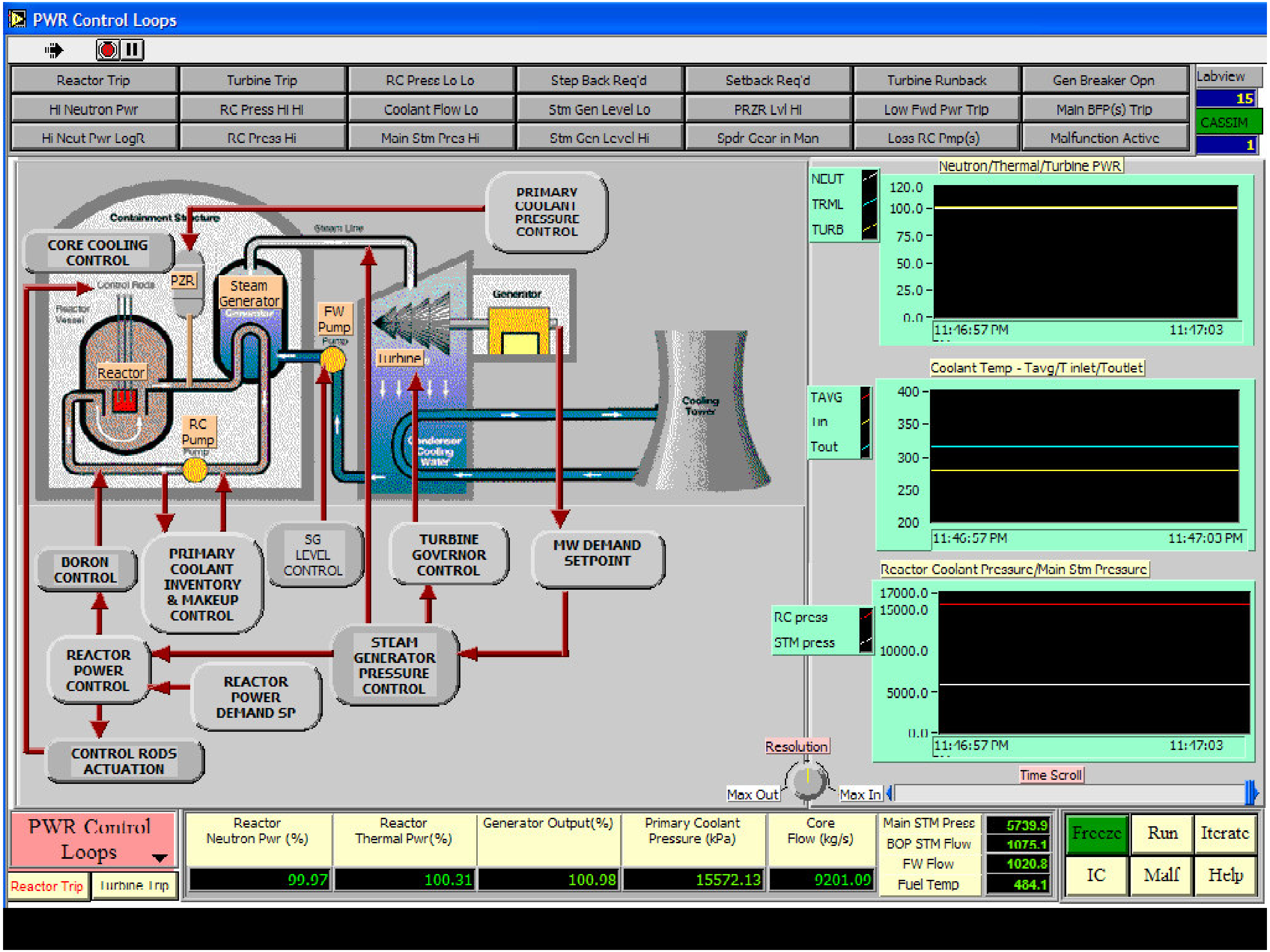
PWR Turbine Generator
Reactor Trip
Turbine Trip
RC Press Lo Lo
Step Back Req'd
Setback Req'd
Turbine Runback
Gen Breaker Opn
Hi Neutron Pwr
RC Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR Lvl Hi
Low Fwd Pwr Trip
Main BFP(s) Trip
Hi Neut Pwr LogR
RC Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
Spdr Gear in Man
Loss RC Pmp(s)
Malfunction Active
Labview
CASSIM
Main Steam Header P
5739.9
To Deaerator
STATION SERVICES
85.00
MW
MSR
CV POS
101
%
5592.2
1075.1
MSV
GENERATOR
OUTPUT
625.05
SPEED
1800.0
RPM
BREAKER
CLOSED
1020.4
BYP VLV
0.0000
0.00
TURBINE
GEN
CONDENSER
BYPASS VLV
AUTO
MAN OUT(%)
MAN SP NOT OK
To Feedwater System
TURBINE TRIP STATUS
RESET
Speeder Gear %
100.07
SPDR GEAR CONTROL
TURBINE RUNBACK
INACTIVE
SRV'S
RCTR Neut/Thrm Pwr
Generator Output (MW)
Turb Steam/BYP Flow
Turbine Speed
Governor Position
MSV Inlet Pressure
8:21:13 PM
8:21:18 PM
Resolution
Time Scroll
Max Out
Max In
PWR Turbine Generator
Reactor Trip
Turbine Trip
Reactor Neutron Pwr (%)
99.97
Reactor Thermal Pwr (%)
100.31
Generator Output(%)
100.98
Primary Coolant Pressure (kPa)
15572.13
Core Flow (kg/s)
9201.09
Main STM Press
5739.9
BOP STM Flow
1075.1
FW Flow
1020.8
Fuel Temp
484.1
Freeze
Run
Iterate
IC
Malf
Help

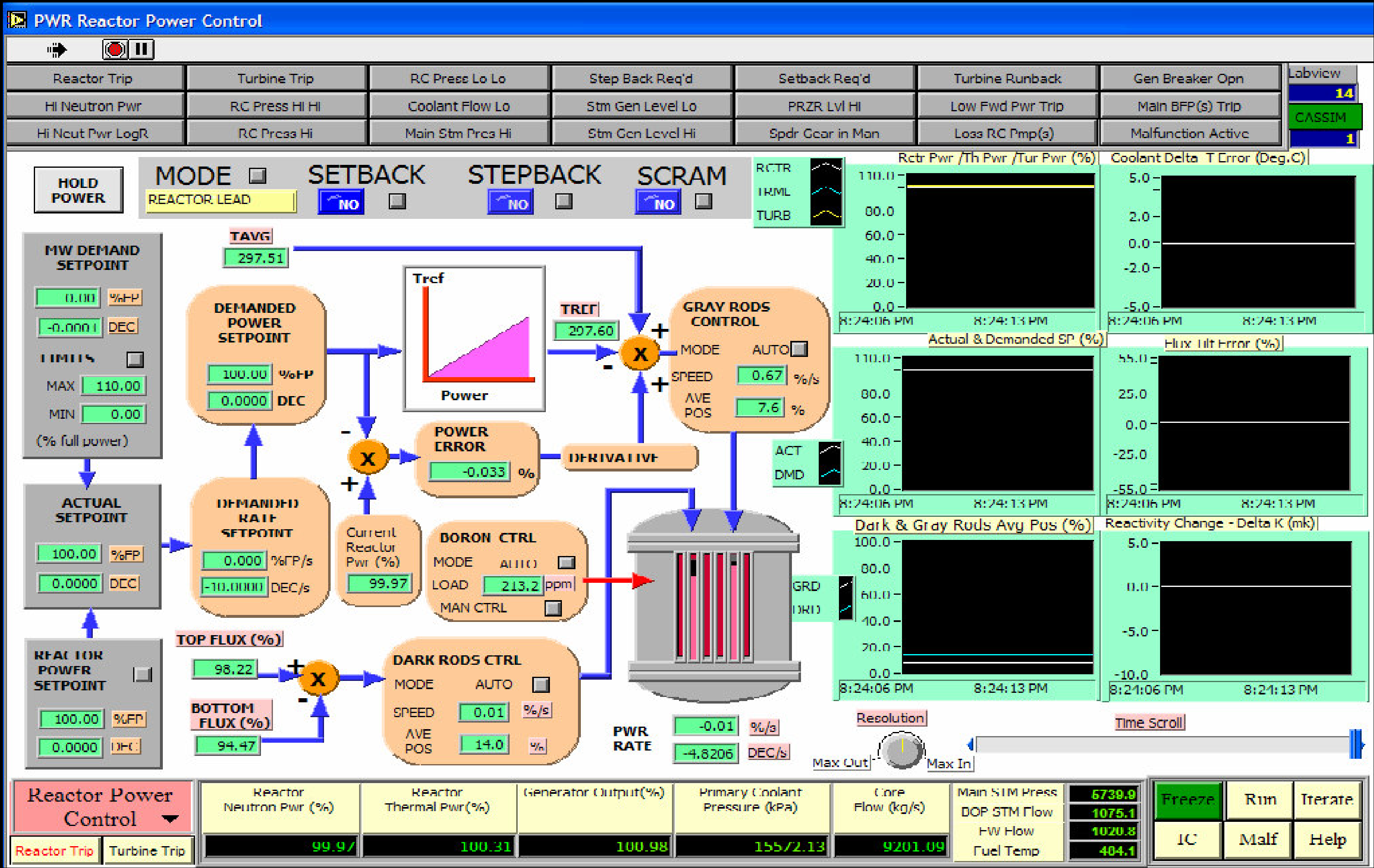
Overall Unit

SYSTEM	SIMULATION SCOPE	DISPLAY PAGES	OPERATOR CONTROLS	MALFUNCTIONS
OVERALL UNIT	• fully dynamic interaction between all simulated systems • overall unit power control with reactor leading mode; or turbine leading mode • unit annunciation & time trends • computer control of all major system functions	• PWR plant overview • PWR control loops • PWR MW demand SP & SGPC		

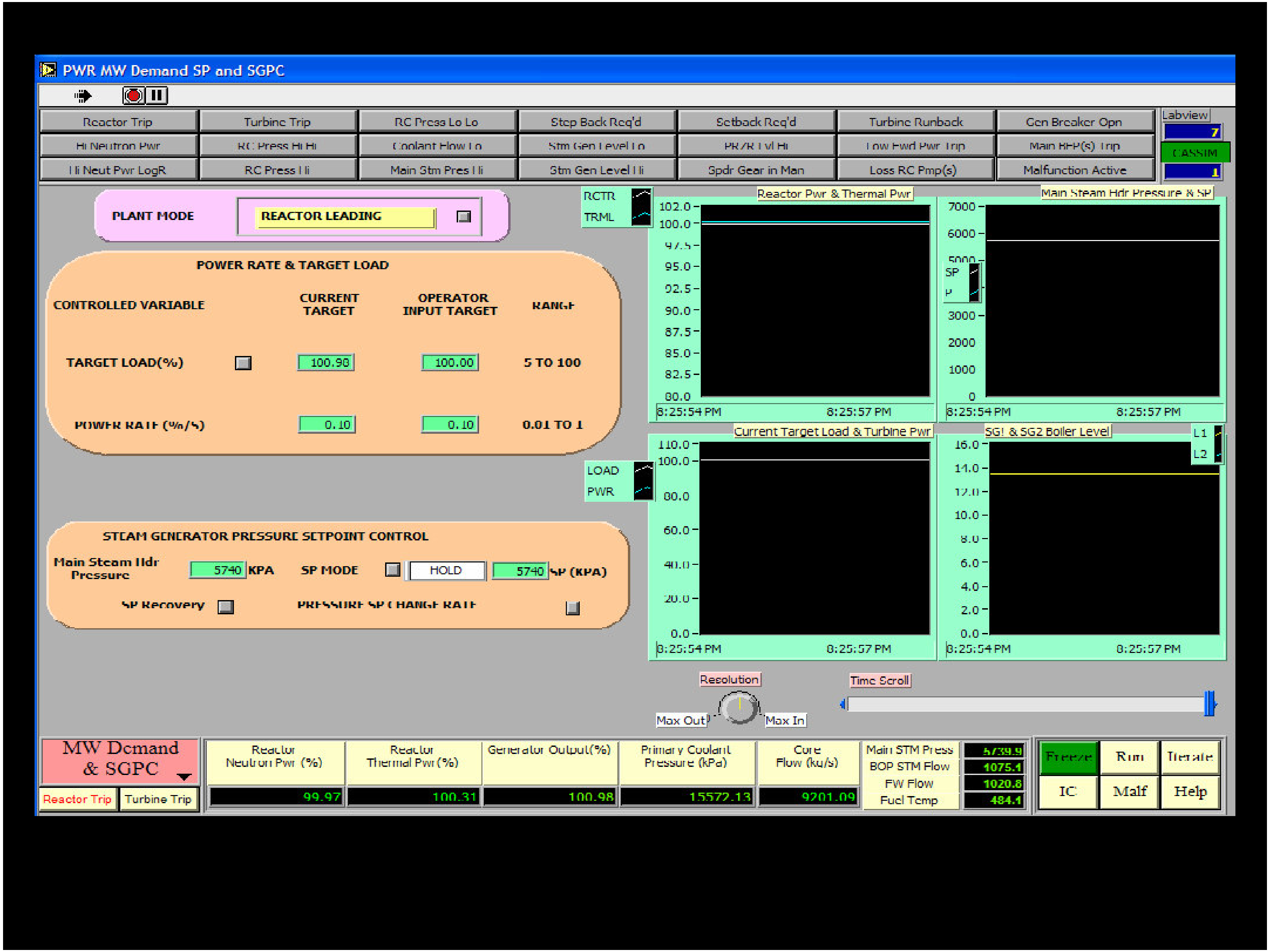


Reactor Trip
Turbine Trip
RC Press Lo Lo
Step Back Req'd
Setback Req'd
Turbine Runback
Gen Breaker Opn
Labview
28
Hi Neutron Pwr
RC Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR Lvl Hi
Low Fwd Pwr Trip
Main BFP(s) Trip
CASSIM
Hi Neut Pwr LogR
RC Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
Turbine Gov in Man
Loss RC Pmp(s)
Malfunction Active
120
PRESSURIZER
SG1
SG2
RPV
CORE
CL - COLD LEG
HL - HOT LEG
RCP #1
RCP #2
RCP #3
RCP #4
Core Flow 9205.64
Coolant Tavg 297.53
Avg Fuel Temp. 484.14
To Deaerator
MSR DRAINS
MSR
Governor Valve
GENERATOR
624.49 MW
HP TURB
LP TURB
BYPASS VLV
0.00 %
CONDENSER
HPHX
DEAERATOR
LPHX
CEP
FWP
SRVs
PWR Plant Overview
Reactor Trip
Turbine Trip
Reactor Neutron Pwr (%) 99.97
Reactor Thermal Pwr(%) 100.32
Generator Output(%) 100.89
Primary Coolant Pressure (kPa) 15515.70
Core Flow (kg/s) 9205.64
Main STM Press 5740.0
BOP STM Flow 1075.2
FW Flow 1020.7
Fuel Temp 484.1
Freeze
Run
Iterate
IC
Malf
Help


PWR Control Loops
Reactor Trip
Turbine Trip
RC Press Lo Lo
Step Back Req'd
Setback Req'd
Turbine Runback
Gen Breaker Opn
Hi Neutron Pwr
RC Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR Lvl Hi
Low Fwd Pwr Trip
Main BFP(s) Trip
Hi Neut Pwr LogR
RC Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
Spdr Gear in Man
Loss RC Pmp(s)
Malfunction Active
Labview
15
CASSIM
1
PRIMARY COOLANT PRESSURE CONTROL
CORE COOLING CONTROL
PZR
Steam Generator
FW Pump
Reactor
RC Pump
Turbine
Generator
Cooling Tower
BORON CONTROL
PRIMARY COOLANT INVENTORY & MAKEUP CONTROL
SG LEVEL CONTROL
TURBINE GOVERNOR CONTROL
MW DEMAND SETPOINT
REACTOR POWER CONTROL
STEAM GENERATOR PRESSURE CONTROL
REACTOR POWER DEMAND SP
CONTROL RODS ACTUATION
Neutron/Thermal/Turbine PWR
NEUT
TRML
TURB
11:46:57 PM
11:47:03
Coolant Temp - Tavg/T inlet/Toutlet
TAVG
Tin
Tout
11:46:57 PM
11:47:03 PM
Reactor Coolant Pressure/Main Stm Pressure
RC press
STM press
11:46:57 PM
11:47:03
Resolution
Max Out
Max In
Time Scroll
PWR Control Loops
Reactor Trip
Turbine Trip
Reactor Neutron Pwr (%)
99.97
Reactor Thermal Pwr(%)
100.31
Generator Output(%)
100.98
Primary Coolant Pressure (kPa)
15572.13
Core Flow (kg/s)
9201.09
Main STM Press 5739.9
BOP STM Flow 1075.1
FW Flow 1020.8
Fuel Temp 484.1
Freeze
Run
Iterate
IC
Malf
Help



Reactor Lead Control


PWR MW Demand SP and SGPC
Reactor Trip
Turbine Trip
RC Press Lo Lo
Step Back Req'd
Setback Req'd
Turbine Runback
Gen Breaker Opn
Hi Neutron Pwr
RC Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR Lvl Hi
Low Fwd Pwr Trip
Main BFP(s) Trip
Hi Neut Pwr LogR
RC Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
Spdr Gear in Man
Loss RC Pmp(s)
Malfunction Active
Labview
CASSIM
PLANT MODE
REACTOR LEADING
POWER RATE & TARGET LOAD
CONTROLLED VARIABLE
CURRENT TARGET
OPERATOR INPUT TARGET
RANGE
TARGET LOAD(%)
100.98
100.00
5 TO 100
POWER RATE (%/S)
0.10
0.10
0.01 TO 1
STEAM GENERATOR PRESSURE SETPOINT CONTROL
Main Steam Hdr Pressure
5740 KPA
SP MODE
HOLD
5740 SP (KPA)
SP Recovery
PRESSURE SP CHANGE RATE
Reactor Pwr & Thermal Pwr
RCTR
TRML
Main Steam Hdr Pressure & SP
SP
P
Current Target Load & Turbine Pwr
LOAD
PWR
SG1 & SG2 Boiler Level
L1
L2
8:25:54 PM
8:25:57 PM
Resolution
Max Out
Max In
Time Scroll
MW Demand & SGPC
Reactor Trip
Turbine Trip
Reactor Neutron Pwr (%)
99.97
Reactor Thermal Pwr (%)
100.31
Generator Output(%)
100.98
Primary Coolant Pressure (kPa)
15572.13
Core Flow (kg/s)
9201.09
Main STM Press
5739.9
BOP STM Flow
1075.1
FW Flow
1020.8
Fuel Temp
484.1
Freeze
Run
Iterate
IC
Malf
Help

Reactor Lead Power Change

- Demonstrate power change using reactor lead

Turbine Lead Power Change

- Demonstrate power change using turbine lead

PWR Response to Boiler Pressure Changes Question

- Demonstrate PWR responses with SG pressure setpoint changes with Reactivity controls in Manual.

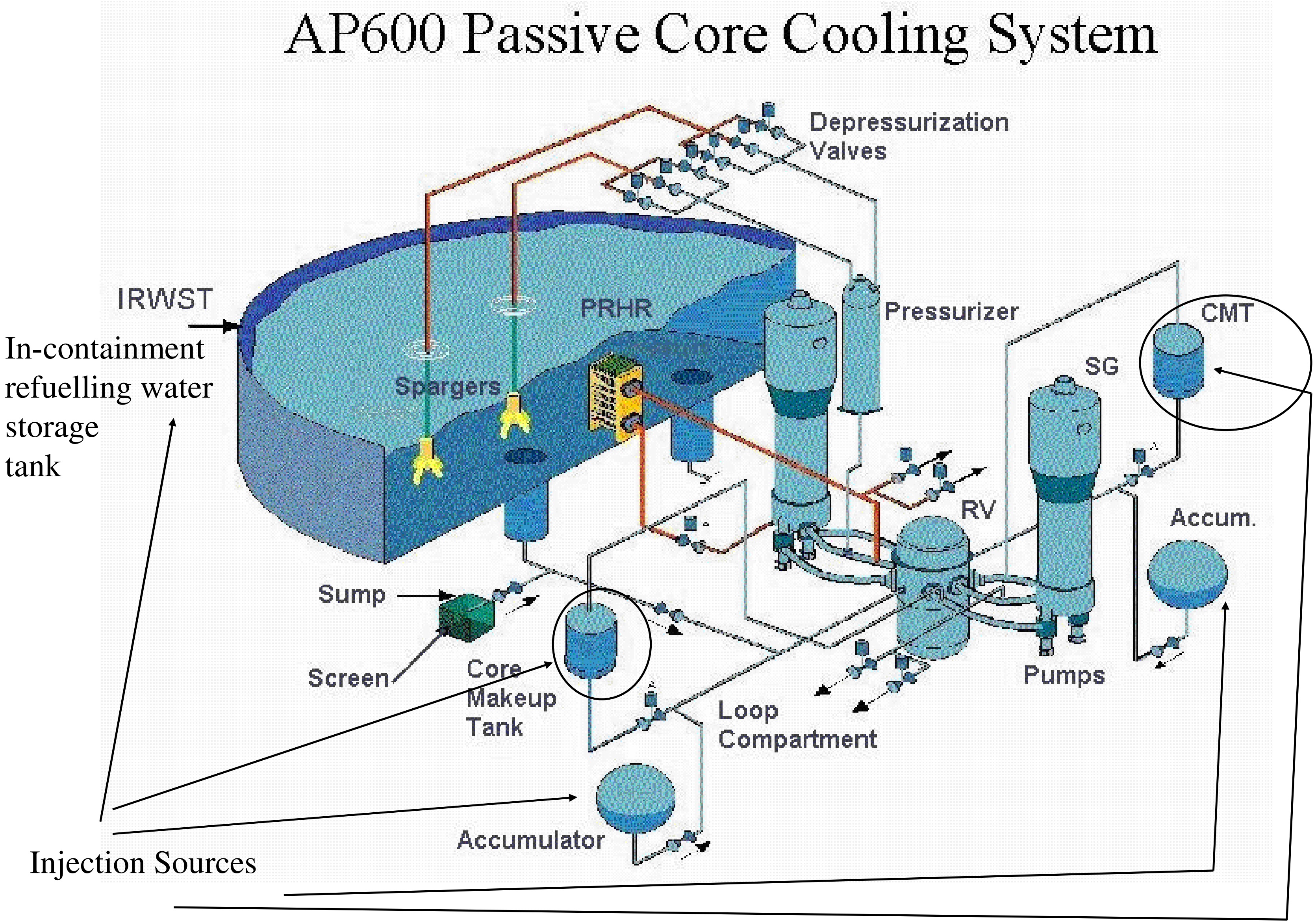
Passive Safety Systems

- Requires no operator actions to mitigate design basis accidents.
- Rely on natural forces - gravity, natural circulation, compressed gas; no pumps, fans diesels, chillers used. Only few simple valves, supported by reliable power sources

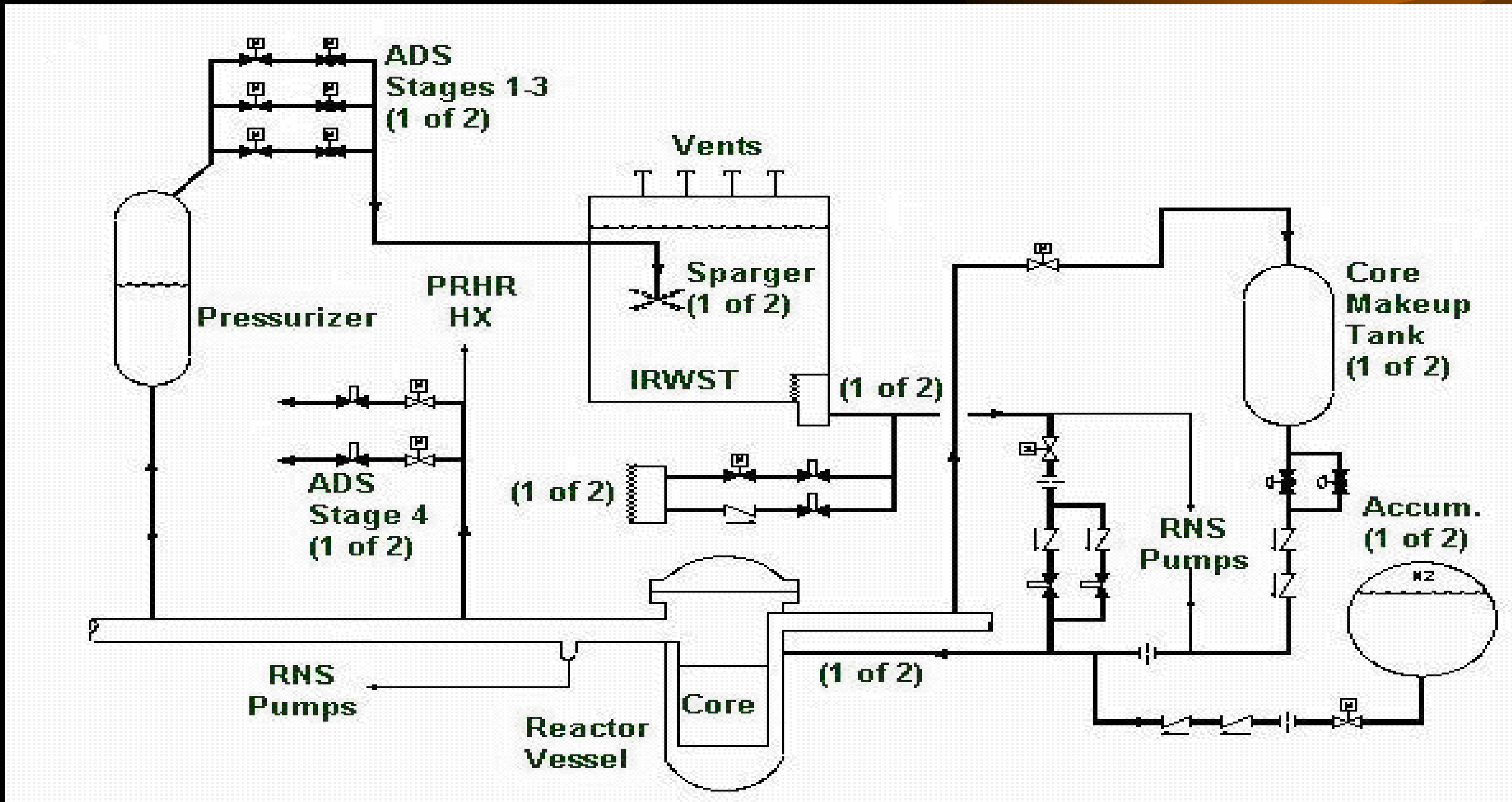
Passive Core Cooling

The PXS uses three sources of water to maintain core cooling:

- Core Makeup Tanks (CMTs)
- Accumulators
- In-containment Refueling Water Storage Tank (IRWST)
- These injection sources are all connected to two nozzles on the reactor vessel.


AP600 Passive Core Cooling System
Depressurization Valves
IRWST
In-containment refuelling water storage tank
PRHR
Spargers
Pressurizer
CMT
SG
RV
Accum.
Sump
Screen
Core Makeup Tank
Loop Compartment
Pumps
Accumulator
Injection Sources

Passive Core Cooling System



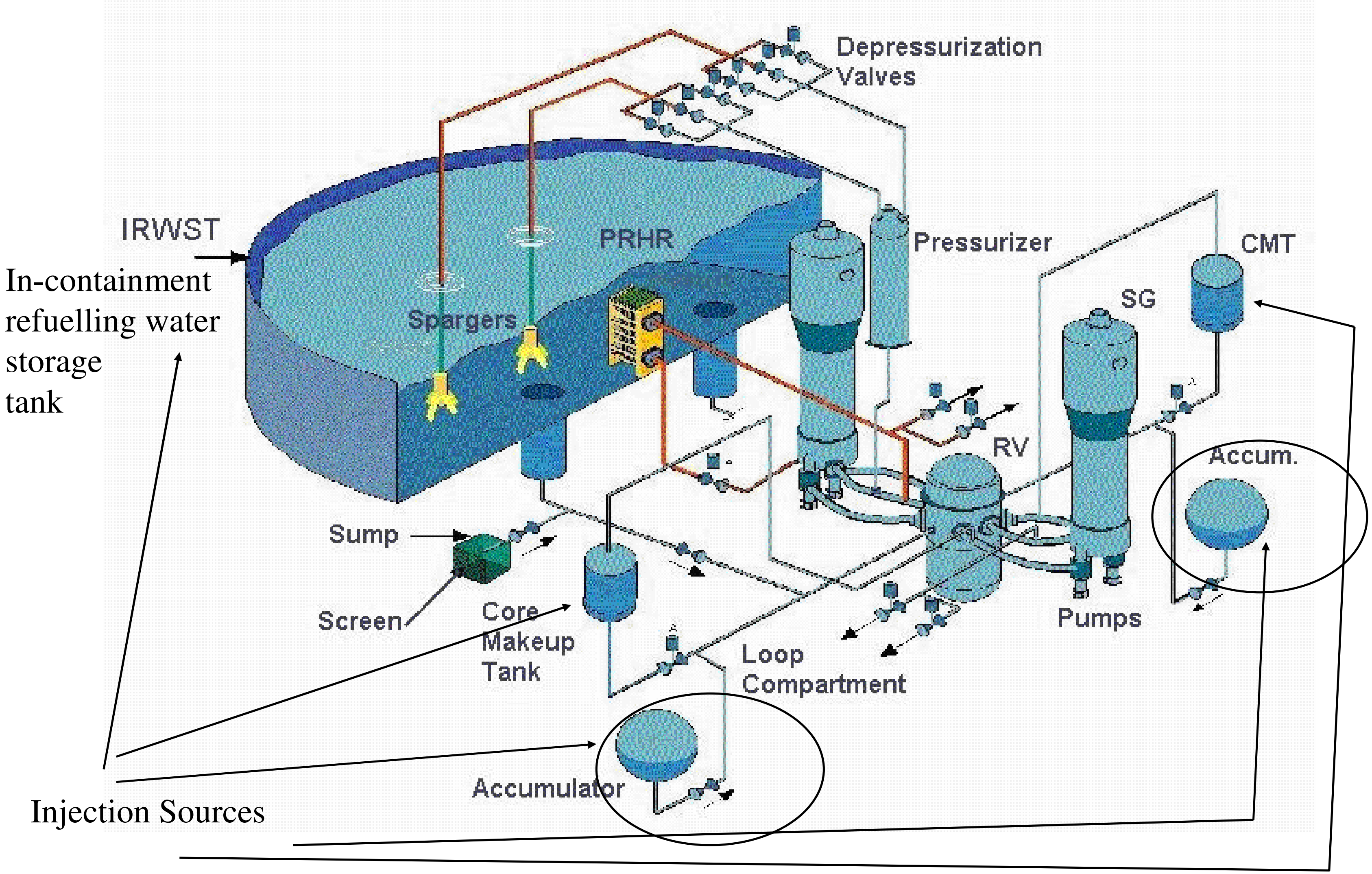
High Pressure Safety Injection with CMTs

- Two Core Makeup Tanks (CMTs), filled with borated water, located above the RCS loop piping.
- Make up for small leaks following transients or whenever the normal makeup system is unavailable.
- Designed for full RCS pressure using gravity.
- Poised to be in-service when water level in the pressurizer reaches a low-low level:
  - reactor scrammed; the reactor coolant pumps tripped; the CMT discharge isolation valves open automatically.
  - The relative elevations of the CMTs and the pressurizer are such that if RCS level continued to decrease, the water in the CMTs would drain into the reactor vessel.

Medium Pressure Safety Injection with Accumulators

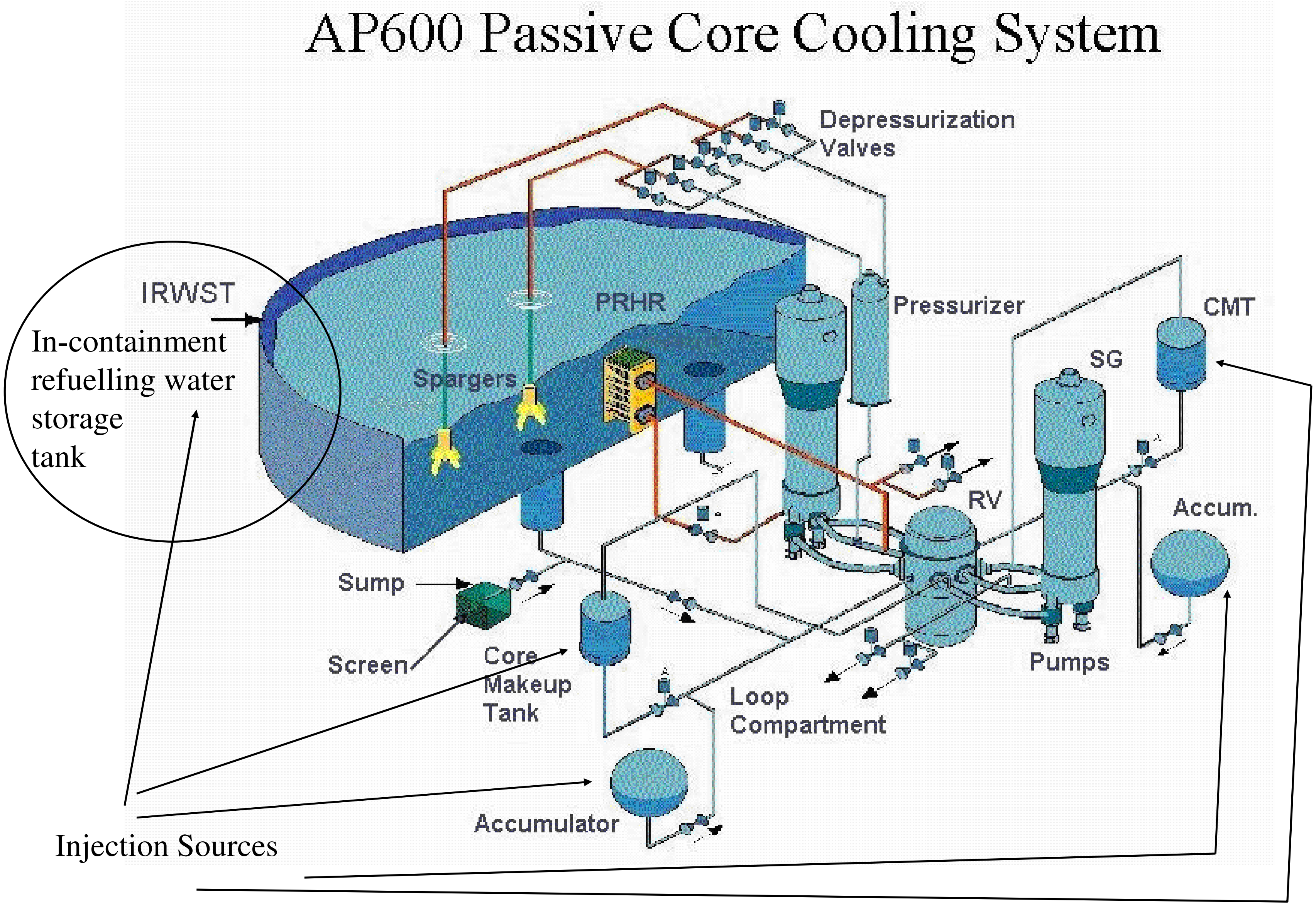
- Accumulators for large LOCAs - for higher initial makeup flows to rapidly refill the reactor vessel lower plenum and downcomer following RCS blowdown.
- The gas pressure forces open check valves that normally isolate the accumulators from the RCS.
- Accumulators sized to respond to complete severance of the largest RCS pipe.
- The accumulators continue delivery to assist the CMTs in rapidly reflooding the core.

AP600 Passive Core Cooling System



Low Pressure Reactor Coolant Makeup from the IRWST - long Term Injection

- In-containment Refueling Water Storage Tank (IRWST) for long-term injection water located in the containment just above the RCS loops.
- IRWST normally isolated from the RCS by self-actuating check valves. This tank is designed for atmospheric pressure.
- The RCS must be depressurized before injection. The automatic depressurization system (ADS) made up of four stages of valves to permit a relatively slow, controlled RCS pressure reduction to 10 psig.
- The ADS stages are actuated by CMT level. The first three stages are connected to the pressurizer and discharge through spargers into the IRWST. The fourth stage is connected to a hot leg and discharges through redundant isolation valves to the containment.

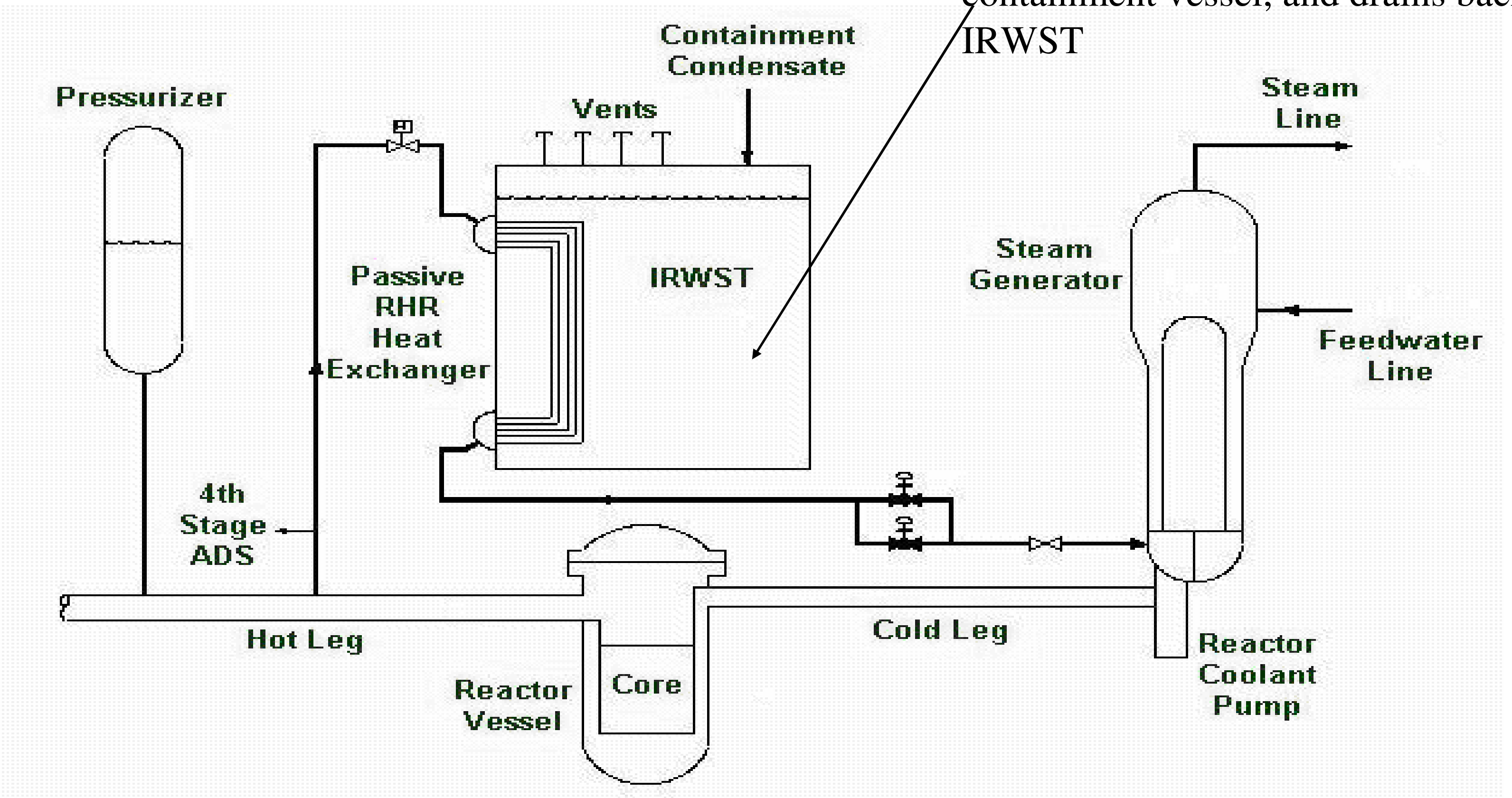

AP600 Passive Core Cooling System
Depressurization Valves
IRWST
In-containment refuelling water storage tank
PRHR
Pressurizer
CMT
Spargers
SG
RV
Accum.
Sump
Screen
Core Makeup Tank
Loop Compartment
Pumps
Accumulator
Injection Sources

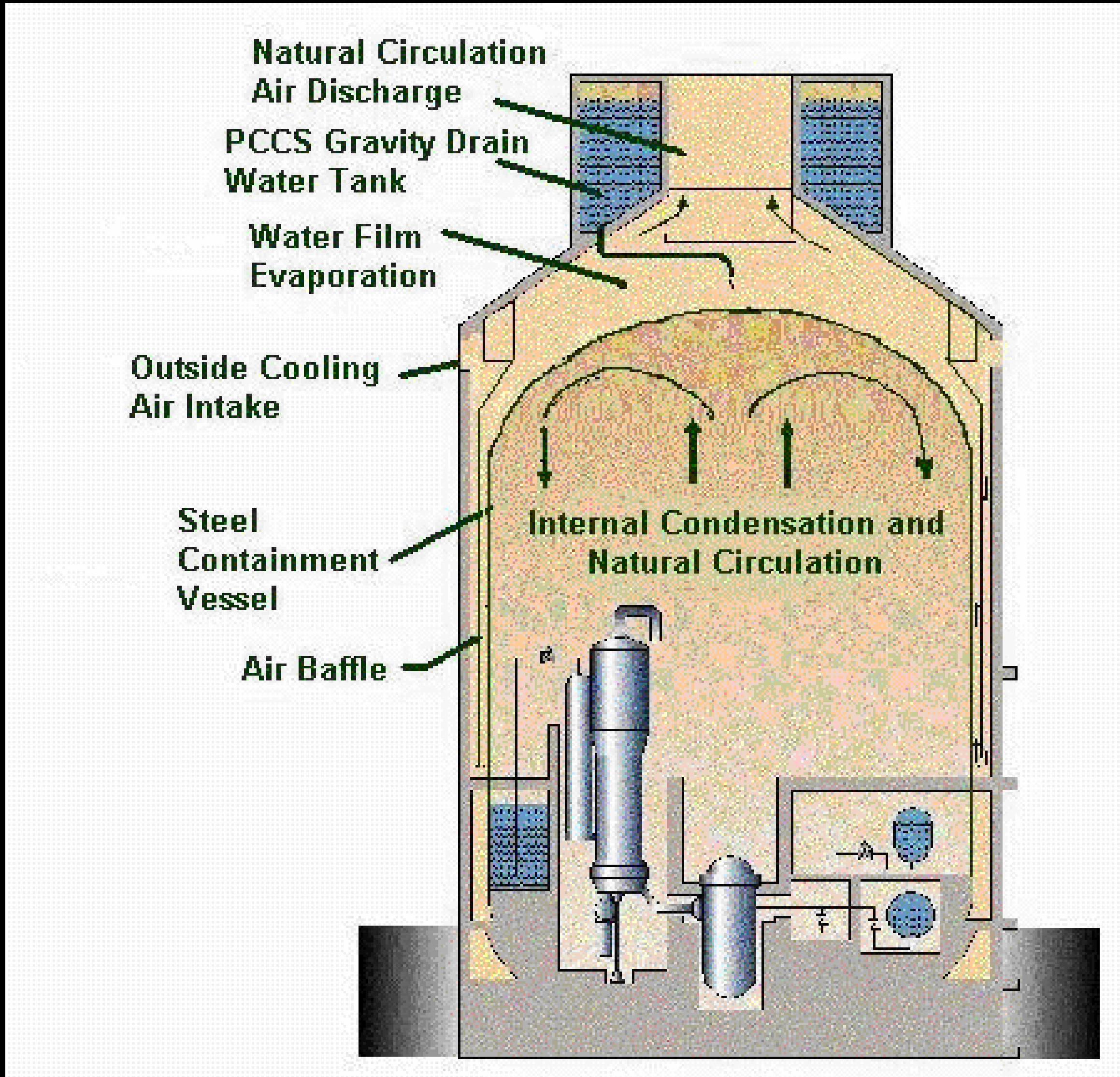
Passive Core Cooling System - Residual Heat Removal

- Passive residual heat removal (PRHR) subsystem protects the plant against transients that upset the normal steam generator feedwater and steam systems - loss of feedwater, feedwater line breaks, and steam line breaks with a single failure.

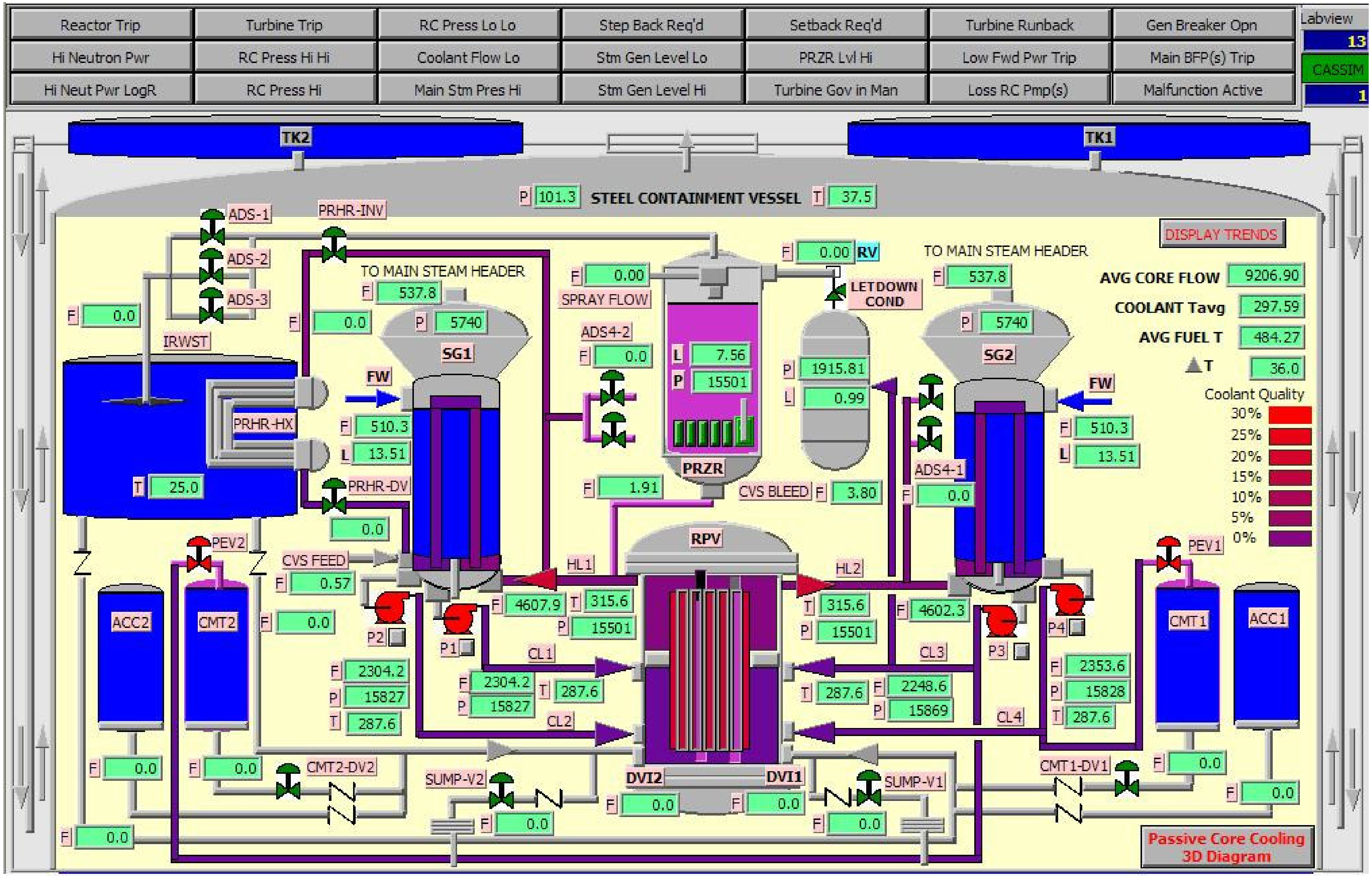
Passive Residual Heat Removal System

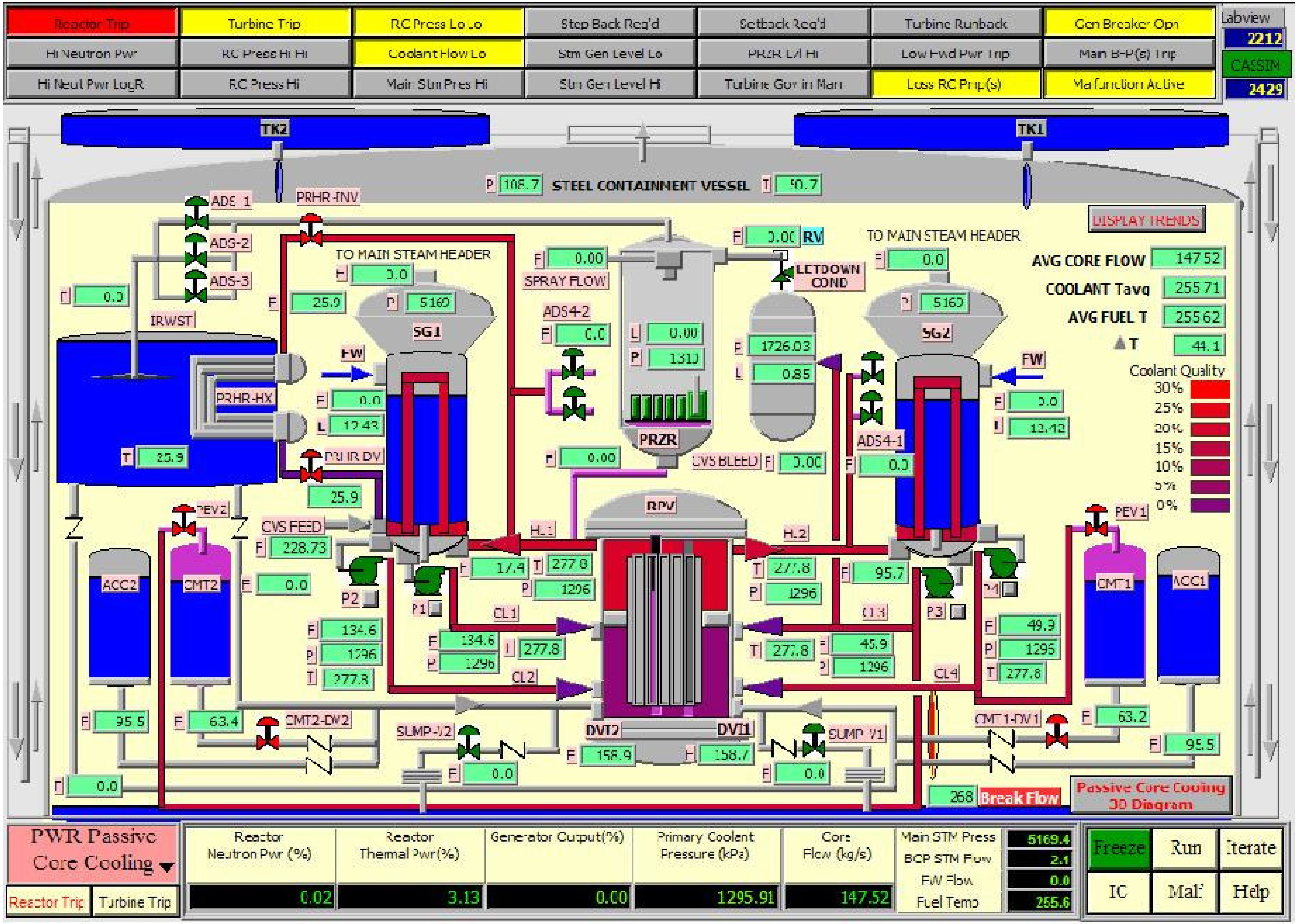
Enough water to absorb
decay heat > 1 hour before water
begins to boil. Steam passes to
containment, and condenses on steel
containment vessel, and drains back to
IRWST



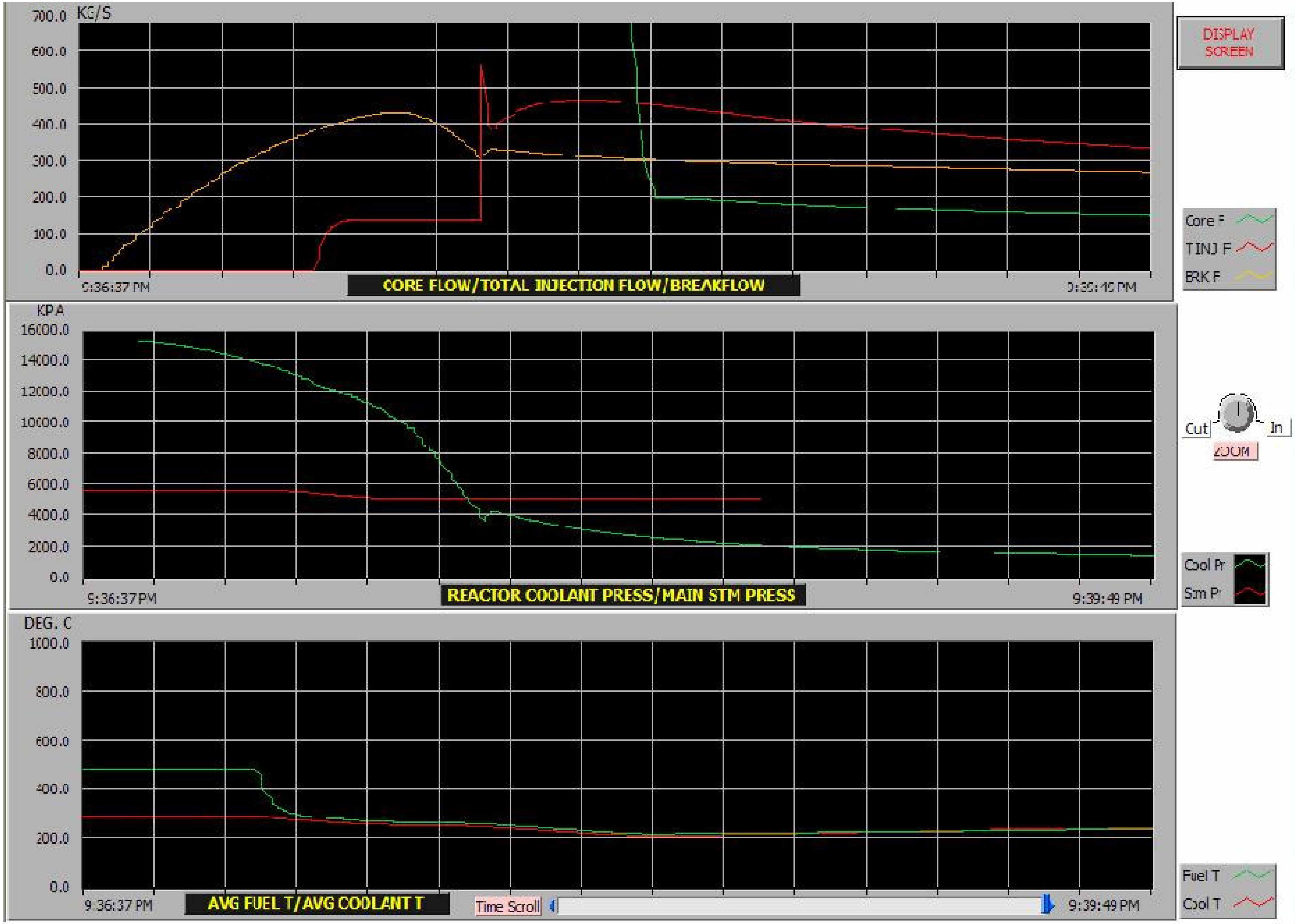


Natural Circulation
Air Discharge
PCCS Gravity Drain
Water Tank
Water Film
Evaporation
Outside Cooling
Air Intake
Steel
Containment
Vessel
Air Baffle
Internal Condensation and
Natural Circulation


Reactor Trip
Turbine Trip
RC Press Lo Lo
Step Back Req'd
Setback Req'd
Turbine Runback
Gen Breaker Opn
Hi Neutron Pwr
RC Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR Lvl Hi
Low Fwd Pwr Trip
Main BFP(s) Trip
Hi Neut Pwr LogR
RC Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
Turbine Gov in Man
Loss RC Pmp(s)
Malfunction Active
Labview
13
CASSIM
1
TK2
TK1
P 101.3
STEEL CONTAINMENT VESSEL
T 37.5
DISPLAY TRENDS
ADS-1
ADS-2
ADS-3
PRHR-INV
TO MAIN STEAM HEADER
F 537.8
P 5740
SG1
F 0.00
SPRAY FLOW
F 0.00 RV
LET DOWN COND
TO MAIN STEAM HEADER
F 537.8
P 5740
SG2
AVG CORE FLOW 9206.90
COOLANT Tavg 297.59
AVG FUEL T 484.27
▲T 36.0
Coolant Quality
30%
25%
20%
15%
10%
5%
0%
F 0.0
IRWST
F 0.0
ADS4-2
F 0.0
L 7.56
P 15501
P 1915.81
L 0.99
FW
FW
PRHR-HX
F 510.3
L 13.51
F 510.3
L 13.51
T 25.0
PRHR-DV
0.0
PRZR
F 1.91
CVS BLEED
F 3.80
ADS4-1
F 0.0
RPV
PEV2
CVS FEED
F 0.57
HL1
HL2
PEV1
ACC2
CMT2
F 0.0
F 4607.9
T 315.6
P 15501
T 315.6
P 15501
F 4602.3
CMT1
ACC1
P2
P1
P3
P4
CL1
CL3
F 2304.2
P 15827
T 287.6
F 2304.2
P 15827
T 287.6
T 287.6
F 2248.6
P 15869
F 2353.6
P 15828
T 287.6
CL2
CL4
F 0.0
F 0.0
CMT2-DV2
SUMP-V2
DVI2
DVI1
SUMP-V1
CMT1-DV1
F 0.0
F 0.0
F 0.0
F 0.0
F 0.0
F 0.0
F 0.0
F 0.0
Passive Core Cooling
3D Diagram



Reactor Trip
Turbine Trip
RC Press Lo Lo
Step Back Req'd
Setback Req'd
Turbine Runback
Gen Breaker Opn
Labview
2212
CASSIM
2429
Hi Neutron Pwr
RC Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR L/l Hi
Low Fwd Pwr Trip
Main B-P(s) Trip
Hi Neut Pwr LogR
RC Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
Turbine Gov in Man
Loss RC Pmp(s)
Malfunction Active
TK2
TK1
STEEL CONTAINMENT VESSEL
ADS-1
ADS-2
ADS-3
PRHR-INV
IRWST
PRHR-HX
PRHR DV
TO MAIN STEAM HEADER
SG1
SG2
FW
SPRAY FLOW
ADS4-2
ADS4-1
PRZR
RV
LETDOWN COND
CVS BLEED
CVS FEED
DISPLAY TRENDS
AVG CORE FLOW 147.52
COOLANT Tavg 255.71
AVG FUEL T 255.62
T 44.1
Coolant Quality
30%
25%
20%
15%
10%
5%
0%
RPV
HL1
HL2
CL1
CL2
CL3
CL4
P1
P2
P3
P4
PEV1
PEV2
ACC1
ACC2
CMT1
CMT2
CMT2-DV2
CMT1-DV1
SUMP-V2
SUMP-V1
DVI2
DVI1
Break Flow
Passive Core Cooling 3D Diagram
PWR Passive Core Cooling
Reactor Trip
Turbine Trip
Reactor Neutron Pwr (%) 0.02
Reactor Thermal Pwr(%) 3.13
Generator Output(%) 0.00
Primary Coolant Pressure (kPa) 1295.91
Core Flow (kg/s) 147.52
Main STM Press 5169.4
BCP STM Flow 2.1
FW Flow 0.0
Fuel Temp 255.6
Freeze
Run
Iterate
IC
Malf
Help



KG/S
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
9:36:37 PM
CORE FLOW/TOTAL INJECTION FLOW/BREAKFLOW
9:39:49 PM
DISPLAY SCREEN
Core F
TINJ F
BRK F
KPA
16000.0
14000.0
12000.0
10000.0
8000.0
6000.0
4000.0
2000.0
0.0
9:36:37 PM
REACTOR COOLANT PRESS/MAIN STM PRESS
9:39:49 PM
Out
In
ZOOM
Cool Pr
Stm Pr
DEG. C
1000.0
800.0
600.0
400.0
200.0
0.0
9:36:37 PM
AVG FUEL T/AVG COOLANT T
Time Scroll
9:39:49 PM
Fuel T
Cool T

AP1000 Operating Characteristics

Withstand the following operations without reactor scram or actuation of safeguard systems -

- From 15 % - 100 % FP, +/- 5 % /minute ramp load change;
- From 15 % - 100 %, +/- 10 % step load change
- 100 % load rejection
- Daily load following
- Grid frequency changes 10 % peak-to-peak, at 2 % per minute rate
- 20 % power step increase or decrease in 10 minutes
- loss of single feedwater pump.

PWR Simulator

- Run the PWR Simulator
- View all the Simulator Screens

Answer to PWR Response to Boiler Press Changes Question

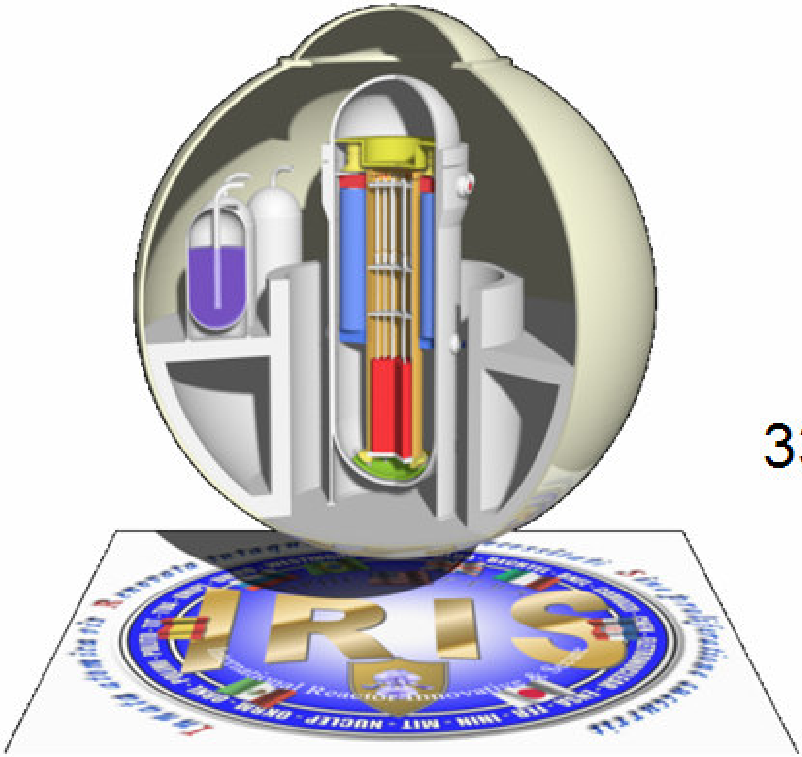
- At steady state: Boiler Q = Core Q
- Boiler Q = UA ((To+Ti)/2 -Ts)

  Ts - Sat Steam Temp.; To, Ti - coolant T's
- Boiler P $\downarrow$ Ts $\downarrow$ Q $\uparrow$ --> Boiler Q > Core Q

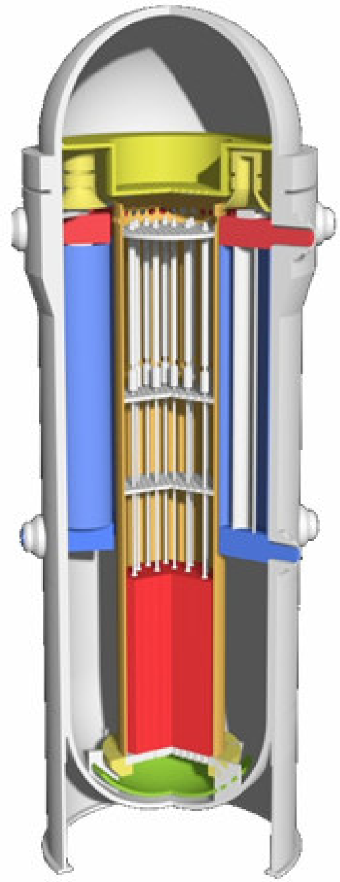
  Prim Coolant T $\downarrow$ --> less -ve feedback
- Boiler P $\uparrow$ Ts $\uparrow$ Q $\downarrow$ --> Boiler Q < Core Q

  Prim Coolant T $\uparrow$ --> more -ve feedback

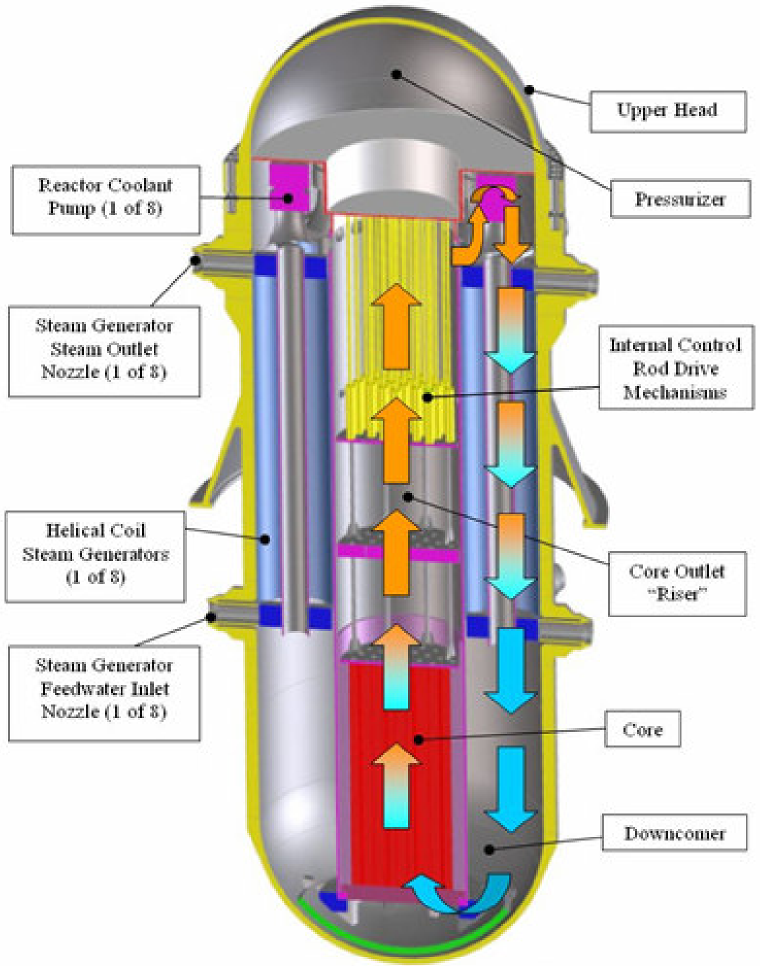
AN ADVANCED, MODULAR, MEDIUM-POWER LWR



335 MWe



IRIS INTEGRAL SYSTEM



Integral configuration (integral primary loop)

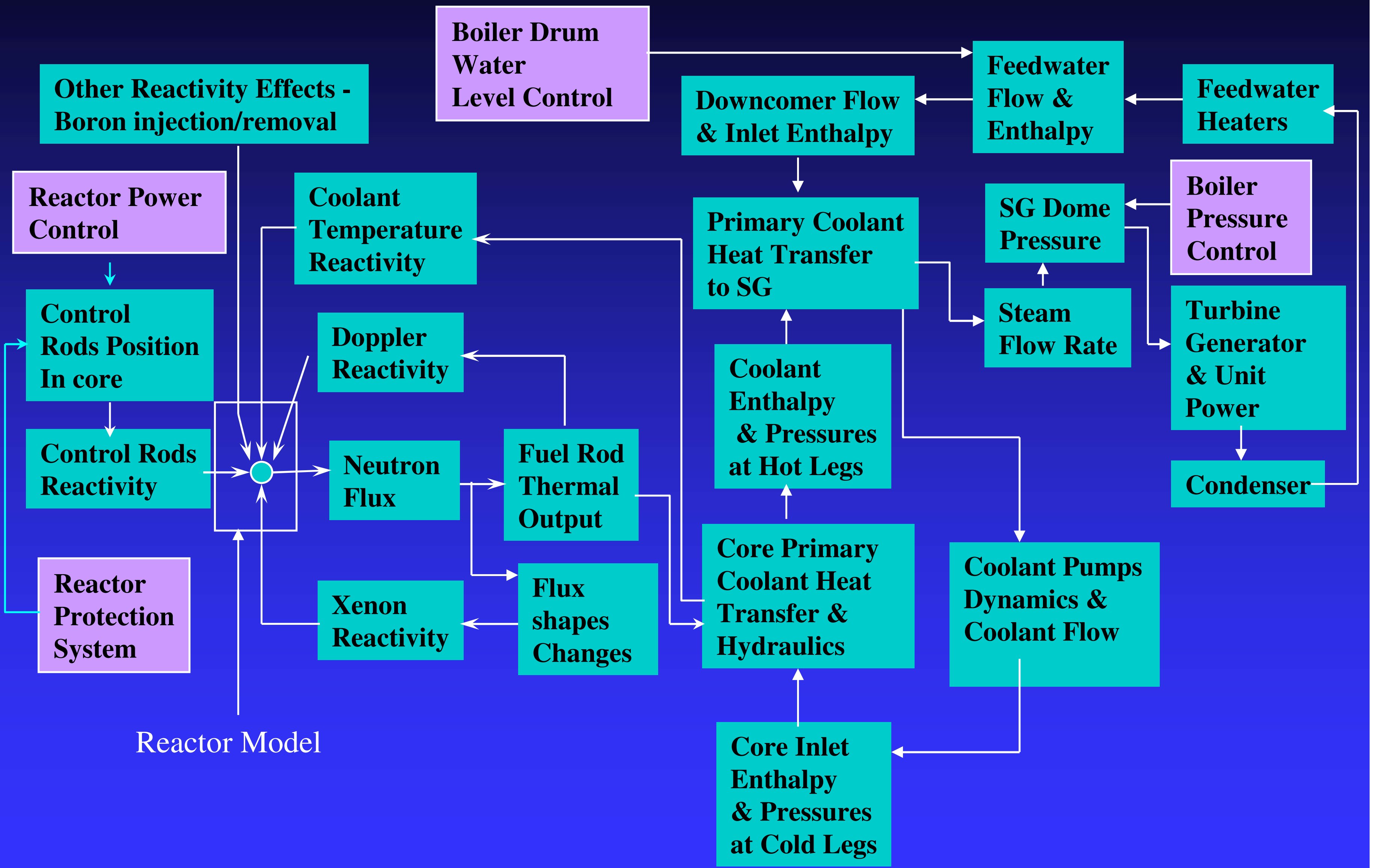
All major primary loop components are inside a single pressure vessel (eliminates loop piping and external components)

NPP Simulators for Education Workshop - Passive PWR Models

Wilson Lam (wilson@cti-simulation.com)
CTI Simulation International Corp.
www.cti-simulation.com

Sponsored by IAEA

PWR Modeling Diagram



Point Kinetic Reactor Model

$$\frac{dn}{dt} = \frac{\Delta K - \beta}{\Lambda} \cdot n + \sum_{i=1}^{m} \lambda_i \cdot C_i$$

$$\frac{dC_i}{dt} = \beta_i \cdot \frac{n}{\Lambda} - \lambda_i \cdot C_i \qquad \text{for I = 1....m}$$

Where

ΔK = (Ke - 1) / Ke

$\Lambda = \ell$ / Ke

Spatial Kinetic Model for Pressurized Water Reactor

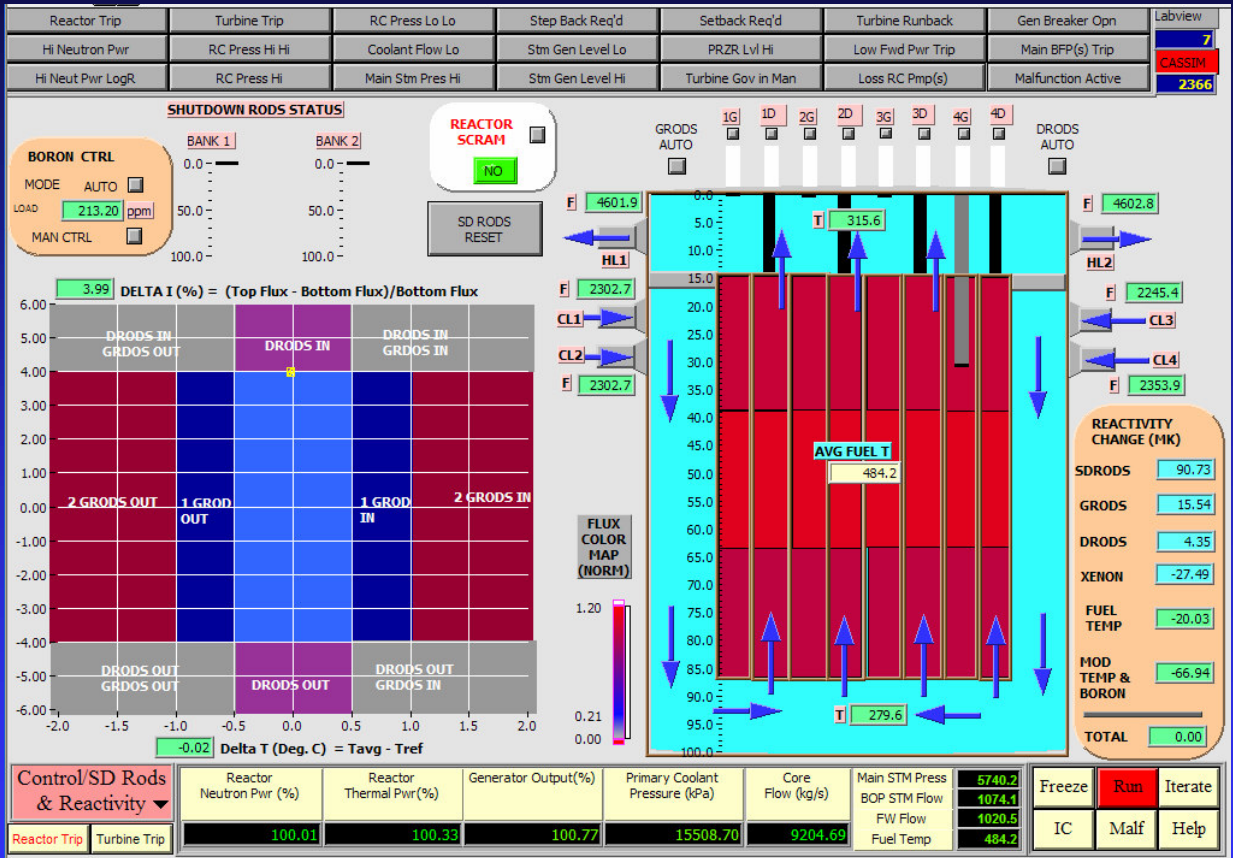
- Nodal approach based on Avery’s coupled region kinetics theory

- 12 point kinetics models to simulate the 12 reactor zones in core.
- Each zone reactor model based neutron balance DE , and 6 different neutron delay groups.
- Reactivity changes in each zone reactor - a function of (a) control rods position, (b) zonal concentration of Xenon (c) zonal fuel temp (d) zonal moderator temp. (e) boron conc. (f) zone reactivity coupling effects.

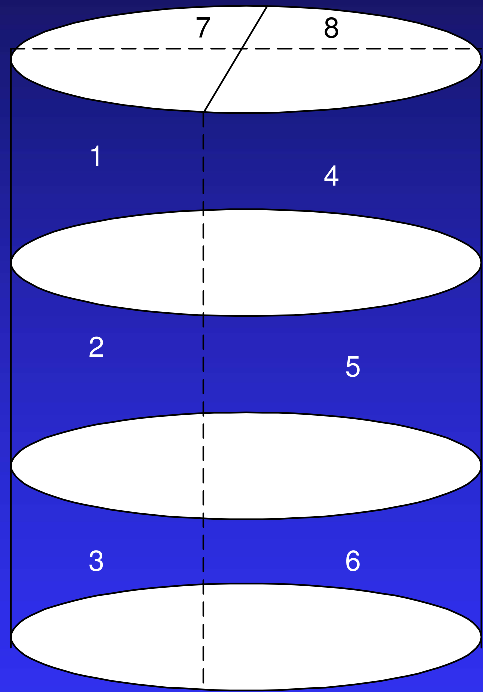
- Reactivity due to zone couplings are calculated separately for each zone using

$$\Delta\rho_{ij} = \Lambda_i K_{ij} \left(\alpha_i \frac{N_j}{N_i} + \frac{1}{l_i} \frac{\sum_{\substack{ZONEj \\ m=1}}^{6} \lambda_m C_m}{N_i} \right)$$

- Sum up all the effects for any particular zone, and enter as one of the reactivity change for that zone.
- Total power from the 12 zone reactors are summed up and then divided by 12 to get normalized overall power.

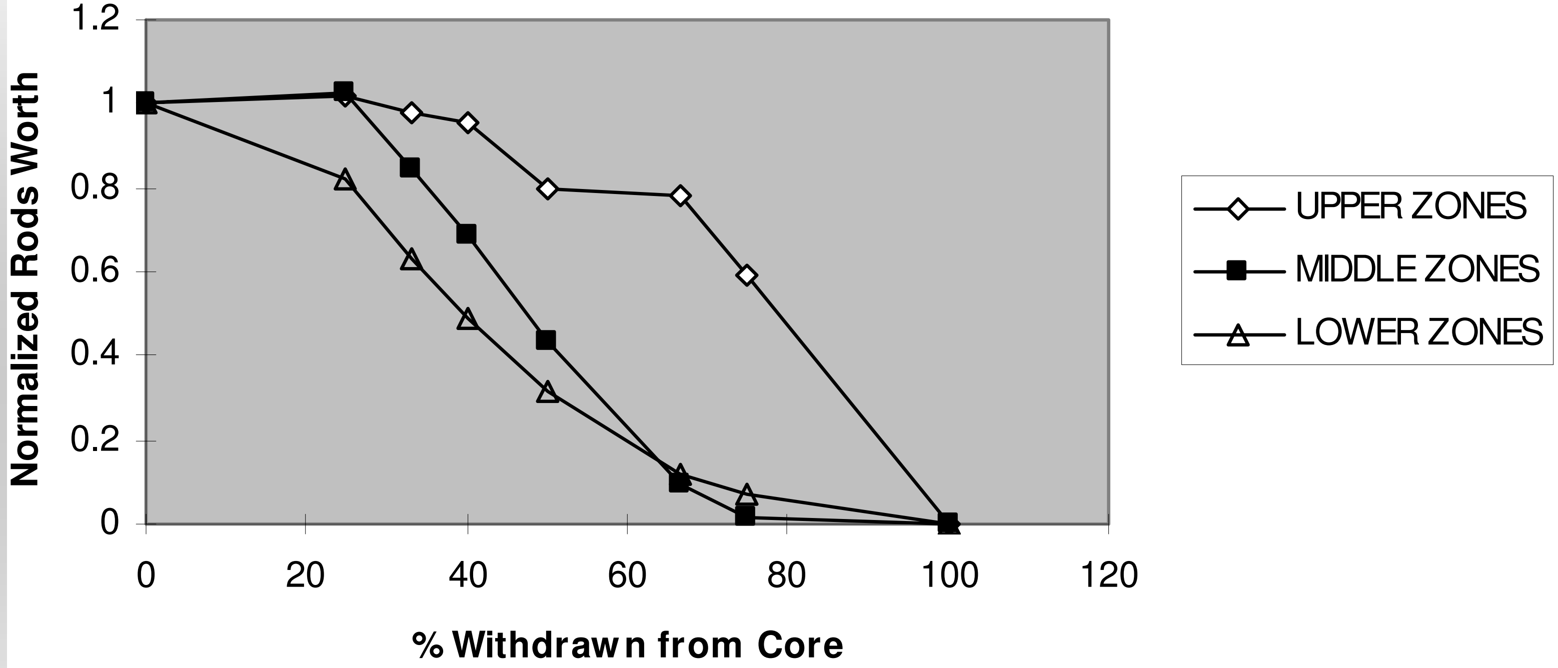


Reactor Trip
Turbine Trip
RC Press Lo Lo
Step Back Req'd
Setback Req'd
Turbine Runback
Gen Breaker Opn
Hi Neutron Pwr
RC Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR Lvl Hi
Low Fwd Pwr Trip
Main BFP(s) Trip
Hi Neut Pwr LogR
RC Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
Turbine Gov in Man
Loss RC Pmp(s)
Malfunction Active
Labview
CASSIM
2366
SHUTDOWN RODS STATUS
BANK 1
BANK 2
BORON CTRL
MODE AUTO
213.20 ppm
MAN CTRL
REACTOR SCRAM
NO
SD RODS RESET
GRODS AUTO
DRODS AUTO
AVG FUEL T
484.2
DELTA I (%) = (Top Flux - Bottom Flux)/Bottom Flux
DRODS IN GRDOS OUT
DRODS IN
DRODS IN GRDOS IN
2 GRODS OUT
1 GROD OUT
1 GROD IN
2 GRODS IN
DRODS OUT GRDOS OUT
DRODS OUT
DRODS OUT GRDOS IN
Delta T (Deg. C) = Tavg - Tref
FLUX COLOR MAP (NORM)
REACTIVITY CHANGE (MK)
SDRODS 90.73
GRODS 15.54
DRODS 4.35
XENON -27.49
FUEL TEMP -20.03
MOD TEMP & BORON -66.94
TOTAL 0.00
Control/SD Rods & Reactivity
Reactor Trip
Turbine Trip
Reactor Neutron Pwr (%) 100.01
Reactor Thermal Pwr(%) 100.33
Generator Output(%) 100.77
Primary Coolant Pressure (kPa) 15508.70
Core Flow (kg/s) 9204.69
Main STM Press 5740.2
BOP STM Flow 1074.1
FW Flow 1020.5
Fuel Temp 484.2
Freeze
Run
Iterate
IC
Malf
Help

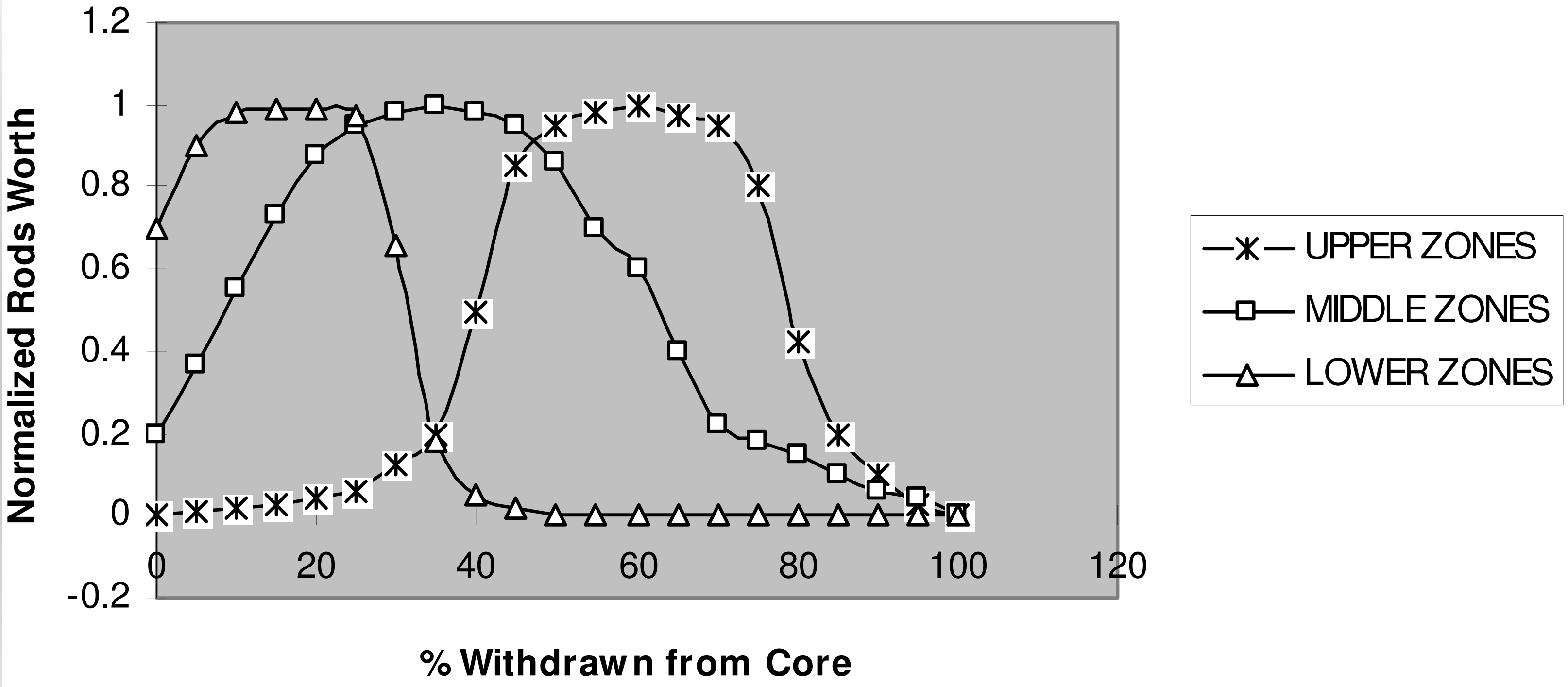


7
8
1
4
2
5
3
6

Gray Rods Worth to Reactor Zones, as a function of Rods Position



Dark Rods Reactivity Worth to Reactor Zones, as a function of Rods Position



- The decay heat calculation within each zone assumes 3 separate decay product groups

$$P = N_{flux} - \Sigma\,(\gamma_i .\ N_{flux} - D_i)$$
$$dDi/dt = \lambda_i .\ (\gamma_i .\ N_{flux} - D_i)$$

γ_i = fission product fraction for Decay Group I
λ_i = decay time constant for Decay group i

- The decay heat from each zone used to calculate zone coolant temperature and fuel temp in each zone.

The average fuel energy equation is given by:

$$\rho_f V_f C_f \frac{dT_f}{dt} = P - UA(T_f - T_c) \quad \text{.....................(5.7-1)}$$

Where

ρ_f = volume average fuel density

V_f = fuel volume in one zone

C_f = average fuel specific heat capacity

T_f = average fuel temperature

T_c = average coolant temperature

P = reactor power

U = overall heat transfer coefficient

A = overall heat transfer area for fuel channel

The average core coolant energy equation is given by:

$$\rho_c V_c \frac{dh_o}{dt} = W_i h_i - W_o h_o + UA(T_f - T_c) \quad \text{…………...(5.7-2)}$$

Where

ρ_c = volume average coolant density

V_c = coolant volume in one zone

h_i = average coolant specific enthalpy at inlet of the zone

h_o = average coolant specific enthalpy at outlet of the zone

A = overall heat transfer area for fuel channel zone

U = overall heat transfer coefficient

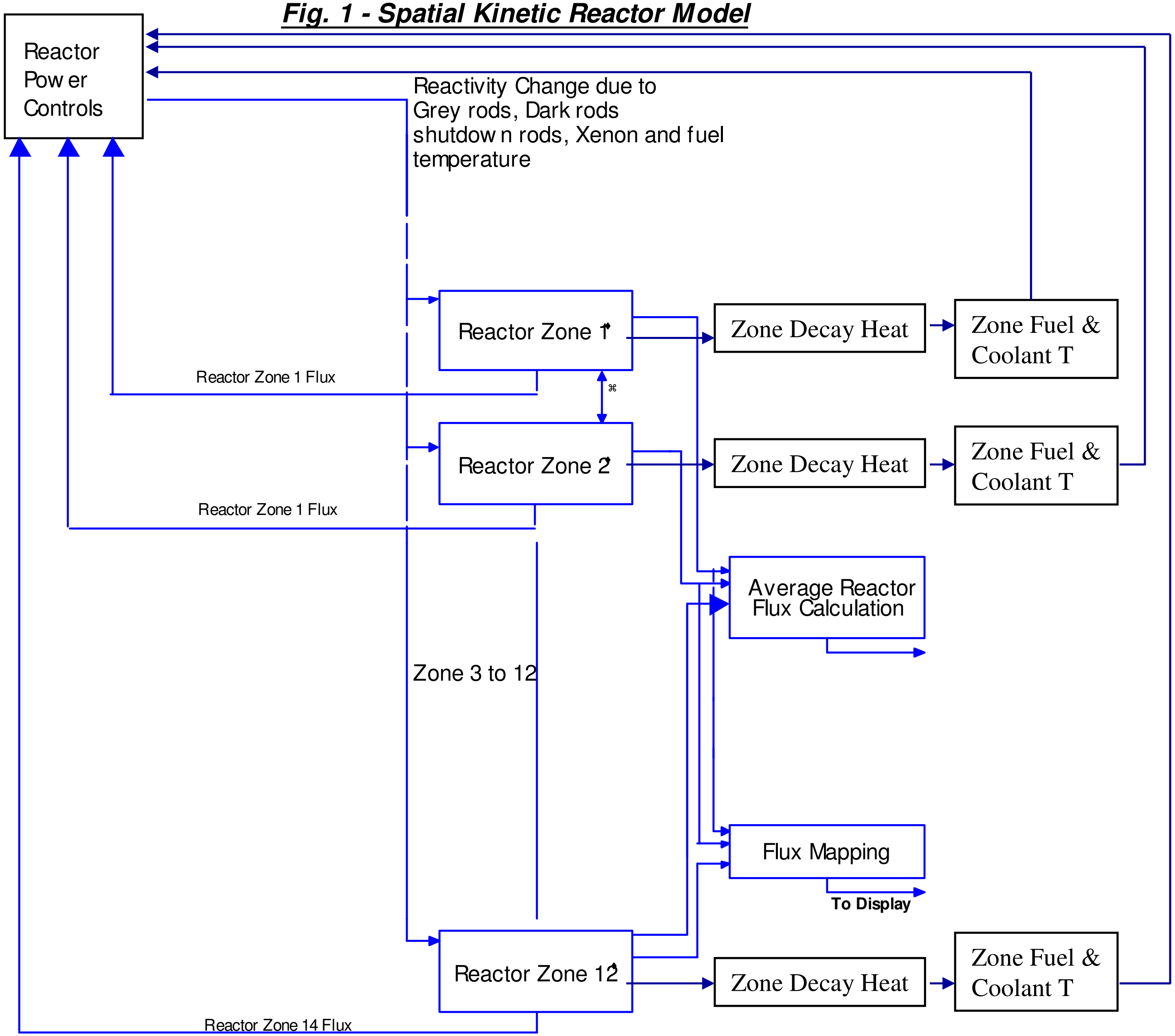
T_f = average fuel temperature

T_c = average coolant temperature

W_i = coolant mass flow rate at fuel channel zone inlet

W_o = coolant mass flow rate at fuel channel zone inlet

Fig. 1 - Spatial Kinetic Reactor Model

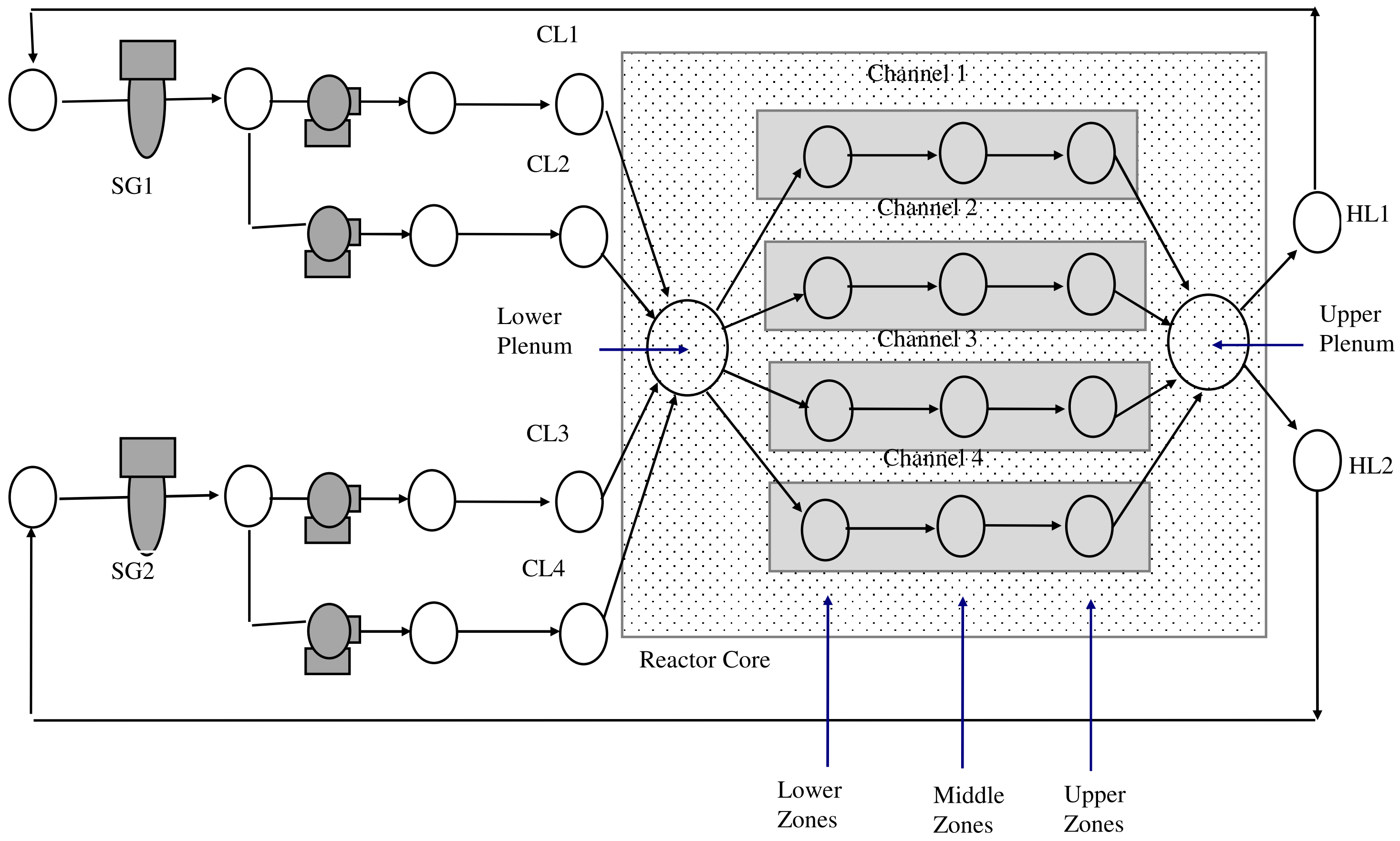


- **reactivity changes due to temperature change, xenon poisoning and voiding are within each reactor zone**

⌘ **coupling is modelled between each neighbouring zones according to prescribed formula**

PWR Core Modeling

Flow & Pressures in zone calculated by Hydraulic Flow Network



The fuel heat transfer calculations (equation 5.7-1, 5.7-2) start with the lower zones, with zones inlet temperatures derived from the core lower plenum temperatures; with coolant flows derived from hydraulic flow network computation at the lower plenum. After obtaining the lower zone coolant outlet temperatures and average fuel temperatures, the calculations proceed to the middle zones, and then to the upper zones accordingly.

At the core upper plenum, the coolant temperatures from the 4 lumped channels are mixed by flow turbulence, and the temperatures at the hot legs will be the coolant mixing temperatures at the upper plenum

Steam Generator Model

- Lump Parameter Model

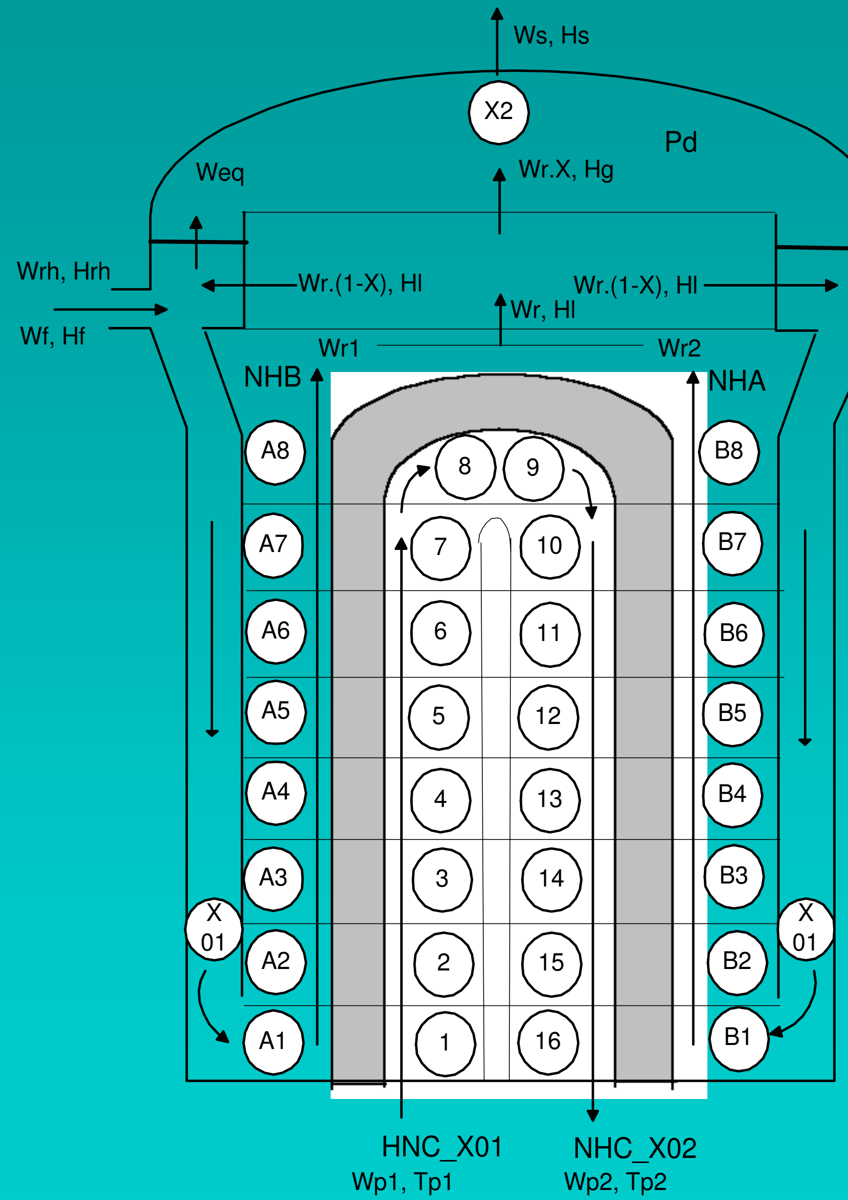
More Detailed Lumped Parameter Model

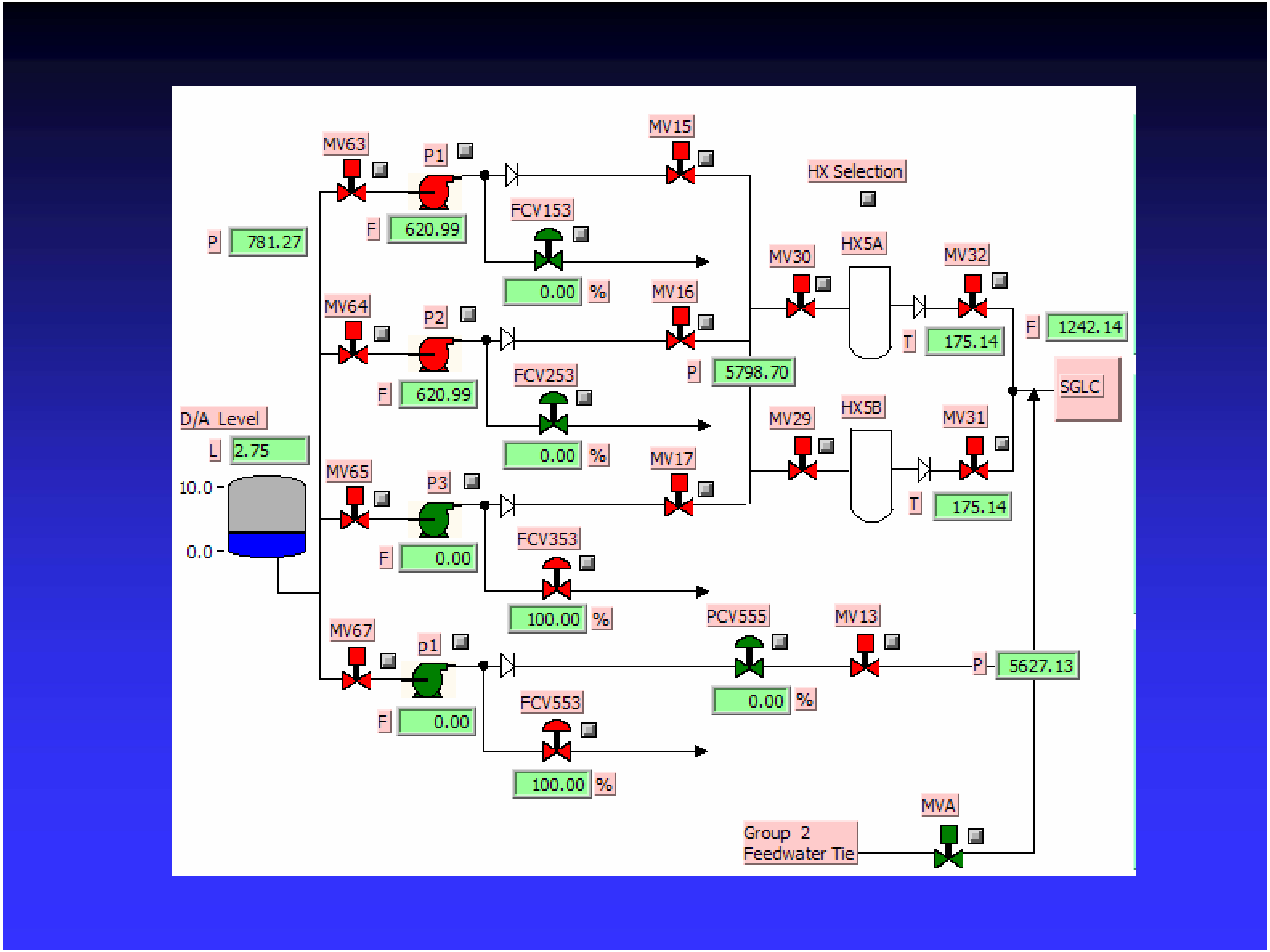
- Add more dynamic details - drum, downcomer, U-tubes heat transfer, riser etc.

Much More Detailed Model

- Depends on training needs or boiler design evaluation requirements etc.
- Multi-Nodal Thermalhydraulic Model

Multi-Nodal Thermalhydraulic Model

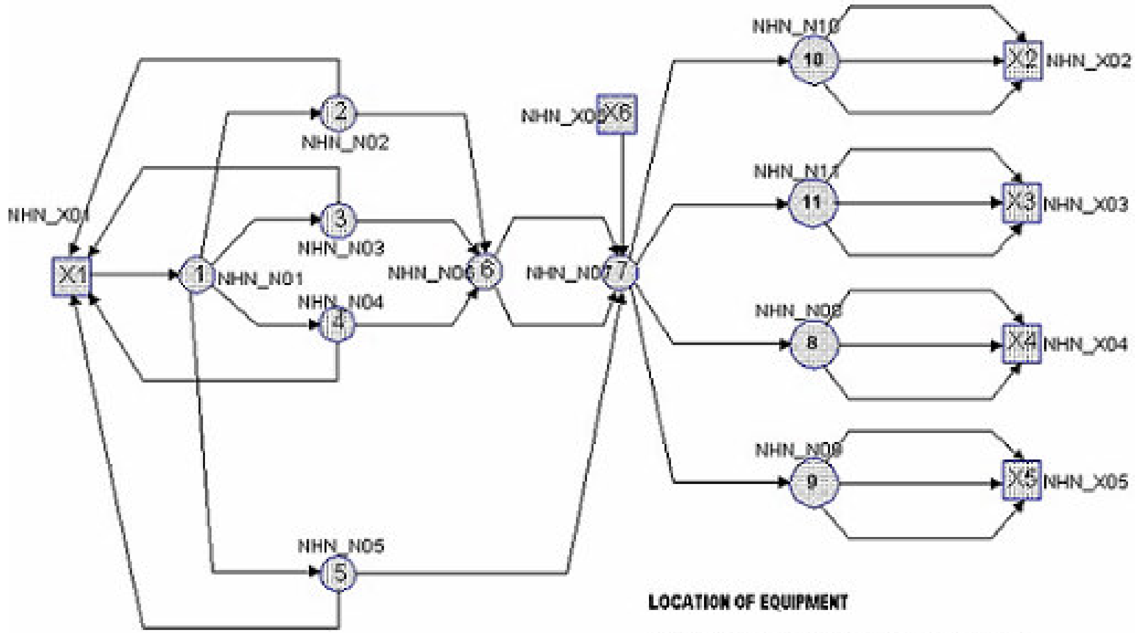




MV63
P1
MV15
HX Selection
P
781.27
F
620.99
FCV153
0.00
%
MV30
HX5A
MV32
MV16
MV64
P2
T
175.14
F
1242.14
P
5798.70
FCV253
SGLC
D/A Level
L
2.75
0.00
%
MV29
HX5B
MV31
MV65
MV17
P3
10.0
0.0
T
175.14
F
0.00
FCV353
100.00
%
PCV555
MV13
MV67
p1
P
5627.13
0.00
%
F
0.00
FCV553
100.00
%
MVA
Group 2
Feedwater Tie

Thermalhydraulic of Feedwater System

FEEDWATER SYSTEM HYDRAULIC FLOW NETWORK



INTERNAL NODE

EXTERNAL NODE

NODE DESCRIPTION

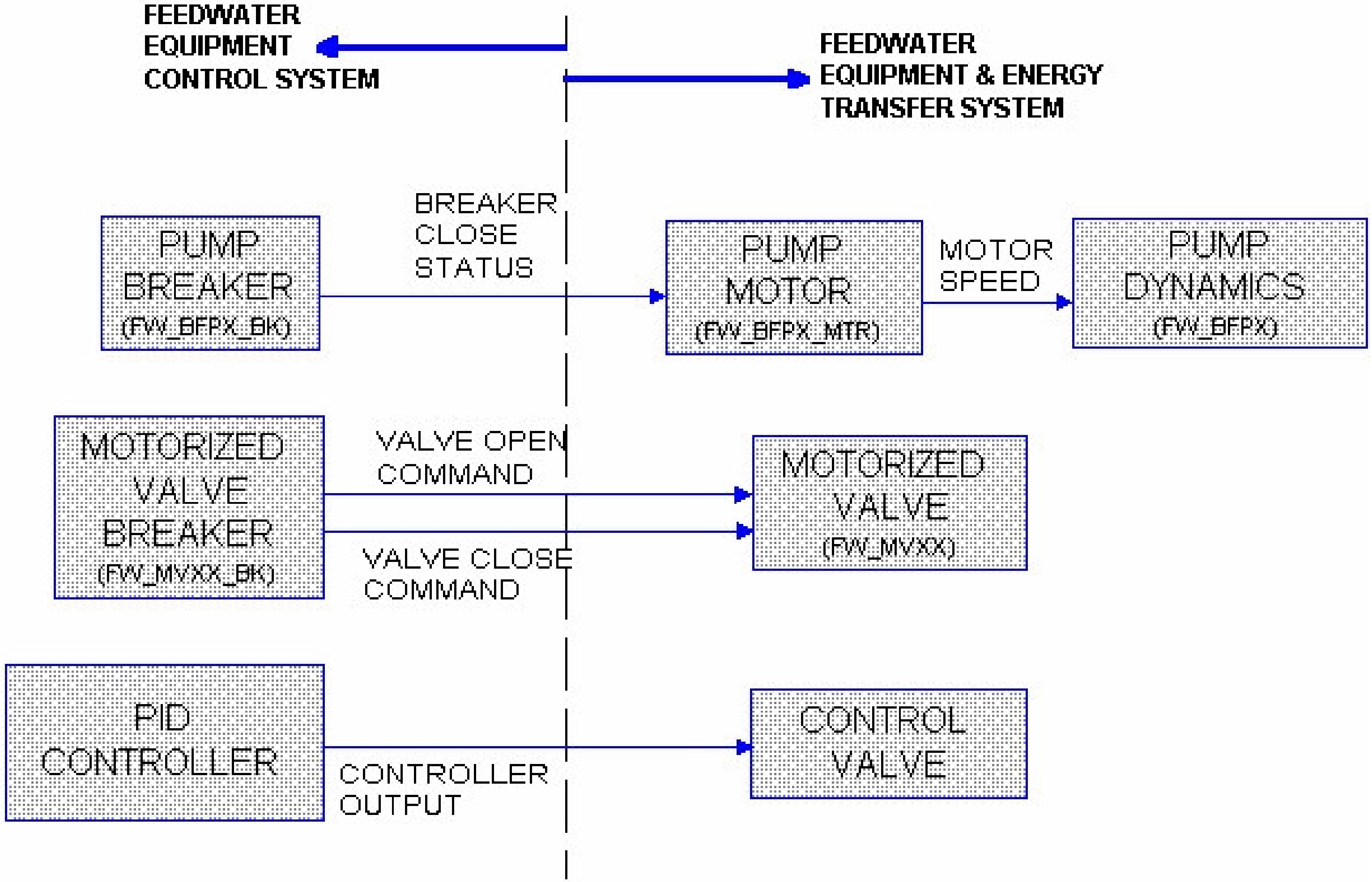
Internal nodes:
N01: Main BFPs suction header
N02: Main BFP #1 discharge
N03: Main BFP #2 discharge
N04: Main BFP #3 discharge
N05: Auxiliary BFP # 1 discharge
N06: Main BFPs discharge header
N07: Main & Aux BFPs common header
N08: Header before LCVs for BO #3
N09: Header before LCVs for BO #4
N10: Header before LCVs for BO #1
N11: Header before LCVs for BO #2

External nodes
X01: Deaerator
X02: Steam Generator Drum #1
X03: Steam Generator Drum #2
X04: Steam Generator Drum #3
X05: Steam Generator Drum #4
X06: Group 2 Feedwater Tie

LOCATION OF EQUIPMENT

NHNN01_N02: MV63, strainer #8, BFP #1
NHNN01_N03: MV64, strainer #9, BFP #2
NHNN01_N04: MV65, strainer #10, BFP #3
NHNN01_N05: MV67, strainer #12, ABFP #1
NHNN02_N06: MV15
NHNN03_N06: MV16
NHNN04_N06: MV17
NHNN02_X01: FCV153
NHNN03_X01: FCV253
NHNN04_X01: FCV353
NHNN06_N07_1: MV30, HX5A, NV34, MV32
NHNN06_N07_2: MV29, HX5B, NV33, MV31
NHNN05_N07: NV1, PCV555, MV13
NHNN05_X01: FCV553
NHNN10_X02_1: LCV101, MV45, NV57
NHNN10_X02_2: LCV102, MV49, NV57
NHNN10_X02_3: LCV103, MV53, NV57
NHNN11_X03_1: LCV201, MV51, NV59
NHNN11_X03_2: LCV202, MV47, NV59
NHNN11_X03_3: LCV203, MV55, NV59
NHNN08_X04_1: LCV301, MV46, NV58
NHNN08_X04_2: LCV302, MV50, NV58
NHNN08_X04_3: LCV303, MV54, NV58
NHNN09_X05_1: LCV401, MV48, NV60
NHNN09_X05_2: LCV402, MV52, NV60
NHNN09_X05_3: LCV403, MV56, NV60
NHNX06_N07: MVA

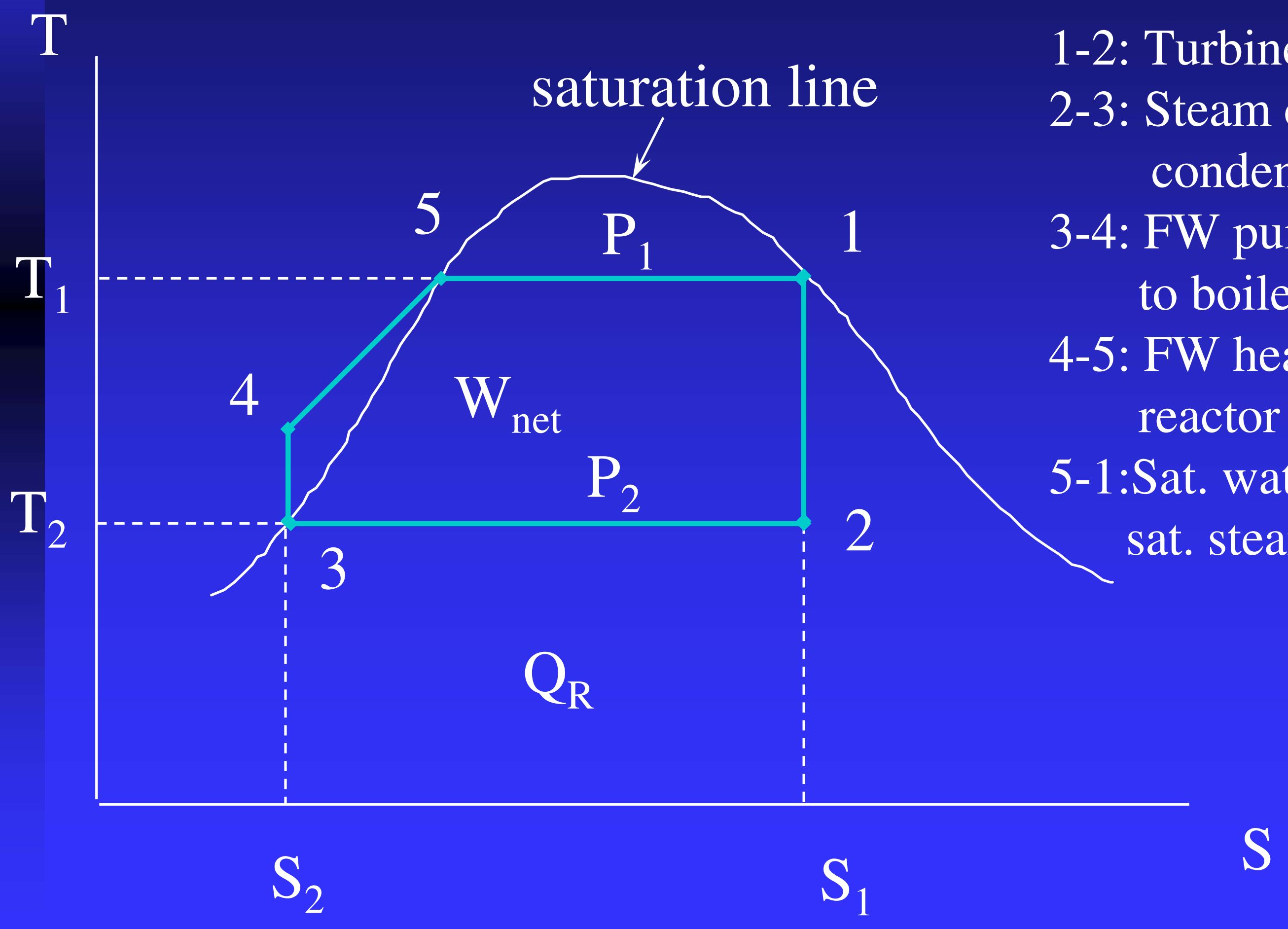
FEEDWATER EQUIPMENT CONNECTIONS



BOP Processes

- Main Steam Utilization: main steam piping; mass and energy distributions.
- Turbine Generator
- Condenser & Condensate Extraction
- Feedwater & Feedwater Heating
- Electrical Systems

Reactor Power Cycle - Rankine Cycle



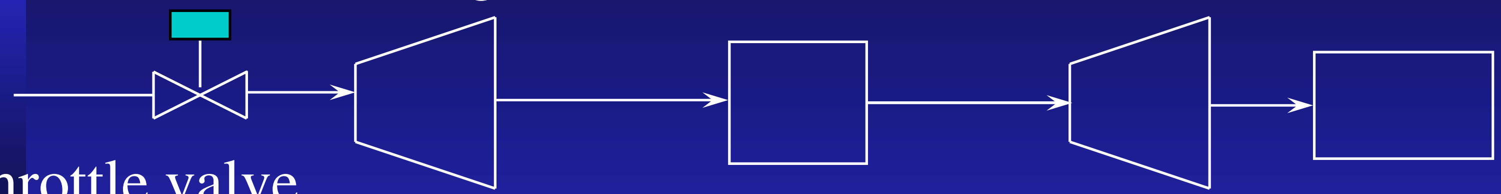
1-2: Turbine Expansion
2-3: Steam condensed in condenser
3-4: FW pump condensate to boiler
4-5: FW heated up by reactor thermal power
5-1:Sat. water vaporizes to sat. steam.

Reactor Power Cycle

- Turbine shaft work $W_T = H_1 - H_2$
- Pumping work $W_P = H_4 - H_3$
- Heat input $Q_{in} = H_1 - H_4$
- NPP Efficiency = Net Work Output/Energy In

$$\eta = \frac{W_T - W_P}{Q_{in}} = \frac{W_{NET}}{Q_{in}}$$

Turbine Generator



- Number of turbine stages for turbine expansion
- Steam expansion is a isentropic expansion:

$$P.V^{\gamma} = C \qquad where\ \gamma = \frac{C_p}{C_v}$$

- Stage efficiency does not change

Turbine Model

Assuming choked flow to HP Cylinder, the turbine steam flow through the throttle valve is :

$$W_s = k_{ttv} A_{ttv} \left(\frac{P_{ttv}}{\sqrt{T_{ttv}}}\right) \sqrt{1 - \left(\frac{\phi - \phi_{cr}}{1 - \phi_{cr}}\right)^2}$$

where $\phi = \frac{P_{1st}}{P_{ttv}}$ is the throttle valve pressure ratio

ϕ_{cr} = critical pressure ratio (superheat steam = 0.547)

P_{ttv} = Upstream pressure at turbine throttle valve

T_{ttv} = Upstream temperature at turbine throttle valve

k_{ttv} = turbine throttle valve flow coefficient

P_{1st} = turbine 1st stage pressure

A_{ttv} = cross-section float area of turbine throttle valve

Turbine Model (cont'd)

The relationship between the 1st stage temperature and throttle valve temperature is given by:

$$T_{1st} = T_{ttv} . \phi^{\frac{k-1}{k}}$$

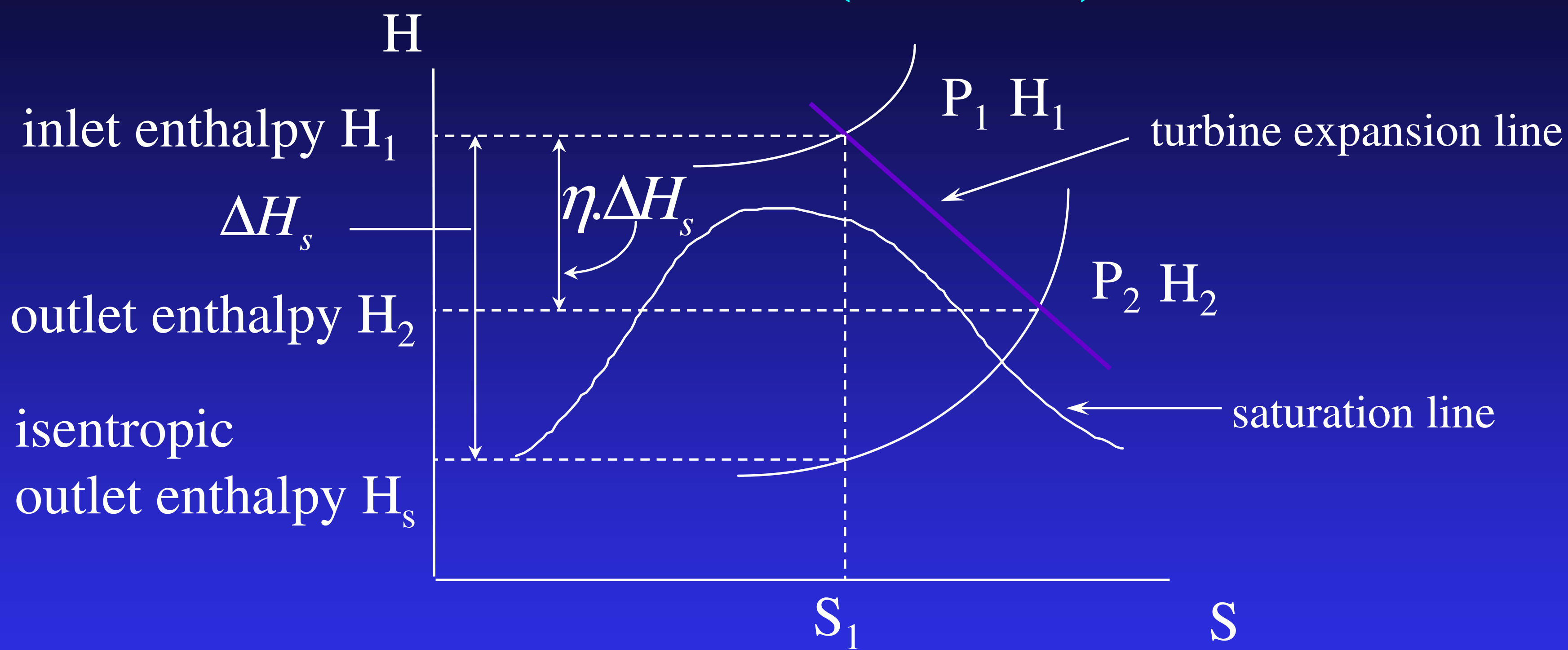
k = constant, 1.3 for superheated steam

The turbine expansion equation is used to determine the pressure stage relationship:

$$\frac{P_2}{P_1} = (1 - (\frac{W_s}{k_{1st}})^2)^{\frac{k}{1+k}}$$

k_{1st} = stage expansion coefficient

Turbine Model (cont'd)



Mollier Diagram for turbine expansion

$$H_2 = H_1 - \eta.\Delta H_s$$

$$H_2 = H_1 - \eta.(H_1 - H(P_2, S_1))$$

Turbine Model (cont'd)

Turbine mechanical power:

$$P_{TB} = W_s(H_1 - H_2)$$

Electrical Power:

$P_e = P_{TB}$ when TG connected to large grid

For grid island situation: $P_e = P_{eb}(1 + \alpha_{PF}\delta f)$

where P_{eb} = island load; δf = turbine frequency deviation

α_{PF} = power/frequency coefficient

Frequency swing equation: $$\frac{d(\delta f)}{dt} = -\frac{D_e}{2I}(\delta f) + \frac{f_s}{2I}(P_{TB} - P_e)$$

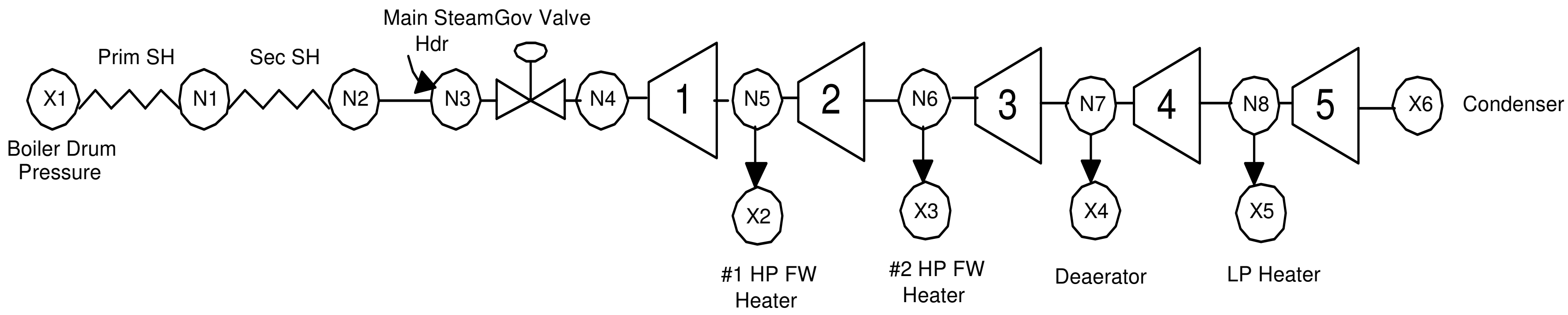
D_e = generator damping constant

I = turbine inertia constant

f_s = turbine synchronous frequency

Approach to Main Steam & Turbine Modeling

- Use Compressible Hydraulic Flow Network and Turbine Stages Algorithms



Main Steam
Hdr
Gov Valve
Prim SH
Sec SH
X1
N1
N2
N3
N4
1
N5
2
N6
3
N7
4
N8
5
X6
Condenser
Boiler Drum
Pressure
X2
X3
X4
X5
#1 HP FW
Heater
#2 HP FW
Heater
Deaerator
LP Heater

-

Thermalhydraulic network models used for Passive Cooling System – single phase & two phase

Explain the Passive Cooling Systems

- Go to the Passive PWR Simulator Manual P.59, Section 4.20

NPP Simulators for Education Workshop - Passive PWR Simulator Exercises

Wilson Lam (wilson@cti-simulation.com)

CTI Simulation International Corp.

www.cti-simulation.com

Sponsored by IAEA

PWR Simulator Exercise - Familiarization

- PWR Simulator Manual.
- Practice PWR Simulator Startup, Initialization.
- Review PWR screens. Note the “hot” buttons on the screens, which bring up control pop-ups for user’s interactions.

PWR Simulator Manual Exercise 3.1 - Power Maneuver, Reactor Lead

- POWER MANEUVER - Reactor Lead: 10% Power Reduction & Return to Full Power. Follow steps in Manual.
- Record Parameters in the table during this maneuver.
- Explain how reactor power is controlled during this maneuver. Can you explain why the differences in parameter values e.g. Boron concentration ?

PWR Simulator Manual Exercise 3.2 - Power Maneuver, Turbine Lead

- POWER MANEUVER - Turbine Lead: 10% Power Reduction & Return to Full Power. Follow steps in Manual.
- Record Parameters in the table during this maneuver.

Discussion for Exercises 3.2

- Why main steam header pressure rises first, then drops back to the steam pressure setpoint ?
- Why steam generator's level drops initially and then recovers ?
- Discuss the 3rd question re: "reactor-lead" versus " turbine-lead" modes

PWR Manual
Exercise 3.4 - Turbine Trip

- Practice Turbine Trip & Recovery (p.34)
- Record Boiler Pressure and Generator Output during the Turbine Trip transient.
- Try to answer the questions in the Manual.

Discussion on Turbine Trip & Recovery

- What is the reactor power when turbine speed settles at 5 RPM ?
- What is the steam flow through the bypass valve ?
- How much gray rods have moved ? How much dark rods have moved ? Any flux tilt ?
- What is the Xenon conc. before and after turbine trip ?
- What happens to the steam bypass valve as turbine re-sync and power is increased ?

PWR Response to Boiler Pressure Changes

- Repeat Lecture Demo - PWR responses with SG pressure setpoint changes with Reactivity controls in Manual.
- Put all reactivity control devices in Manual - PWR Control Rods & SD Rods Screen: Boron, Grods; Drods.
- In MW Demand SP & SGPC Screen, change SG pressure SP to "Increase"; change Target to 5.3 Mpa, at 1 Mpa/minute.
- Explain why reactor power increases.

Exercise 3.5 - Reactor Scram & Recovery

- Note the reactor reactivity after reactor scram.
- Note the reactor reactivity after shutdown rods are withdrawn. Discuss reactor state.
- Follow steps in Manual

Malfunction Exercises

PWR Malfunctions: Exercises 4.1 Fail closed all FW LCV's

- Explain process systems responses.
- Boiler Drum Level ? Loss of boiler Inventory - impact of loss of boiler heat sink to primary coolant ?
- Safety protection action ?
- Coolant pressure transient ?
- Boiler pressure transient ?
- Turbine power response ?

Exercise 4.6 - Turbine Throttle PT Fails Low

- Explain process systems responses.
- Turbine Power response ?
- Boiler pressure response ?
- Observe “cold” leg temp. Why the cold leg temperatures go up in this transient ?

Exercise 4.7- All Atmospheric SRV's fail Open

- Explain process systems responses.
- Malfunction will cause immediate depressurization of the steam generators.
- Turbine Power response ?
- Observe cold leg temperatures - why decreasing ?
- Why there is a reactor power step reduction on high reactor flux ?

Exercise 4.8 - Turbine Bypass Valve fails closed

- Trip turbine. Explain process systems responses.
- Boiler pressure response ?
- Safety protection actions ?
- Explain coolant temperature transients.

Exercise 4.13 - PRZR pressure relief valve fails open

- Explain process systems responses.
- Impact on coolant pressure ?
- What devices in the pressurizer will be activated ?
- Impact on pressurizer level ?
- Safety trip actions ?

Exercise 4.14 - One bank of Dark Rods drops

- Explain process systems responses.
- Large reduction of reactor power.
- Observe flux tilt. Explain the actions of the Gray rods, and the remaining Dark rods.
- Explain why reactor power slowly decreases to zero ?

Exercise 4.15 - All Dark Rods "stuck" to Manual

- Explain process systems responses.
- Make a power change to 70 % at 0.5 % per sec.
- Observe flux tilt.

Exercise 4.17 - Loss of one RC Pump

- Explain process systems responses.
- Observe coolant flow, pressure and temperature transients.
- Repeat with *second* malfunction “reactor setback and stepback both failed”.
- Explain the differences in responses.
- Discuss how control and safety systems can cope with these challenges.

Exercise 4.19 - 100 % main steam line break

- Explain process systems responses.
- Observe turbine power response.
- Discuss how the safety and control systems can cope with this malfunction.

Exercise 4.20 - RC Cold Leg #4 LOCA Break

- Explain process systems responses.
- Observe the sequence of events and injection paths shown on PWR Passive Core Cooling Screen.
- Explain the RC pressure “bumps”- when do they occur ?
- Explain why the accumulator is necessary ?
- Explain why RC depressurization is necessary ?