AREVA NP

Joint ICTP IAEA Training course on Physics and Technology of Water Cooled Reactors through the Use of PC-based Simulators

BWR Technology and Advanced BWR Simulator

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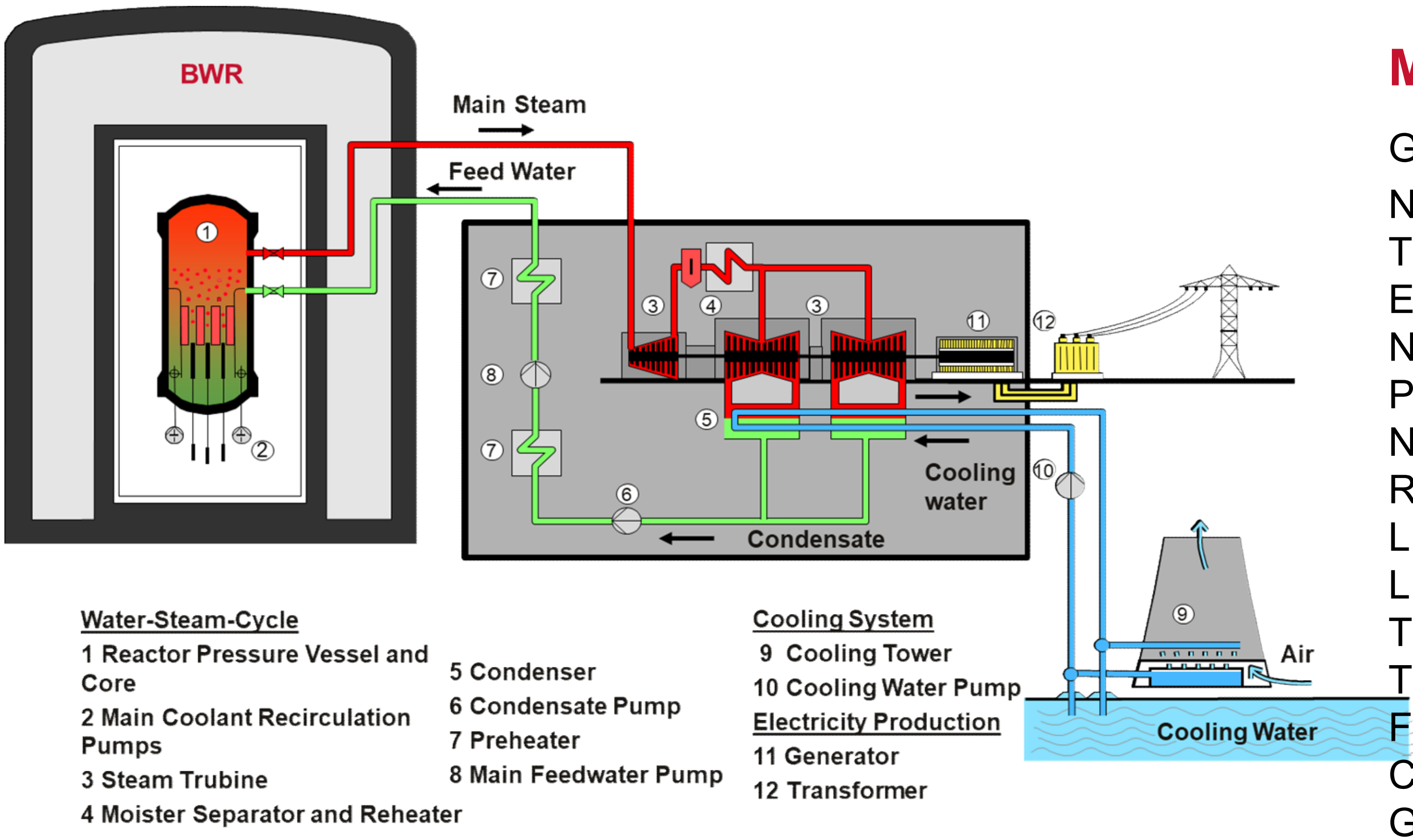
- **Advanced BWR Simulator Fundamentals**
- **Exercises Parts 1 (Normal operation)**
  - Normal Operation and Load Variations
  - Shut down cooling
- **Exercises Part 2 (Transients)**
  - Inadvertent Reactor Isolation
  - Steam Line Break Inside Drywell

Learning Objectives

- **Understand of the functionality of a BWR and its main Features/Components**
  - Steam and Feed water flow paths
  - Type of Coolant Recirculation
  - Active/Passive Safety Related Systems
- **Describe the main differences between conventional and advanced BWRs**
- **Understand and describe the main differences of a BWR and DWR**
- **Demonstrate the use of the simulator**
- **Perform a few exercises related to normal operations and transients in order to improve the understanding of the reactor operation and behavior.**

► Principal Plant Arrangement and main parts of a BWR Plant

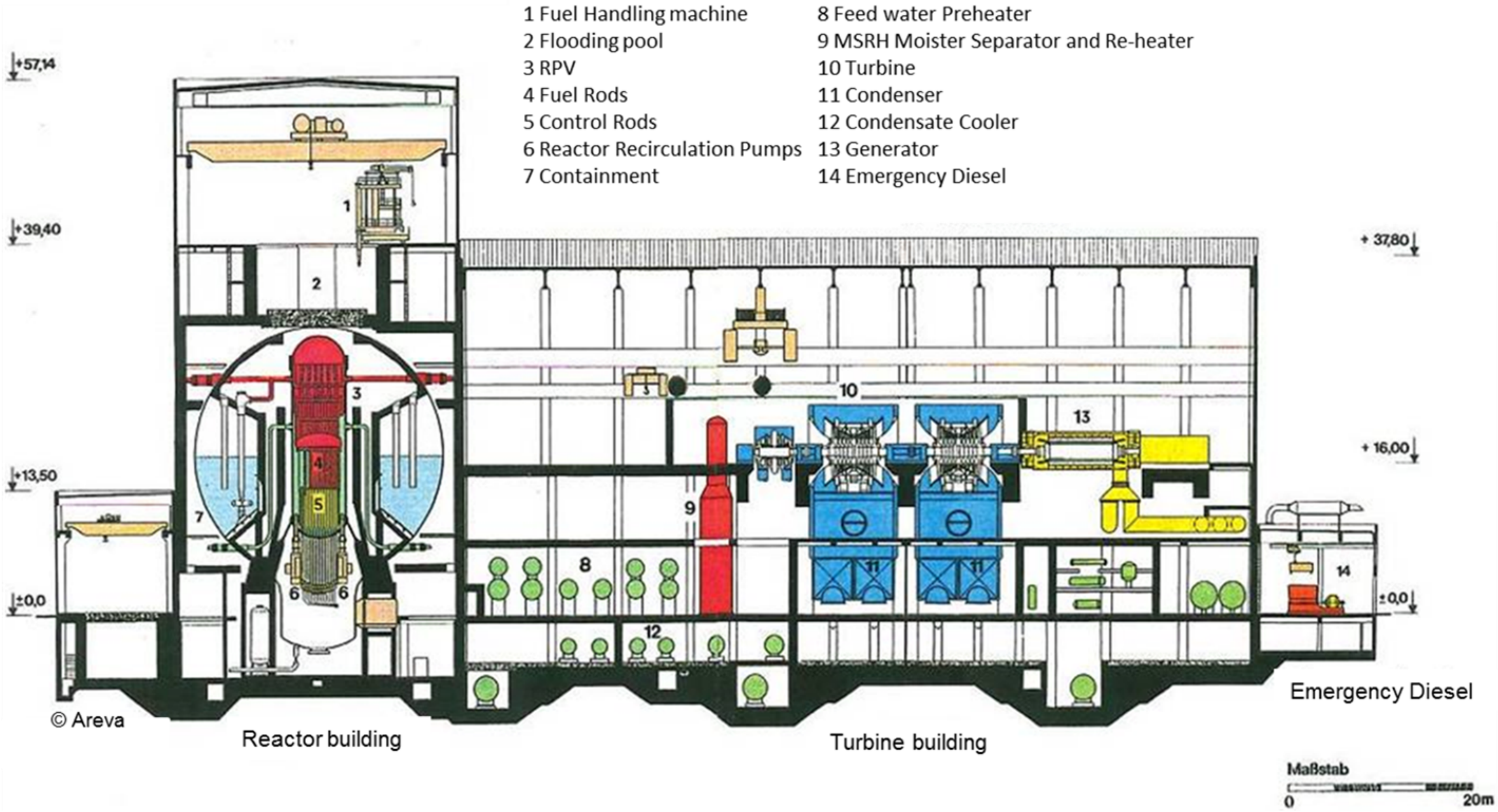


Main Data Conventional BWR

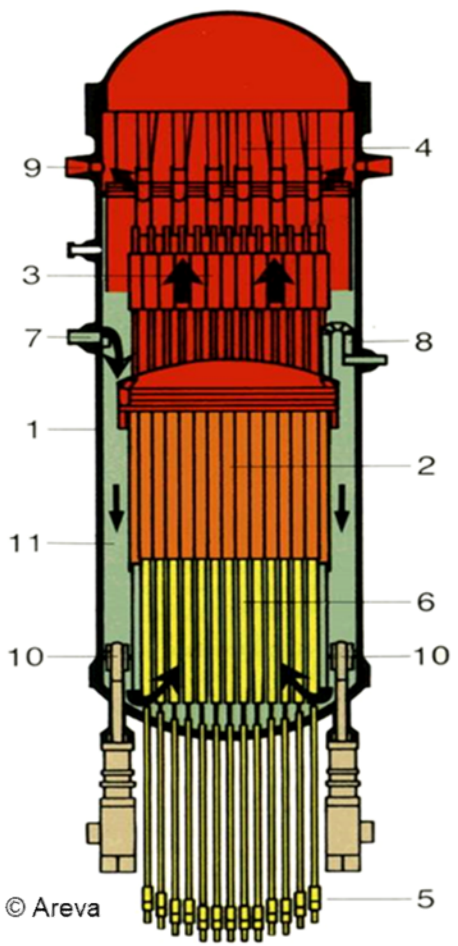
Gross Power	723 MWe
Net Power	692 MWe
Thermal Power	2100 MWt
Efficiency	33 %
No. Fuel Elements	484 (10x10)
Power density	50,3 kW/l
No. MCP	6
Reactor coolant flow	29200 t/h
Live Steam Pressure	71,6 bar
Live Steam Flow	4082 t/h
Turbine	1HP / 3 LP
Turbine Speed	3000 U/min
Feed Water Temp.	215 °C
Condenser Pressure	0,064 bar
Generator Power	880 MVA

Introduction in BWR and Advanced BWR Design and Technology

► Principal Plant Arrangement and main parts of a BWR Plant



► Reactor Pressure Vessel of a conventional BWR



Reactor Pressure Vessel and Internals

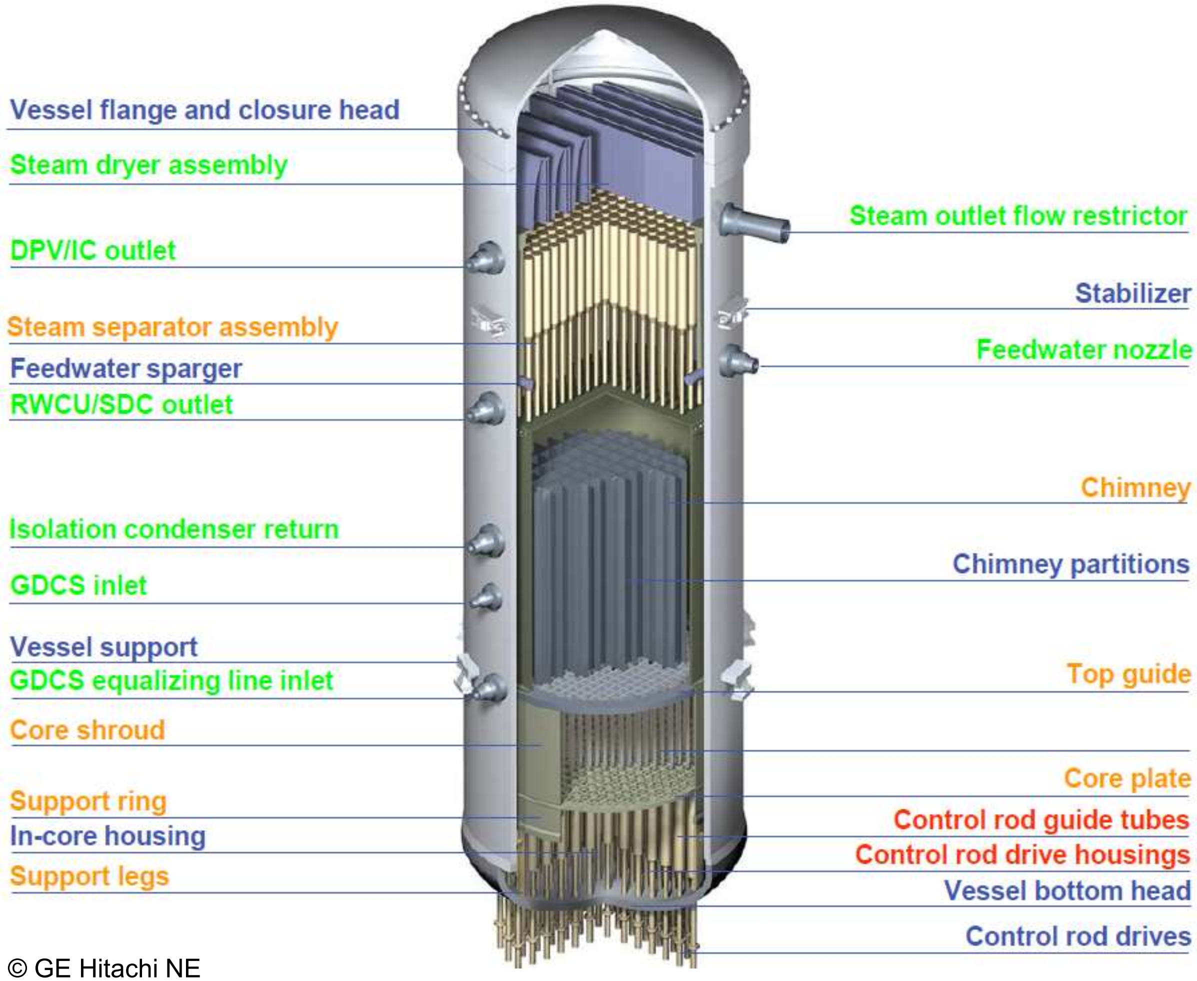
1	Reactor Pressure Vessel
2	Core
3	Steam water separator
4	Steam dryer
5	Control rod drives
6	Control rods
7	Feed water nozzle
8	Core spray line
9	Main steam nozzle
10	Main Recirculation pumps
11	Down comer

Reactor Pressure Vessel Data:

Design Pressure	88 bara
Operating Pressure	70,6 bara
Design Temperature	300 °C
Operating Temperature	286°C
Inner Diameter	5400 mm
Height	20351mm
Wall Thickness	137 mm
Weight	ca. 500 t

Introduction in BWR and Advanced BWR Design and Technology

► Reactor Pressure Vessel of an advanced BWR



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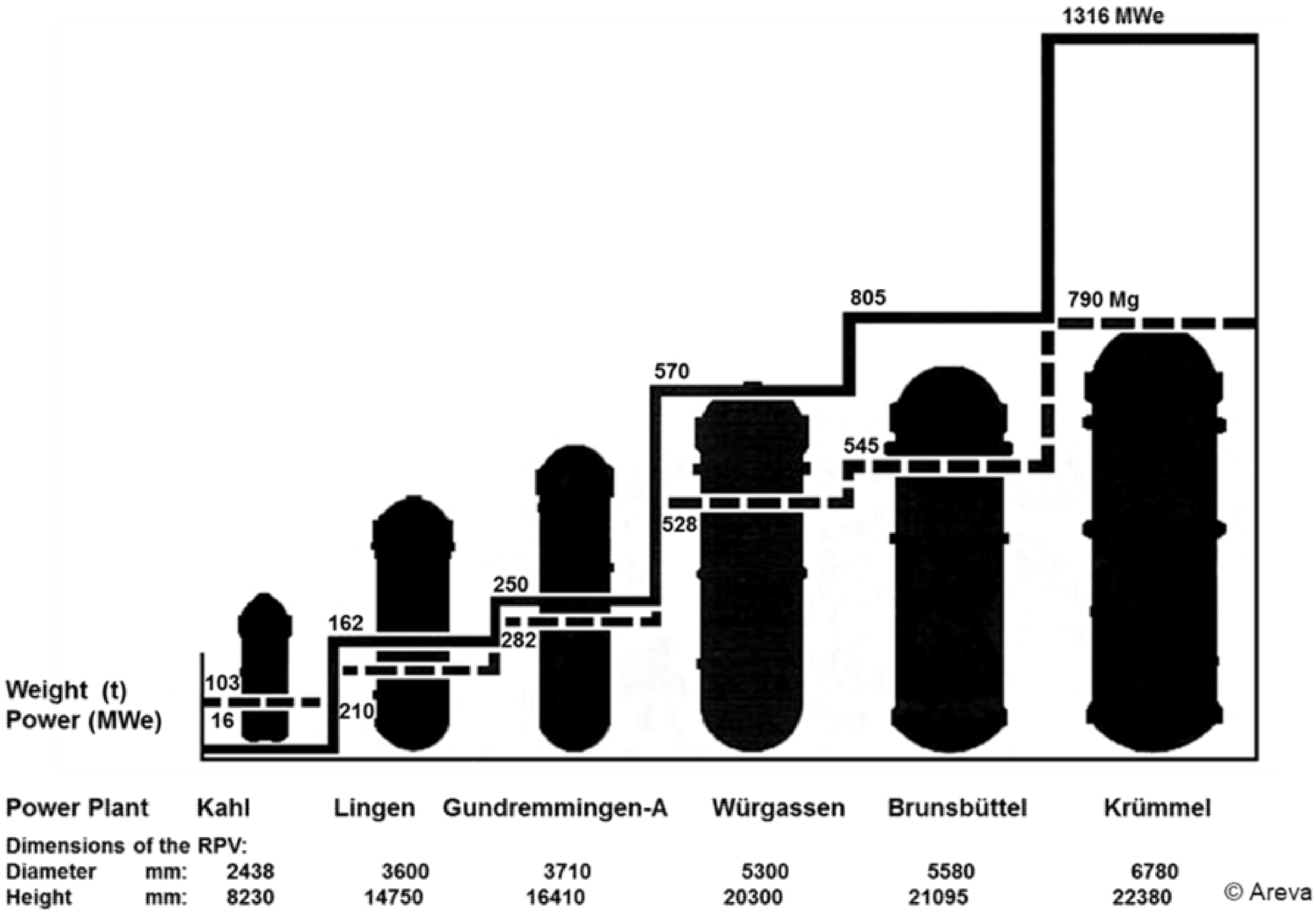
Reactor Pressure Vessel Data:

Thermal Power	4500MWth
Net Electrical Power	1520MWel
Natural Circulation	
Design Pressure	87,2 bara
Operating Pressure	72,7 bara
Inner Diameter	7100 mm
Height	27600 mm

► Evolution of RPV size and weight



► Evolution of BWR nuclear steam supply system

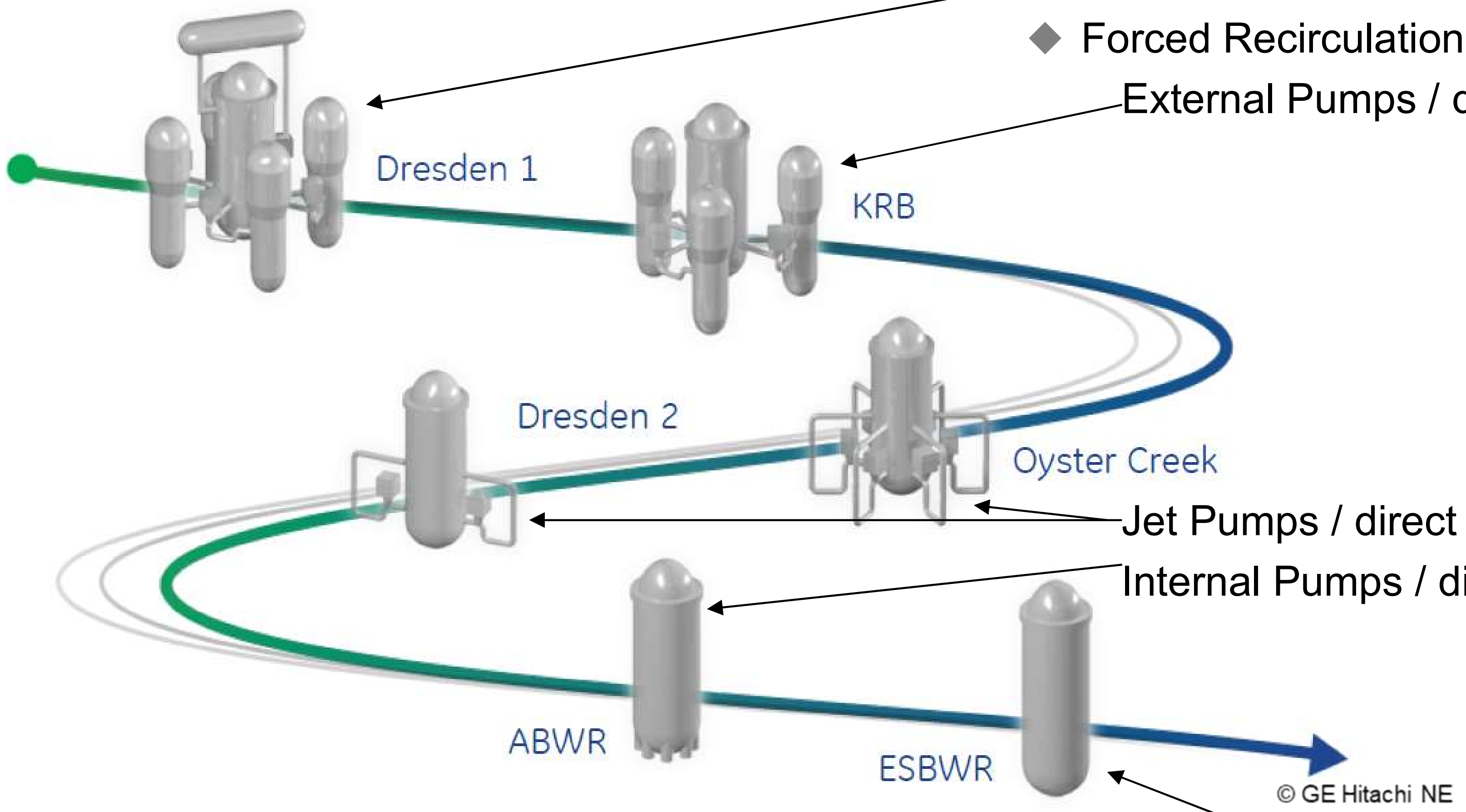
◆ Natural Circulation / Two circuits

◆ Forced Recirculation Flow:

External Pumps / direct Circuit

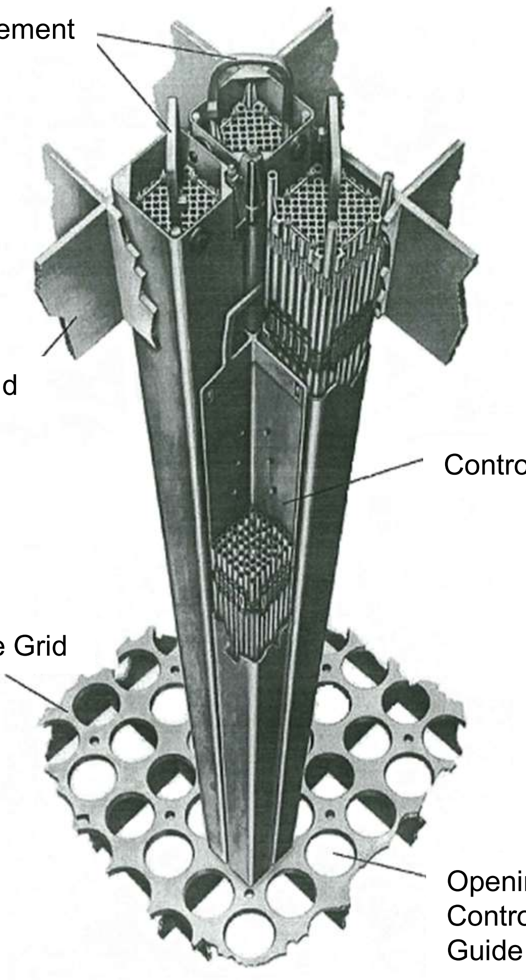
Jet Pumps / direct Circuit

Internal Pumps / direct Circuit



◆ Natural Circulation / direct circuit

► Design and Arrangement of Fuel Elements and Control Rods in a BWR



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Core Design conventional BWR:

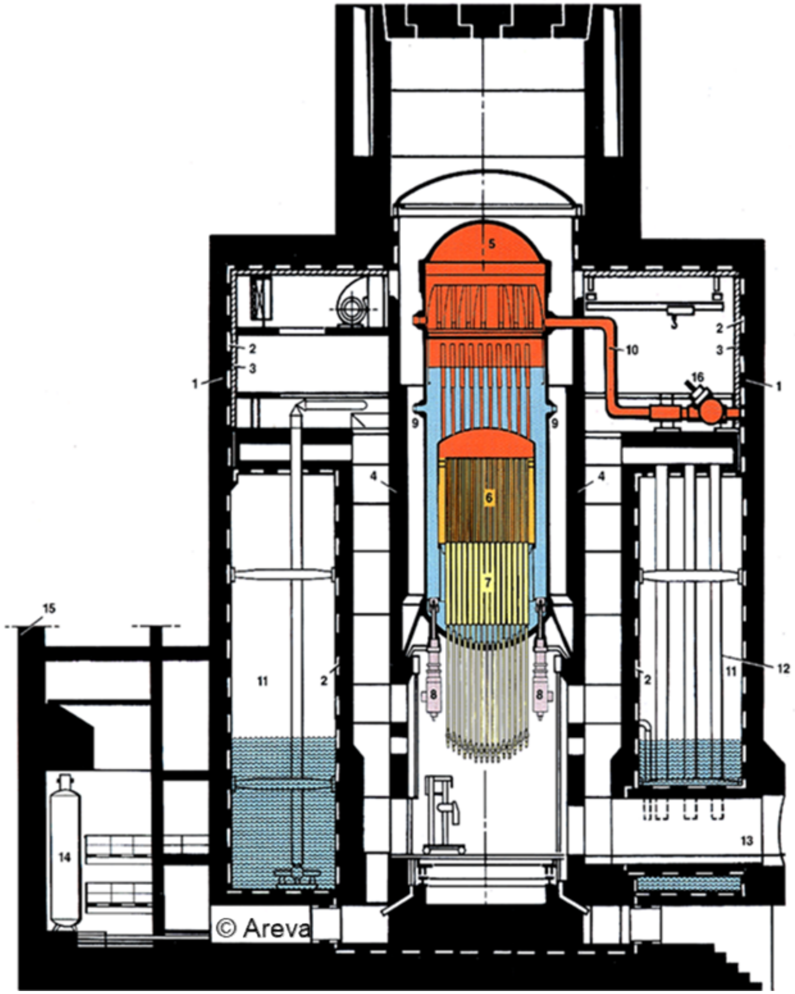
No. Fuel Elements	484
No. Control Rods	113

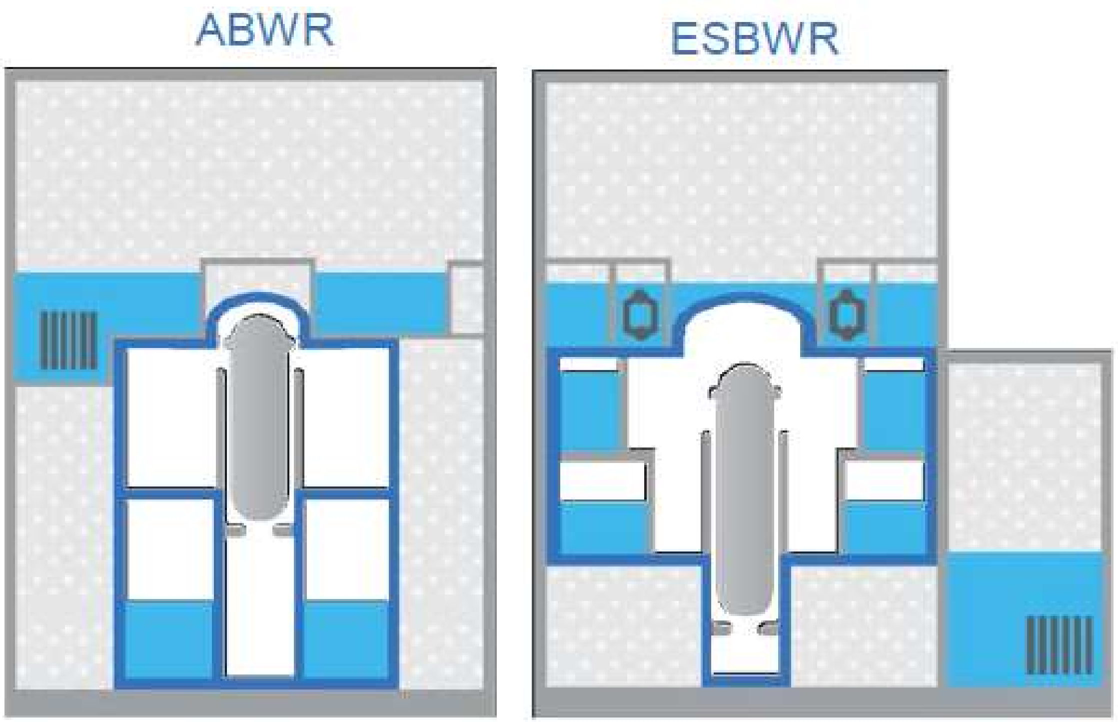
Core Design advanced BWR:

No. Fuel Elements	1132
No. Control Rods	269

► **Principal Containment Design of conventional and advanced BWR**

KWU Mark 72 (Baulinie 72)





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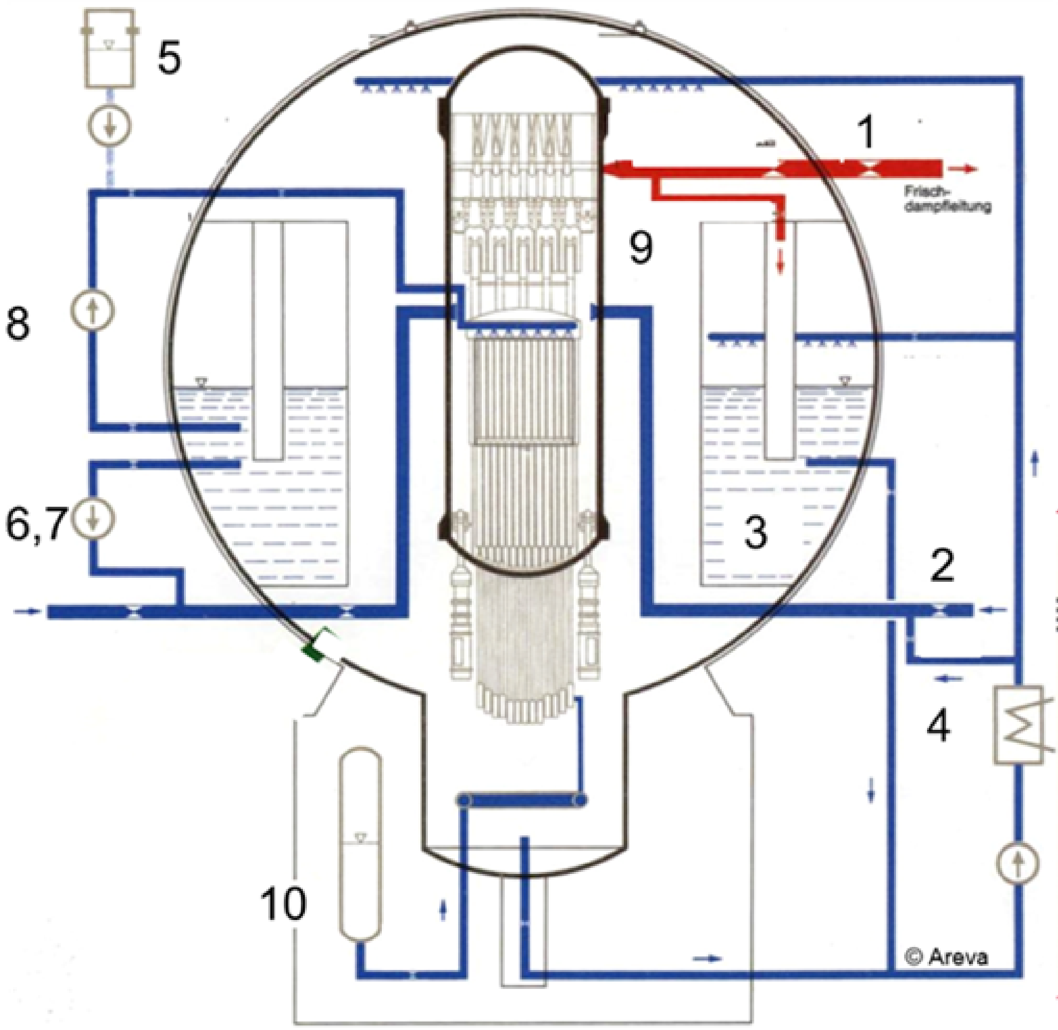
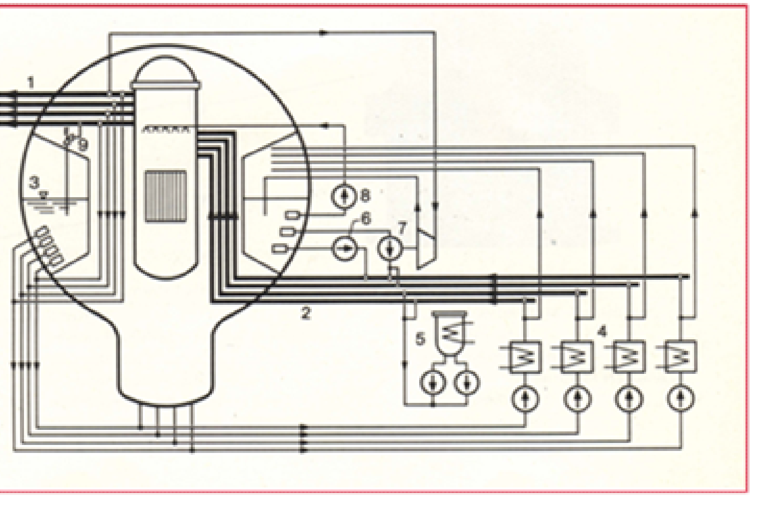
► Containment Design and main Safety Systems of a conventional BWR



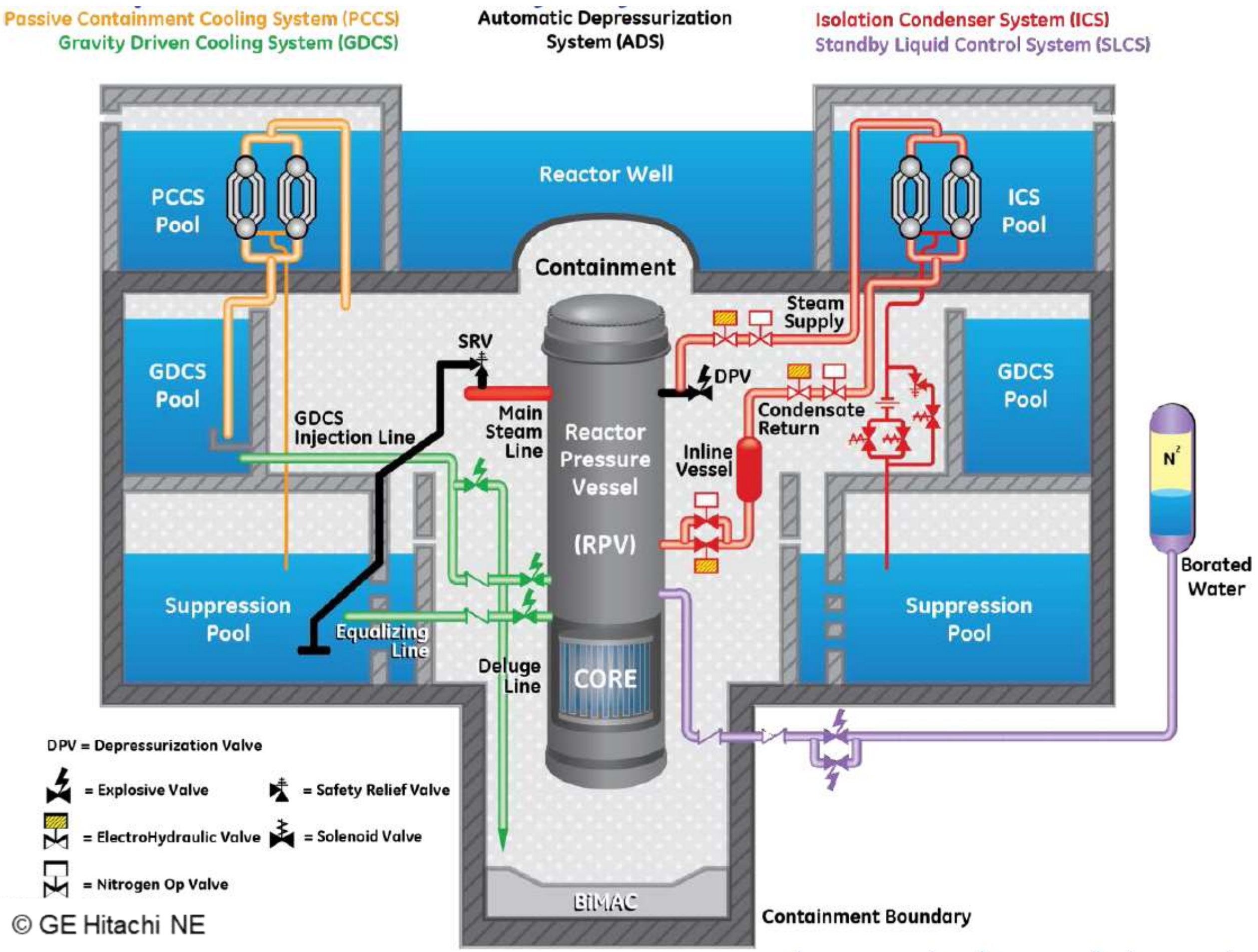
1. Main Steam Line isolation valves
2. Main Feed Water Isolation Valves
3. Pressure suppression pool
4. Residual Heat Removal System
5. Boron Injection System
6. Auxiliary feed water system
7. High Pressure Injection System
8. Core Spray System
9. Pressure Relief system
10. SCRAM system



► Summary Main Safety Features of an conventional BWR

- The SCRAM system (reactivity control, 10)
  - control rods
  - hydraulic actuation system (fast, SCRAM)
  - electrical actuator (shut down, control)
- High Pressure safety injection system (core cooling, 7)
  - Ensures the core cooling and water content in the RPV at high pressure
- Low Pressure safety injection system (core cooling, 8)
  - Ensures core cooling at low reactor pressure and water content in the RPV at low pressure
- Pressure Relief System (core cooling, activity confinement, 9)
  - Pressure limitation and RCPB de-pressurization (ADS) in order to enable low pressure injection

► Containment Design and main Safety Systems of an advanced BWR



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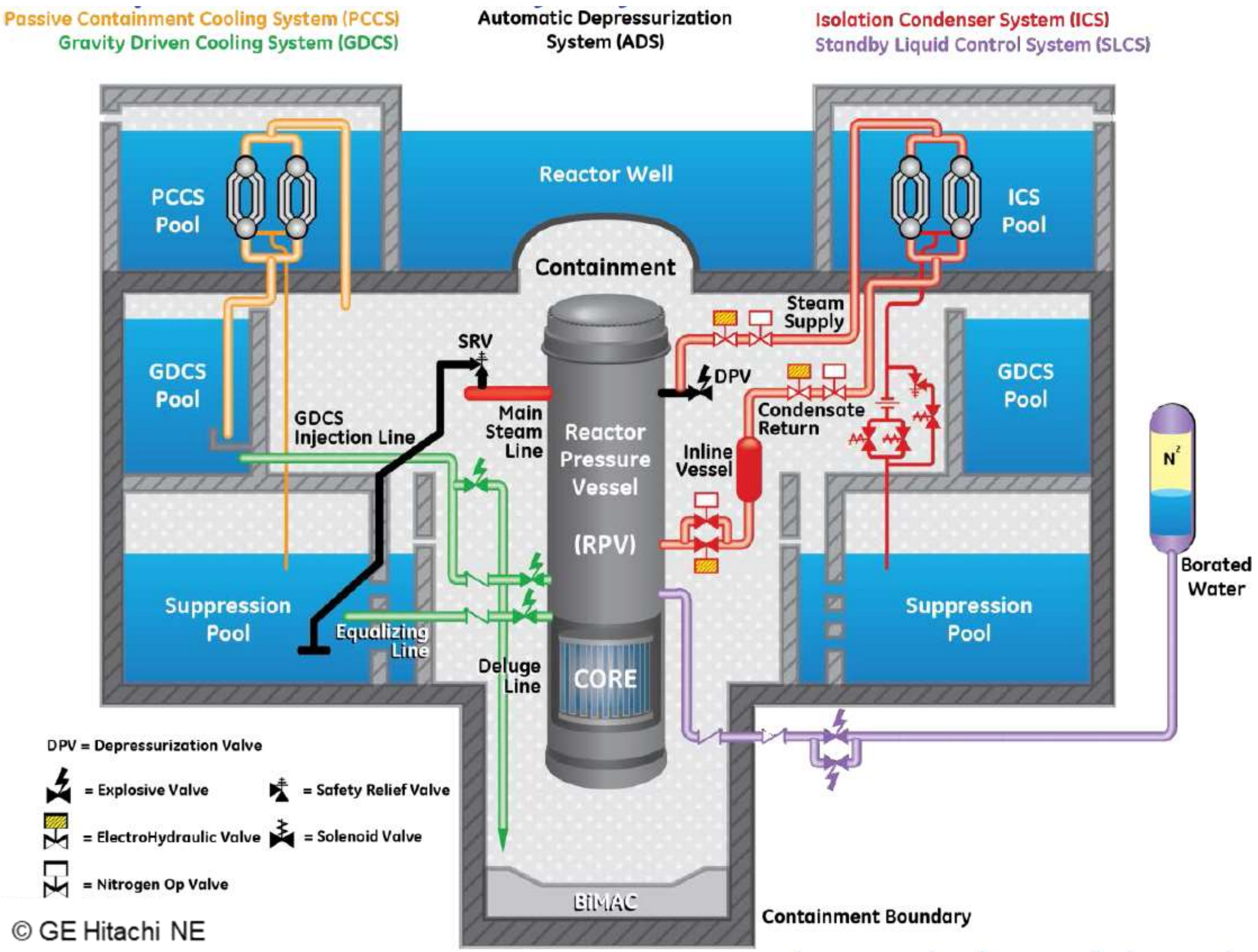
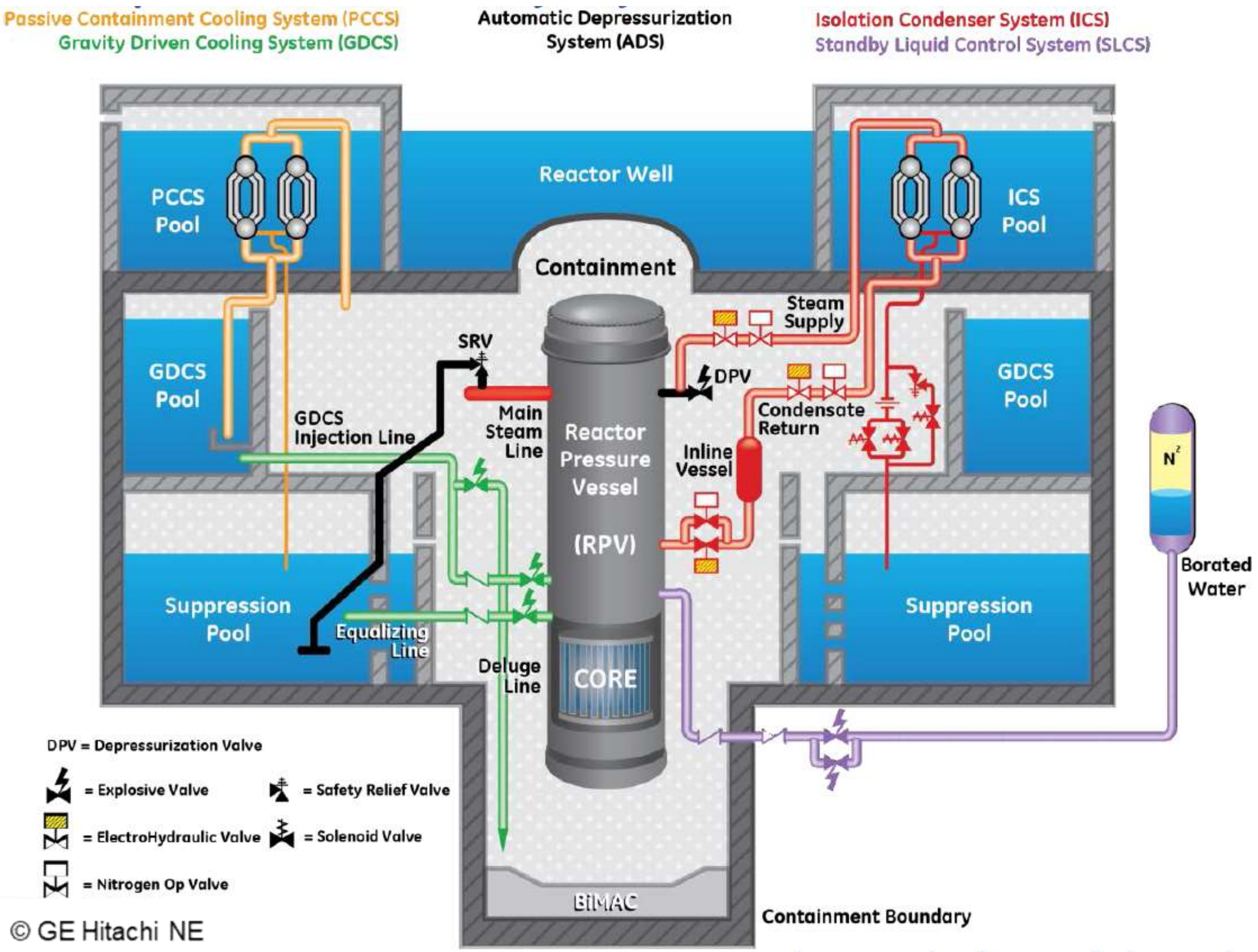
- **Gravity-Driven Cooling System (GDCS)**
- The GDCS provides flow to the annulus region of RPV
- gravity-driven from three separate water pools located within the drywell at an elevation above the active core region.
- flow from the suppression pool to meet long-term post-LOCA core cooling requirements.
- by gravity forces alone once the reactor pressure is reduced to near containment pressure.

► Containment Design and main Safety Systems of an advanced BWR



- **Automatic Depressurization System (ADS)**
- The ADS provides reactor depressurization capability in the event of a pipe break.
- 18 Safety Relief Valves (SRVs)
- 8 Depressurization Valves (DPVs)

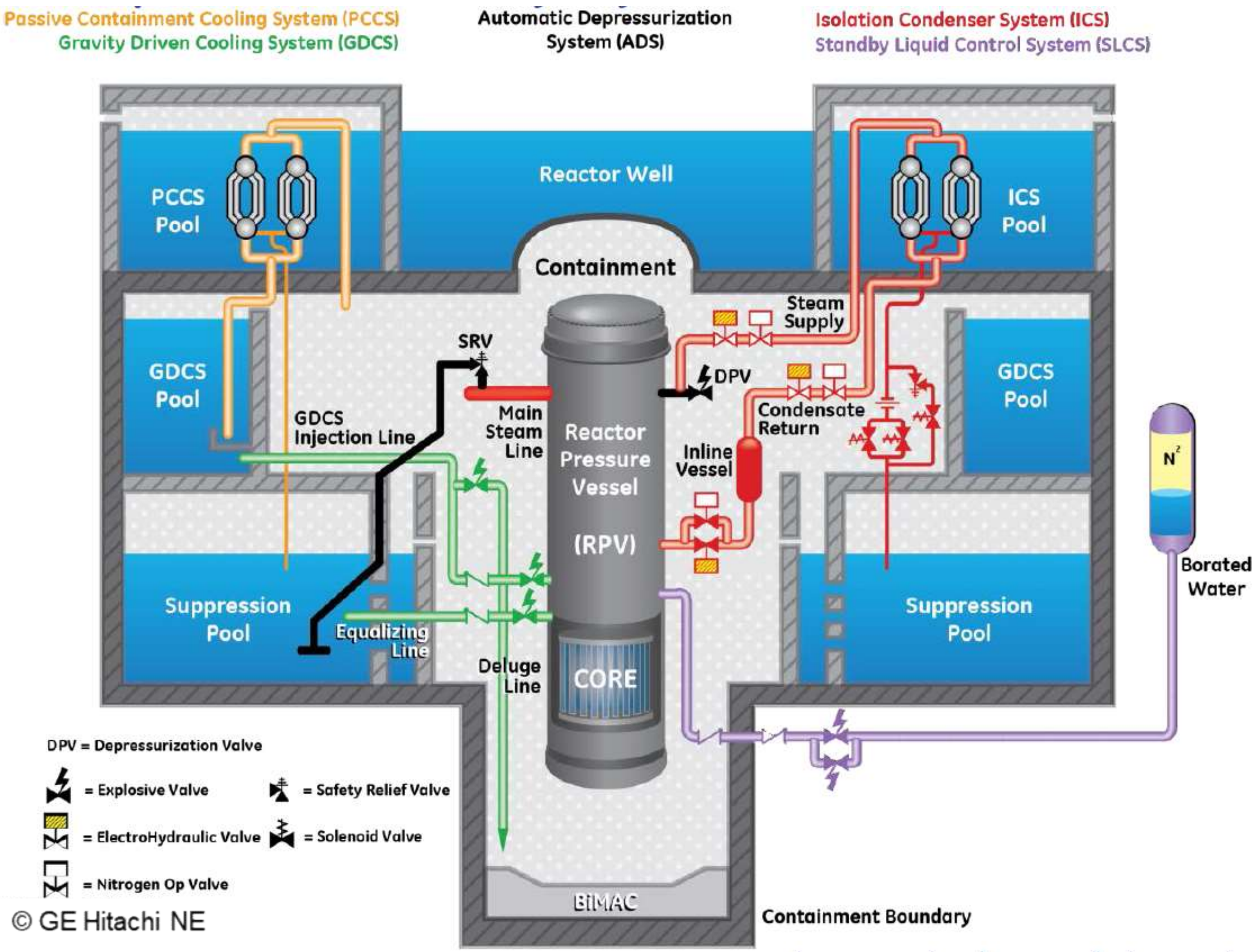
► Containment Design and main Safety Systems of an advanced BWR



- **Isolation Condenser System (ICS)**
- The ICS provides additional liquid inventory upon opening of the condensate return valves to initiate the system (High Pressure Injection)
- The IC system also provides initial depressurization of the reactor before ADS

Introduction in BWR and Advanced BWR Design and Technology

► Containment Design and main Safety Systems of an advanced BWR



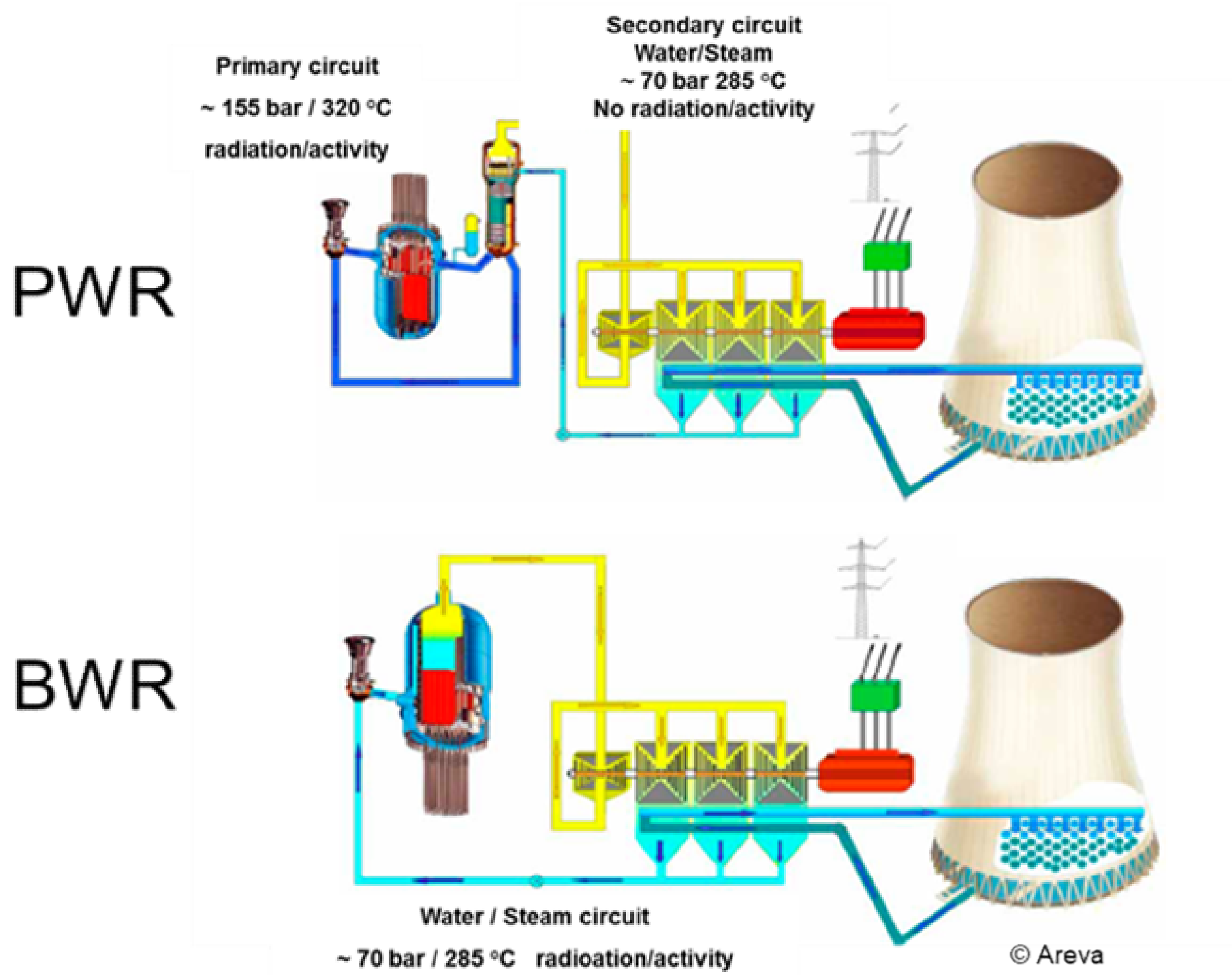
- **Standby Liquid Control System (SLCS)**
- The SLC system provides reactor additional liquid inventory in the event of DPV actuation.
- accomplished by firing squib type injection valves
- Borated Water

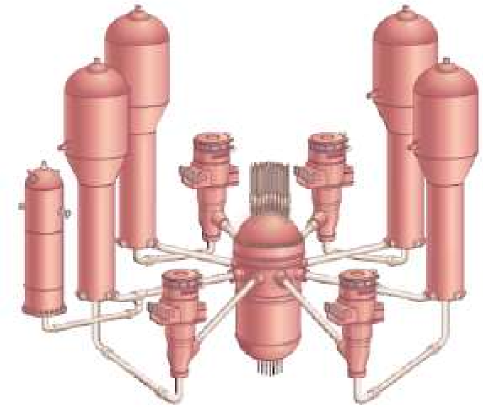
► Summary Main Safety Features of an advanced BWR

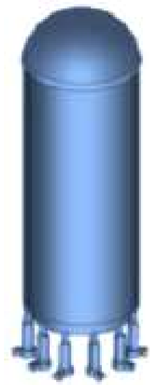
- The ECCS systems ADS and GDCS are designed to cool the reactor core following a LOCA
- The ECCS system SLCS is designed to be used during an ATWS (Anticipated Transient Without Scram),
- The ECCS system ICS is designed to avoid unnecessary use of other Engineered Safety Functions (ESFs) for residual heat removal
- Both SLCS and ICS provide additional liquid inventory upon actuation.

Introduction in BWR and Advanced BWR Design and Technology

► Main Design differences of BWR and PWR







► Main Design differences of BWR and PWR

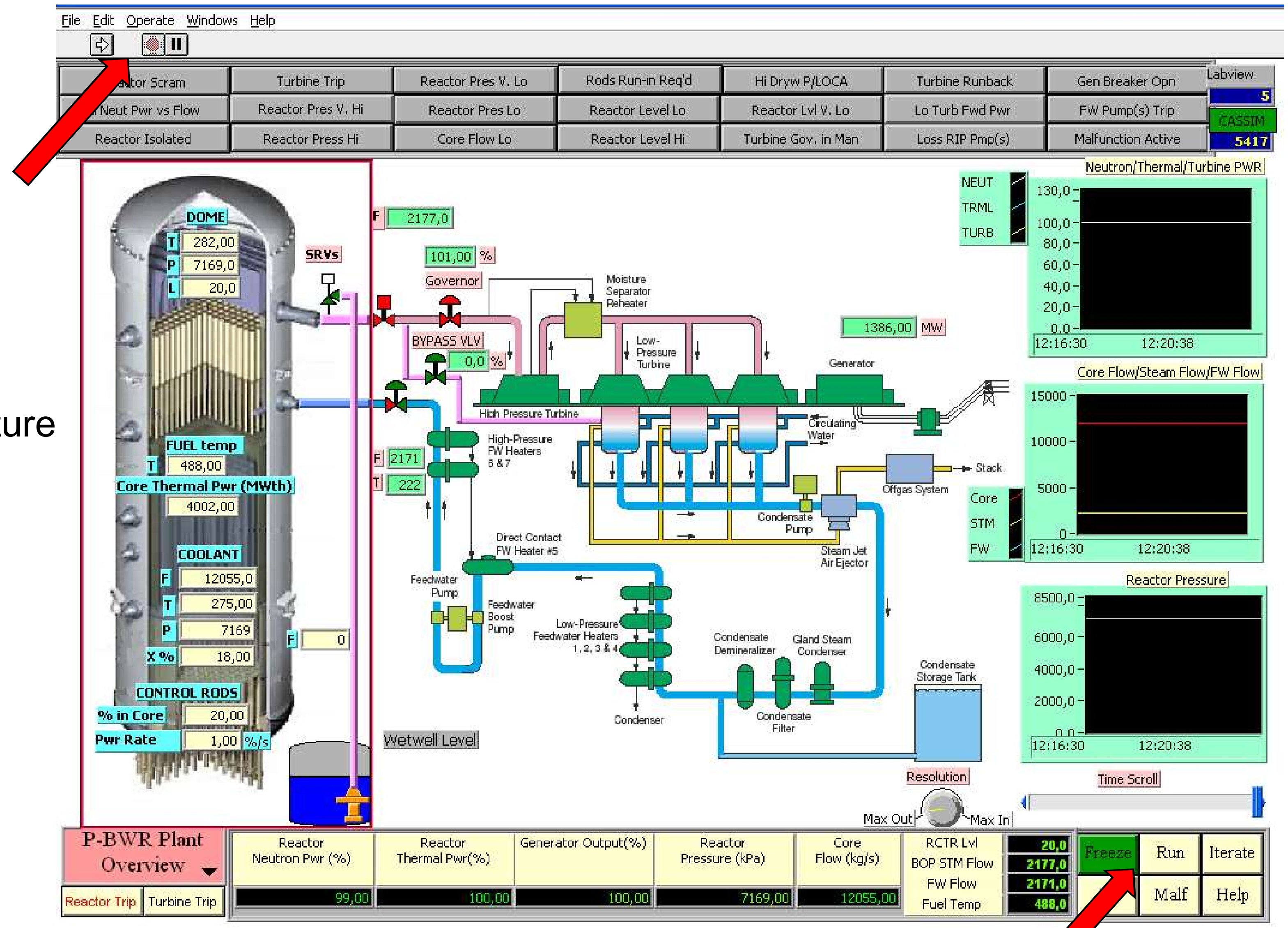
PWR		**BWR**	
Two circuits	primary / secondary circuit	One circuit	direct cycle
Turbine island	non controlled area	Turbine Island	is controlled area
Coolant pumps	1 pump per Loop, constant speed	Coolant pumps	6-10 pumps inside RPV, variable speed
Control rods	Guided inside the fuel elements	Control rods:	Guided between the fuel elements
SCRAM	From above the core by gravity	SCRAM	underneath the core; hydraulic pressure
Actuator	Magnets, Gravity	Actuator	motor driven, hydraulic pressure
Power control		Power control	
Fast	Control rods	Fast	internal recirculation pumps
Slow/long term	Boric acid in the coolant	Slow/long term	Control rods, NO boric acid
RPV		RPV	
Height	~12 m	Height	~20 m
Operation pressure	~157 bar	Operation pressure	~70 bar

- **Display Features:**
- Color Code:
  - GREEN: Valve closed, pump stopped, heater off.
  - RED: Valve open, pump started, heater on.
- Units:
  - Temperature: ºC
  - Pressure: kPa
  - Flow: kg/s
  - Level: m
  - Reactivity: mk
- Pop-up controls:
  - Click on **Return** to continue.

Simulator Fundamentals

- ► **Stop / Run**
- ► **Freeze / Run**

- ► **Default Trend**
  - ◆ Screen-Specific
  - ◆ Modify Bands
  - ◆ Time Scroll Feature
  - ◆ Resolution



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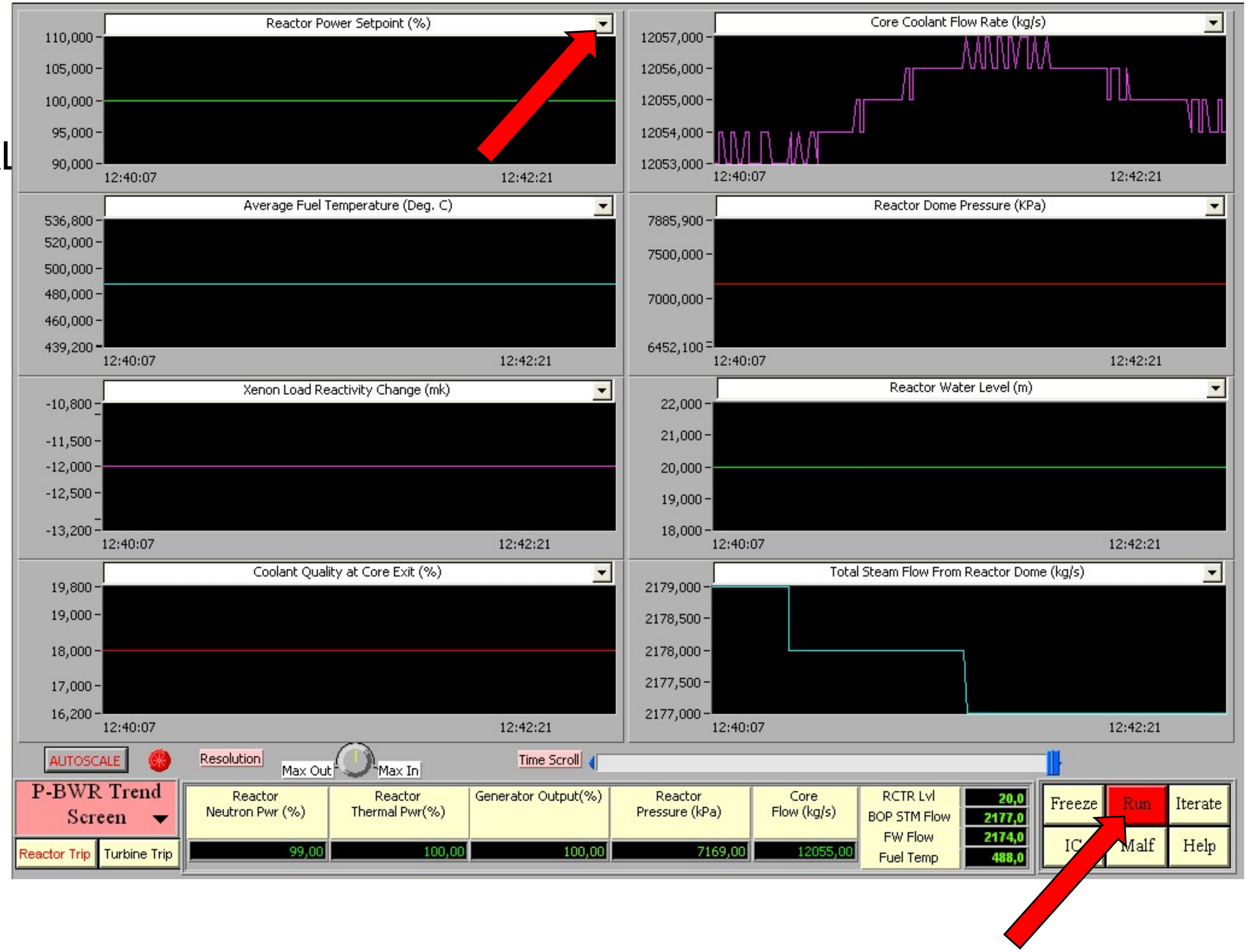
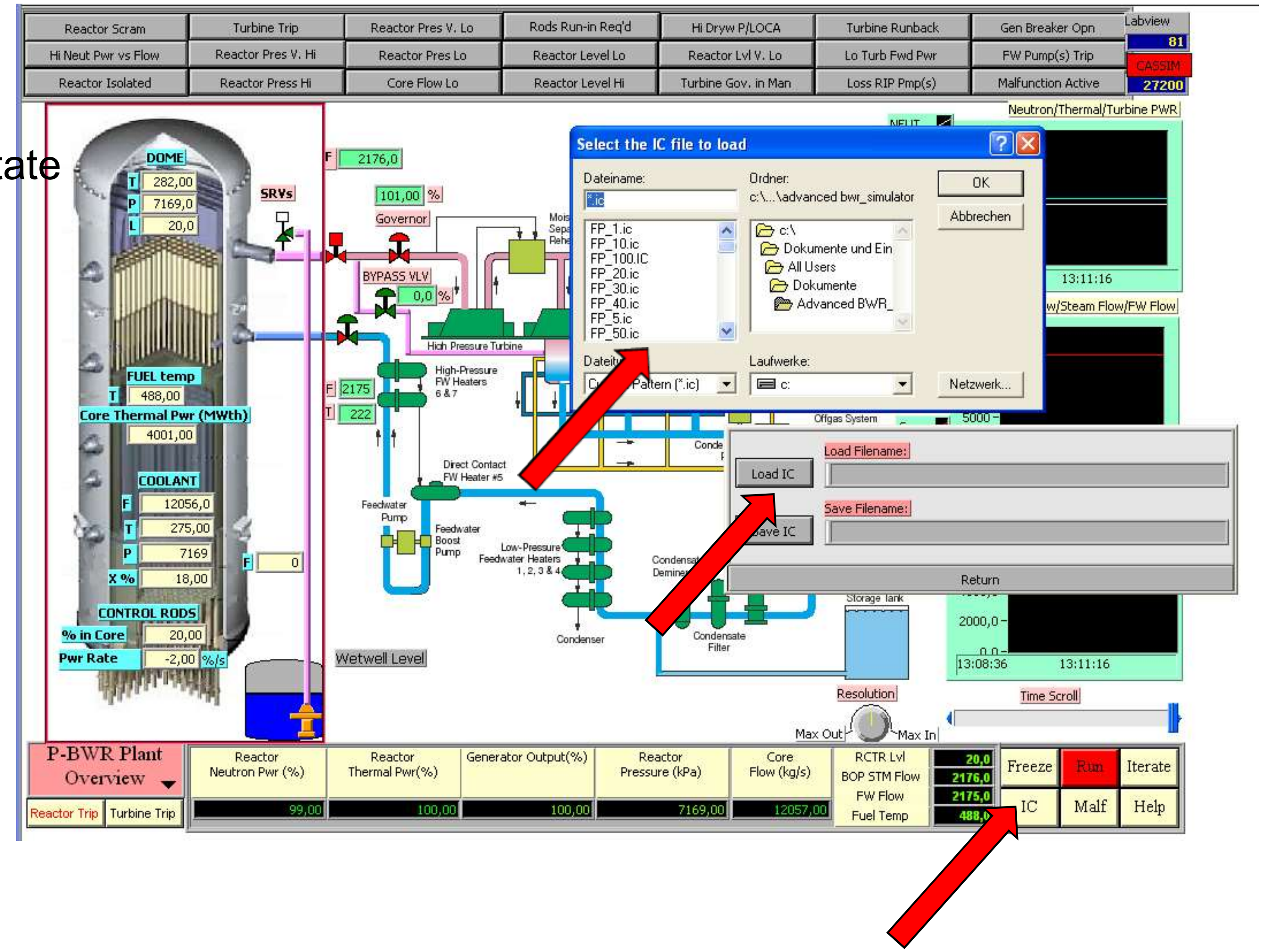
- **Create New Trends**
  - PWR Trend Screen
  - Modify Bands -AUTOSCAL
  - Time Scroll Feature
  - Resolution

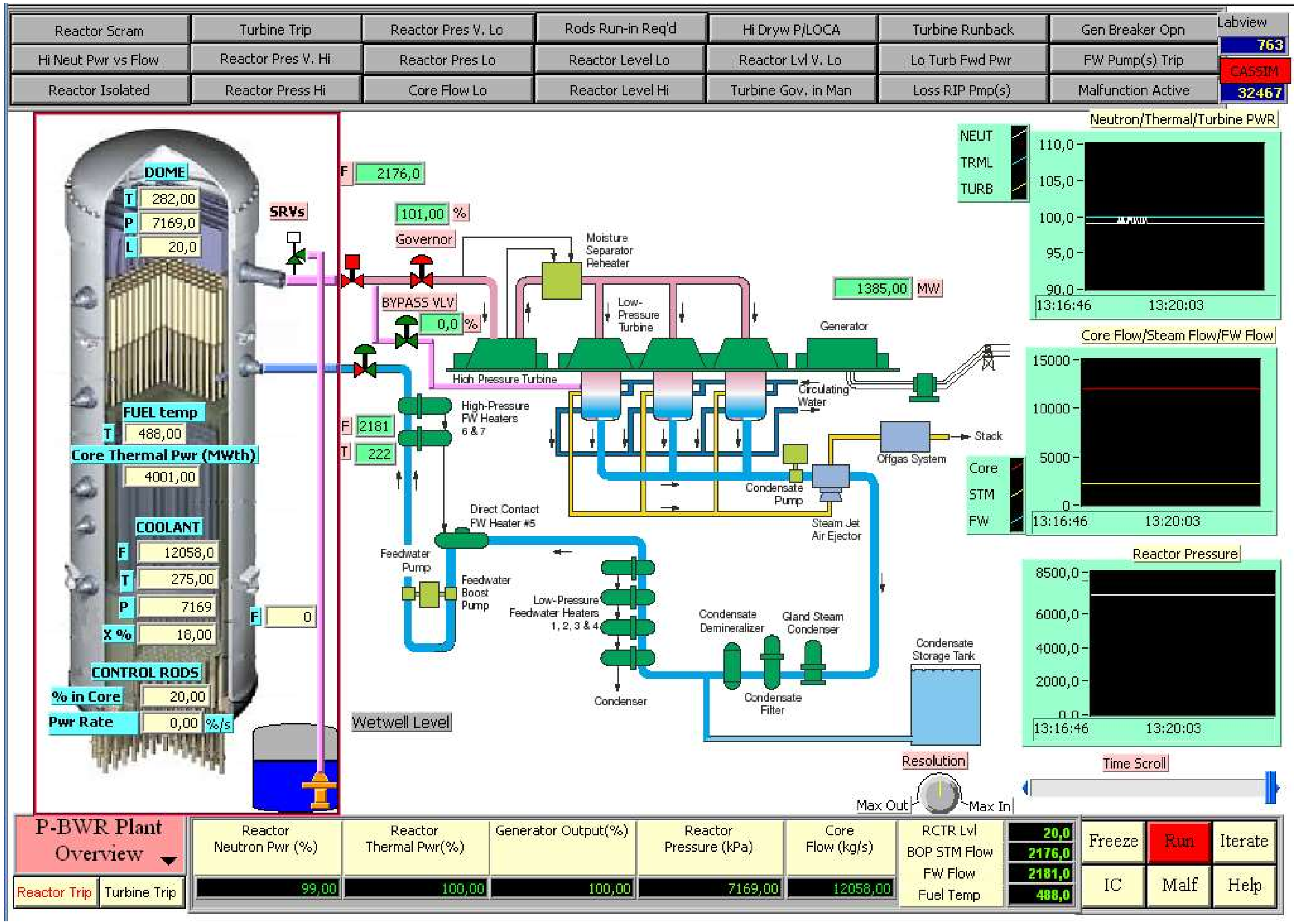


- ► **Load IC (initial condition)**
  - ◆ Initial Condition File
  - ◆ Presets a certain Reactor state



Simulator Fundamentals – Display Screens

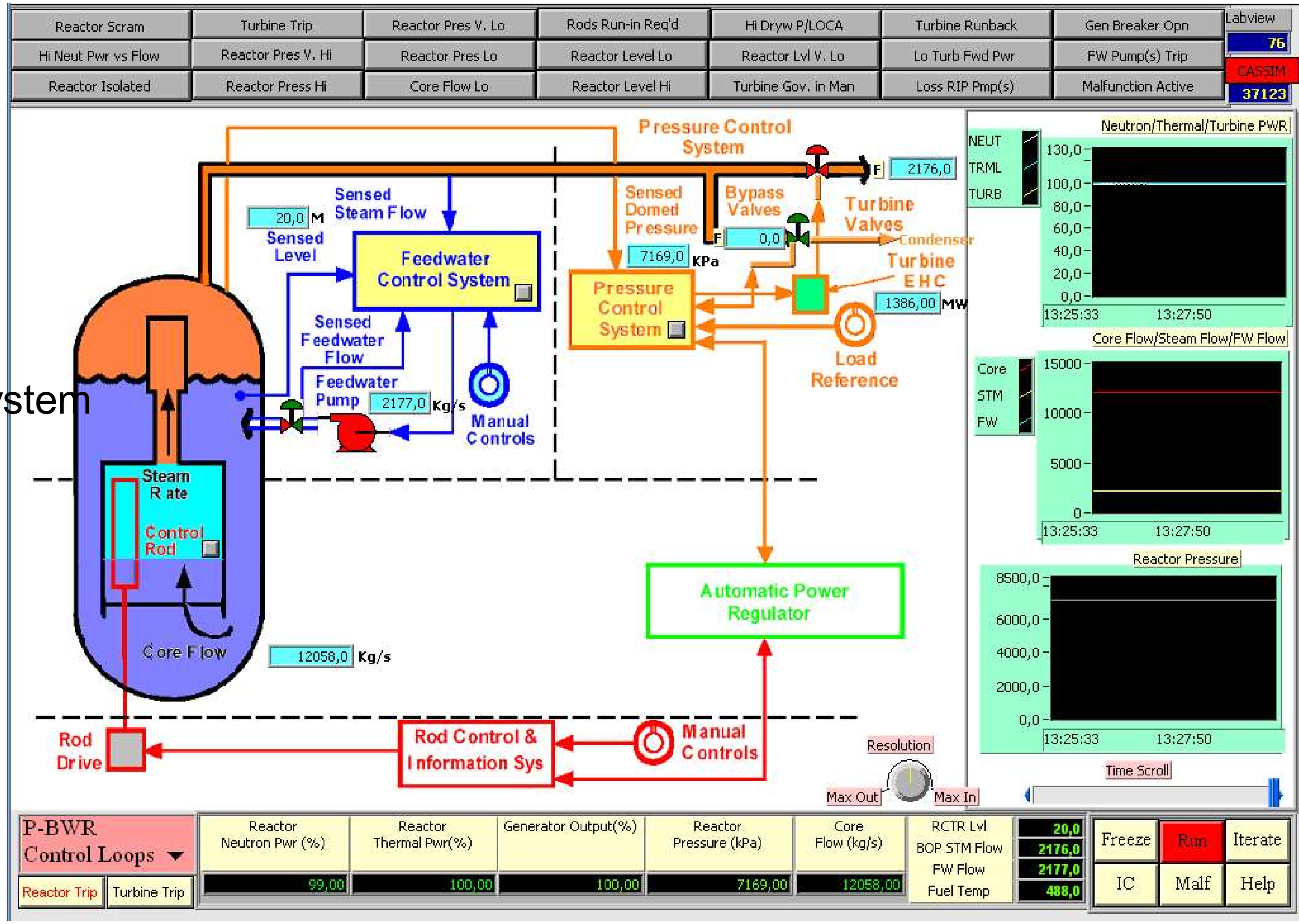
- ► **Main Plant Overview**
  - ◆ Water Steam Circuit
  - ◆ Main Parameters
    - Reactor
    - Turbine
    - Generator
    - Only Monitoring
    - No Input



Simulator Fundamentals – Display Screens

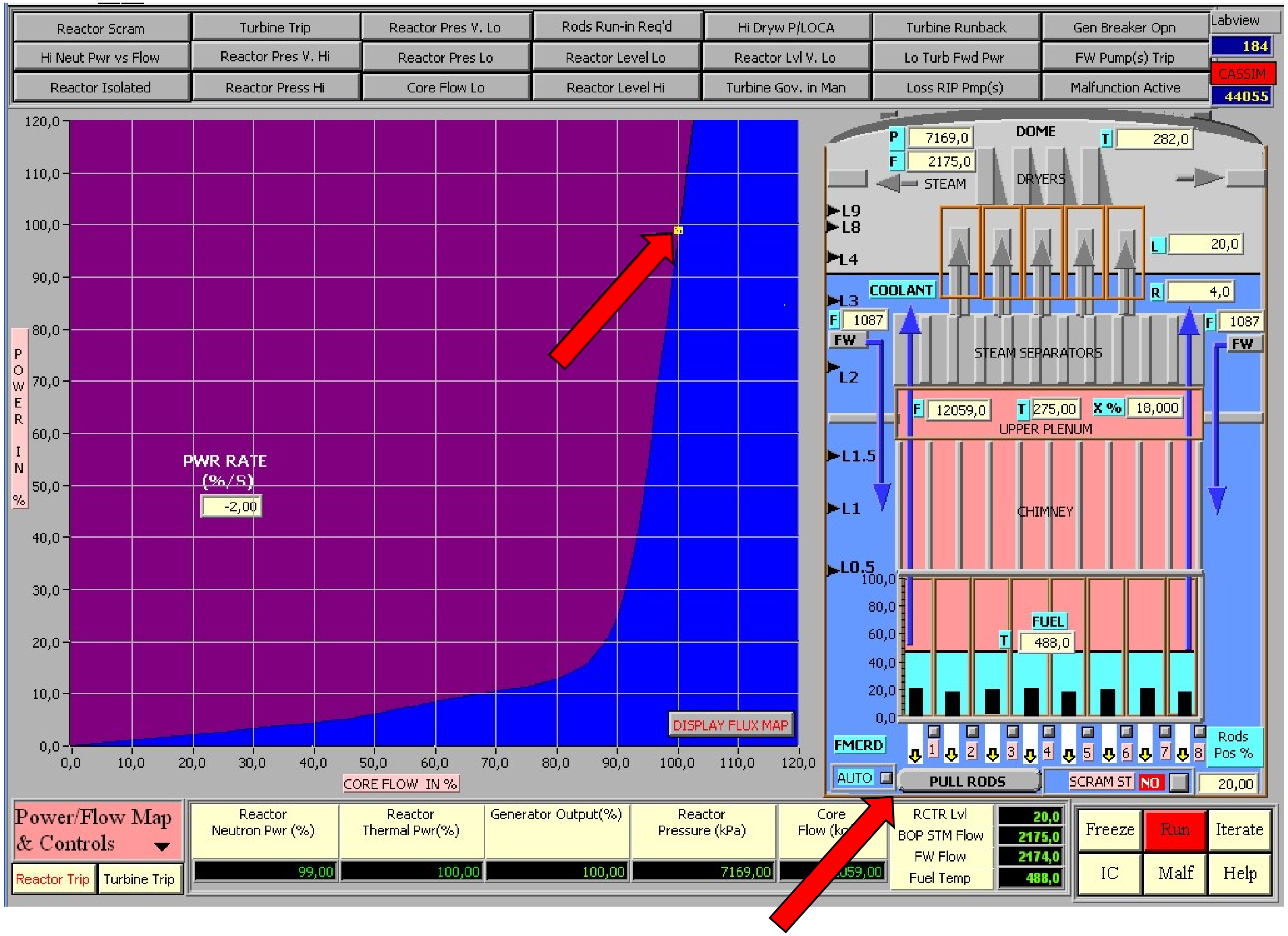
► **Main Control Loops**

- Control Rods
- Reactor Power
- Reactor pressure
- Reactor Water Level
- Turbine Control
- Turbine Steam Bypass System



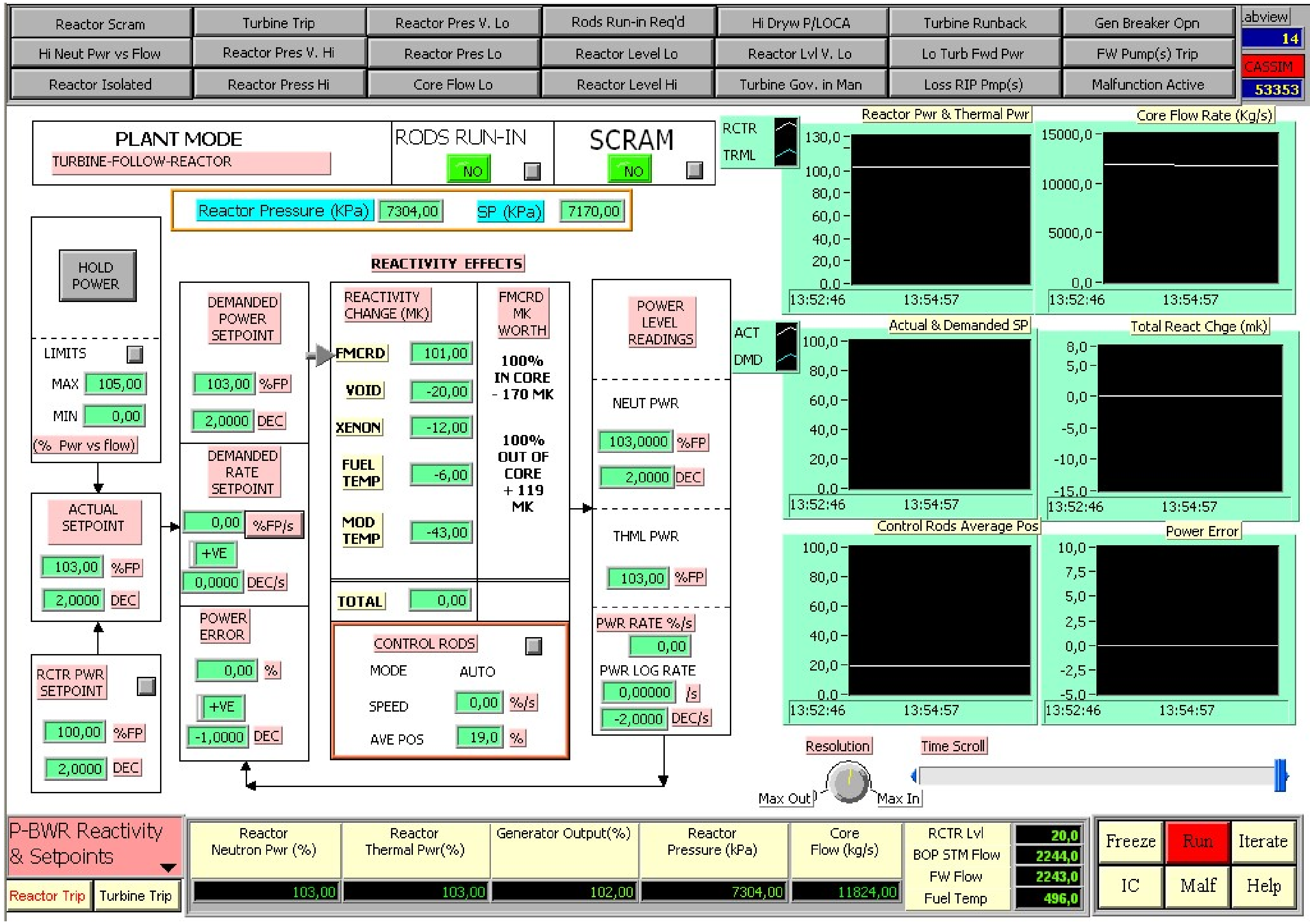
Simulator Fundamentals – Display Screens

► **Power Flow Map**
- Flow vs Power
- Operating Point
- Core Conditions
- CRD Controls
- SCRAM



Simulator Fundamentals – Display Screens

- **Reactivity and Control**
  - Power Setting
  - Power Change Rate
  - Manual Rod Insertion
  - Manual SCRAM



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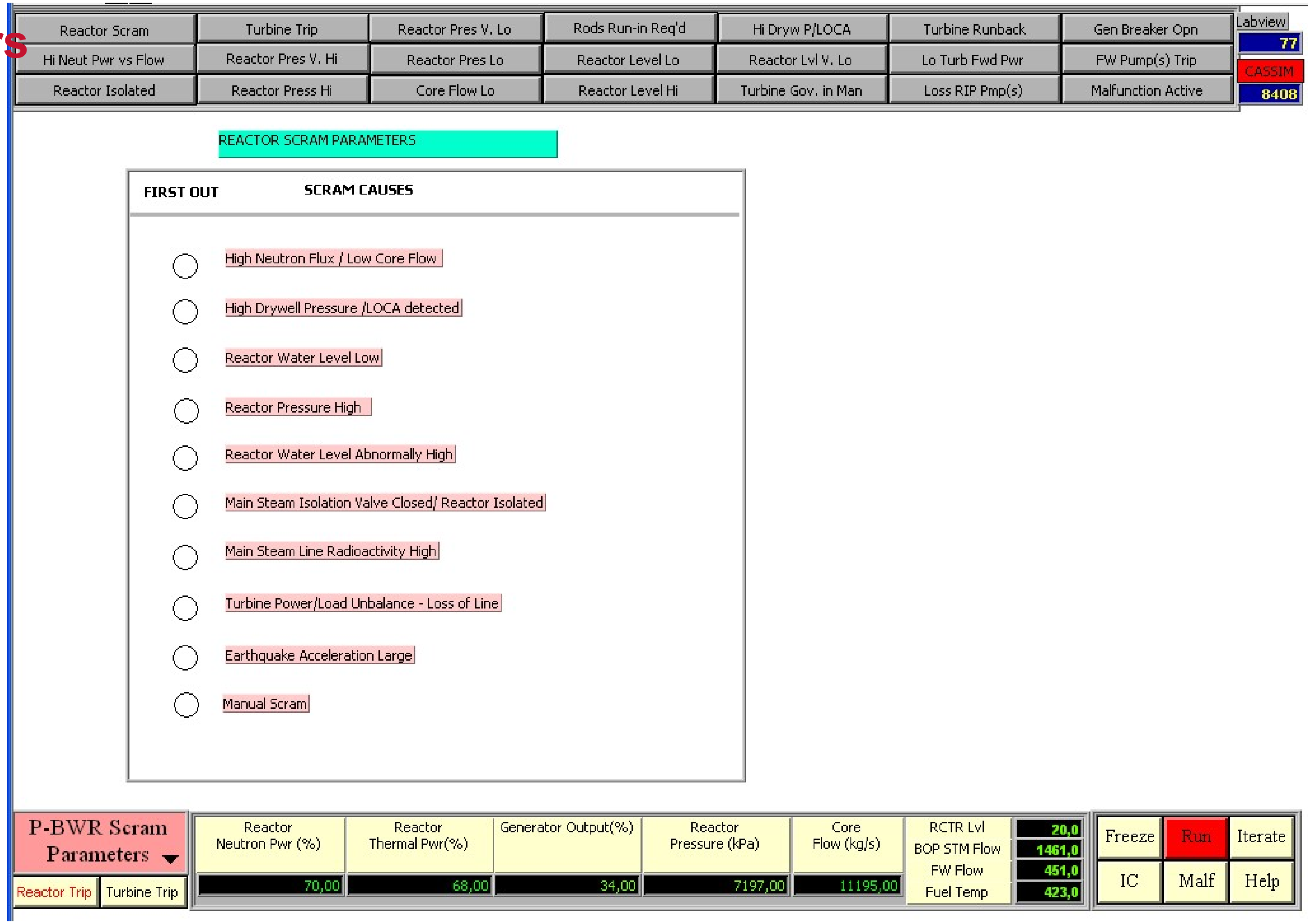
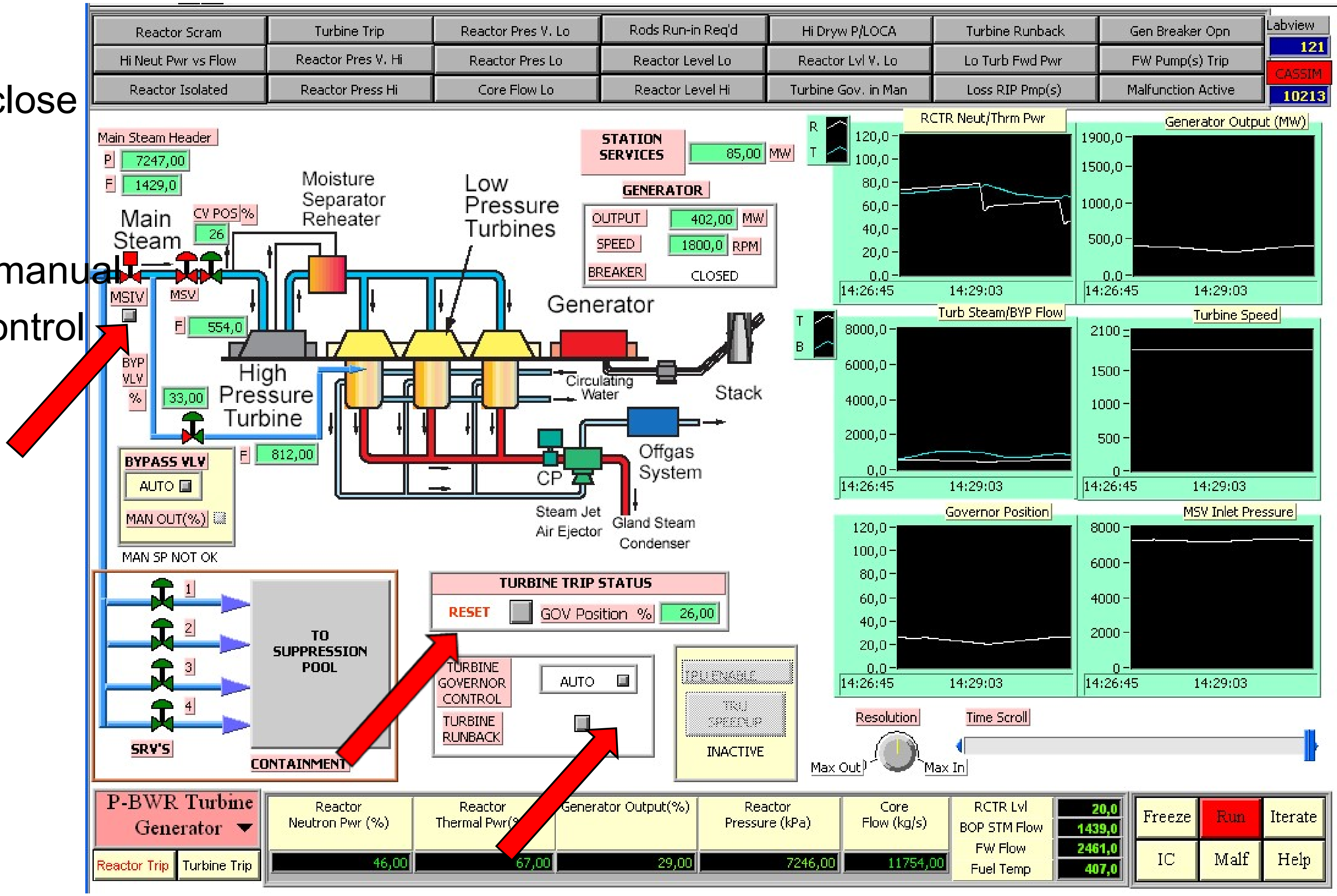
► **Reactor Scram Parameters**



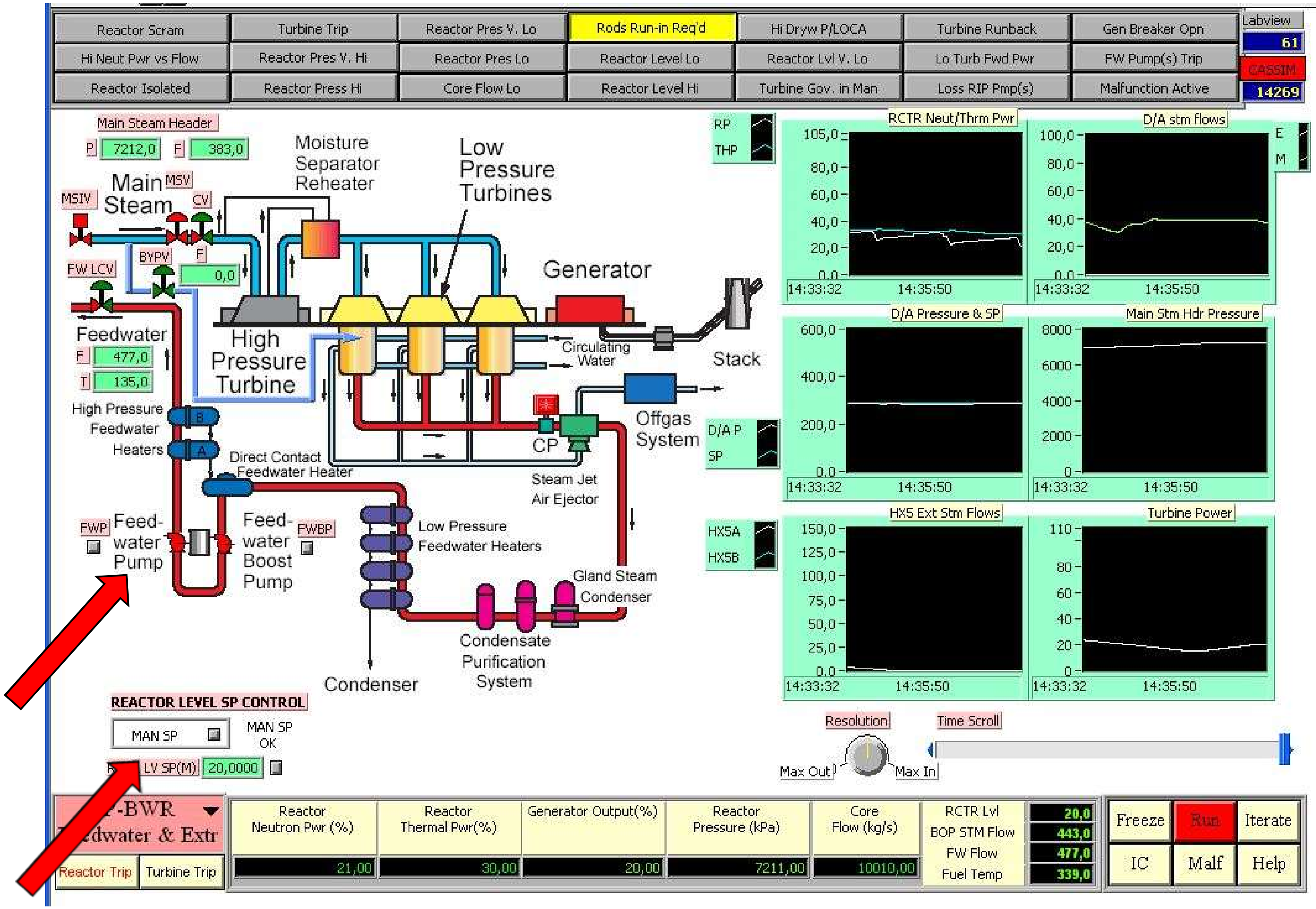
Simulator Fundamentals – Display Screens

- **Turbine / Generator**
  - MSIV manual open/close
  - Turbine Runback
  - Turbine Trip Status
  - Steam Bypass auto/manual
  - Turbine Governor Control



Simulator Fundamentals – Display Screens

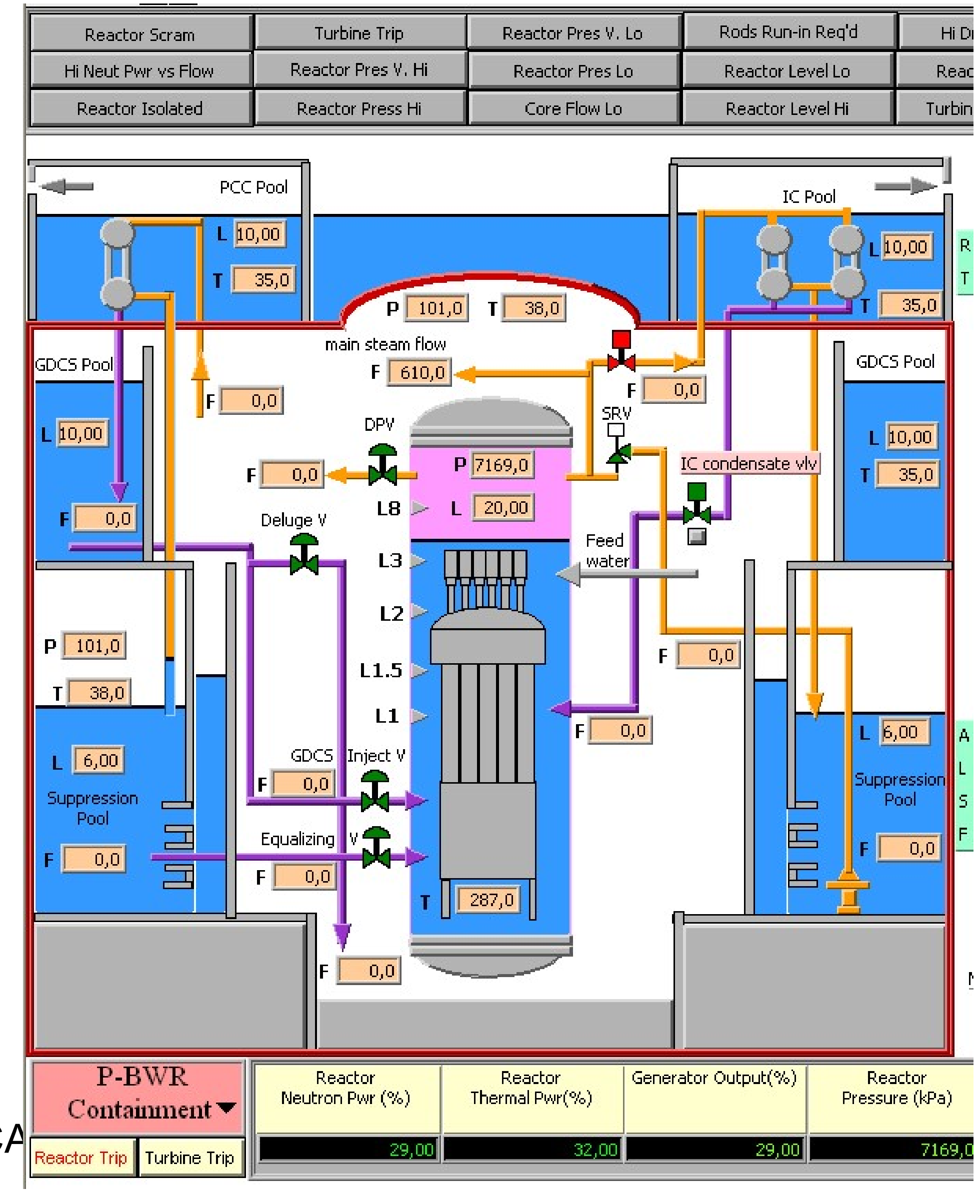
► **Feed Water System**
 ◆ Reactor Level
 ◆ Feed Water Pump Op



Simulator Fundamentals – Display Screens

► **Containment**

- IC Pool and Condenser:
  - steam supply isolation valve status
  - Steam flow to IC Pool from RPV
- PCC Pool and Condenser:
  - steam flow from Drywell to PCC Pool,
  - condensate flow from PC to GDCS Pool.
- RPV:
  - DPV valve status, SRV status
- Drywell
  - Drywell pressure, temperature;
  - water level (in case of LOCA)
- GDCS Pool:
  - deluge valve status and flow;
  - GDCS injection valve status and flow.
- Wetwell (Suppression Pool):
  - level; equalizing valve status and flow;
  - dynamic simulation of vent clearing in case of LOCA



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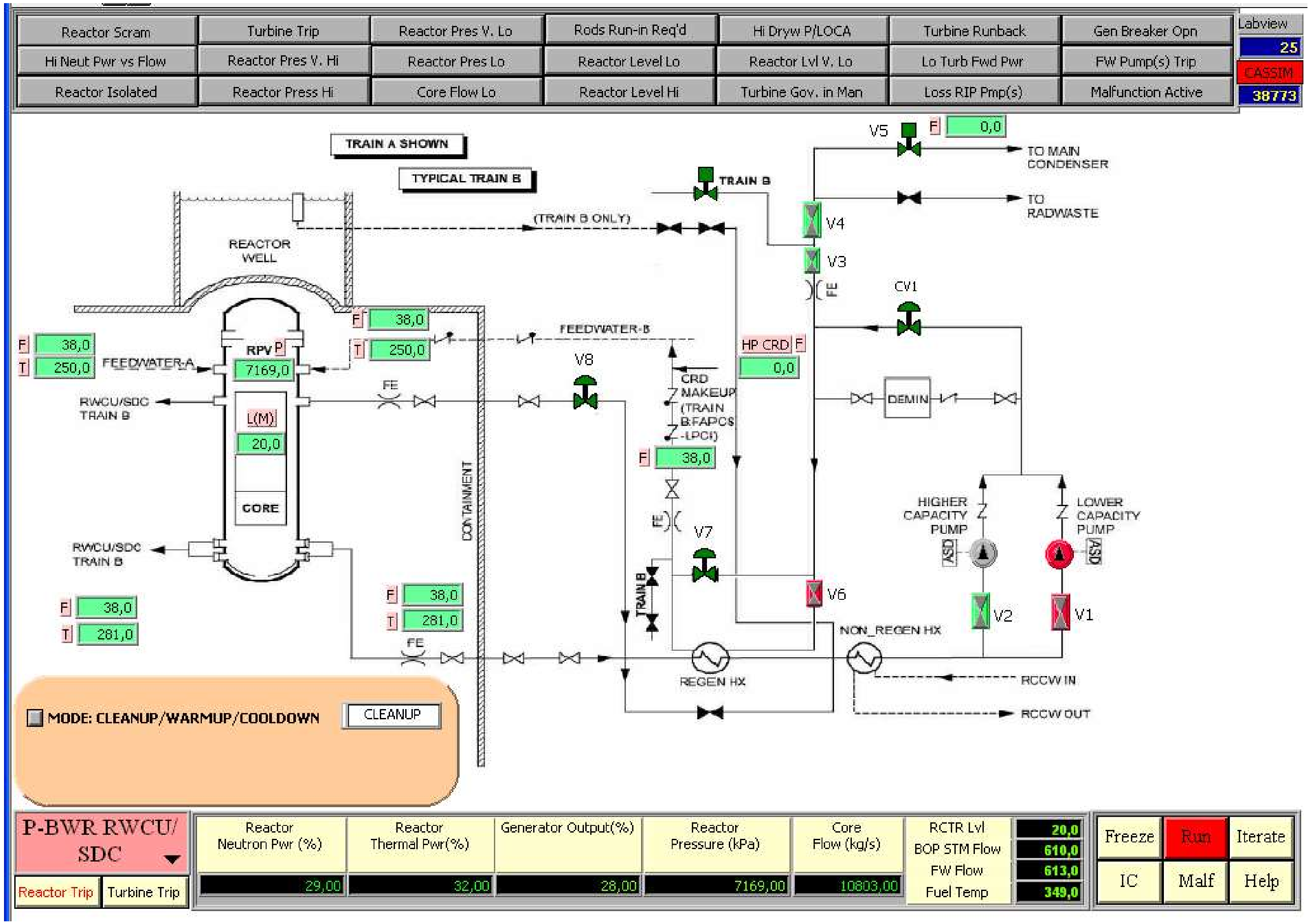
Simulator Fundamentals – Display Screens

- **Turbine / Generator**
  - Clean Up Mode
    - Power Operation
  - Shut Down Cooling
  - Plant Start / Warm Up



Simulator Fundamentals – Protection Signals / Setpoints

► Reactor Trips (SCRAM)

- High neutron flux/low core flow
  - if the current power exceeds 113% of the power designed for the current flow rate
- High drywell pressure/LOCA detected
  - if the drywell pressure exceeds 114.6 KPaa, then the LOCA logic senses that a LOCA condition has occurred.
- Reactor level low
  - L3 the scram setpoint is 19 meters above reactor bottom. Normal level is 20.6 meters above reactor bottom.
- Reactor pressure high
  - the scram setpoint is 7870 KPa. Normal reactor pressure is 7170 KPa.
- Reactor level very high
  - L9 the scram setpoint is 22.39 meters above reactor bottom.
- Main steam isolation valve closed/reactor isolated.
- Turbine power/load unbalance or loss of line (load rejection).
- Manual scram.

Simulator Fundamentals – Protection Signals / Setpoints

► Reactor Water Level Trip Set Points

- L 9 = 22.39 m – action: Reactor scram
- L 8 = 21.89 m – action: Turbine Trip.
- L 4 = 20.60 m – normal Reactor Level.
- L 3 = 19.00 m – action: Reactor Scram.
- L 2 = 16.50 m – action : initiate Isolation Condenser System; 29 delay, close MSIV
- L 1.5 = 13.00 m - action: start ADS blow down; initiate ICS.
- L 1 = 11.00 m – action: start equalizing valve.

Advanced BWR Operation Modes

- **Normal Operation**
  - Plant startup / warmup and startup
  - operation at any power
  - Load following operation
  - plant shutdown, cooldown, refueling,
- **Abnormal Operation:**
  - Loss of instrument air,
  - feed water system malfunction,
  - turbine trip
  - …
- **Emergency Operation:**
  - Design Basis Accidents (SLB, LOCA, SGTR, FLB…)
  - Beyond Design Basis Accidents (incl. severe accidents)

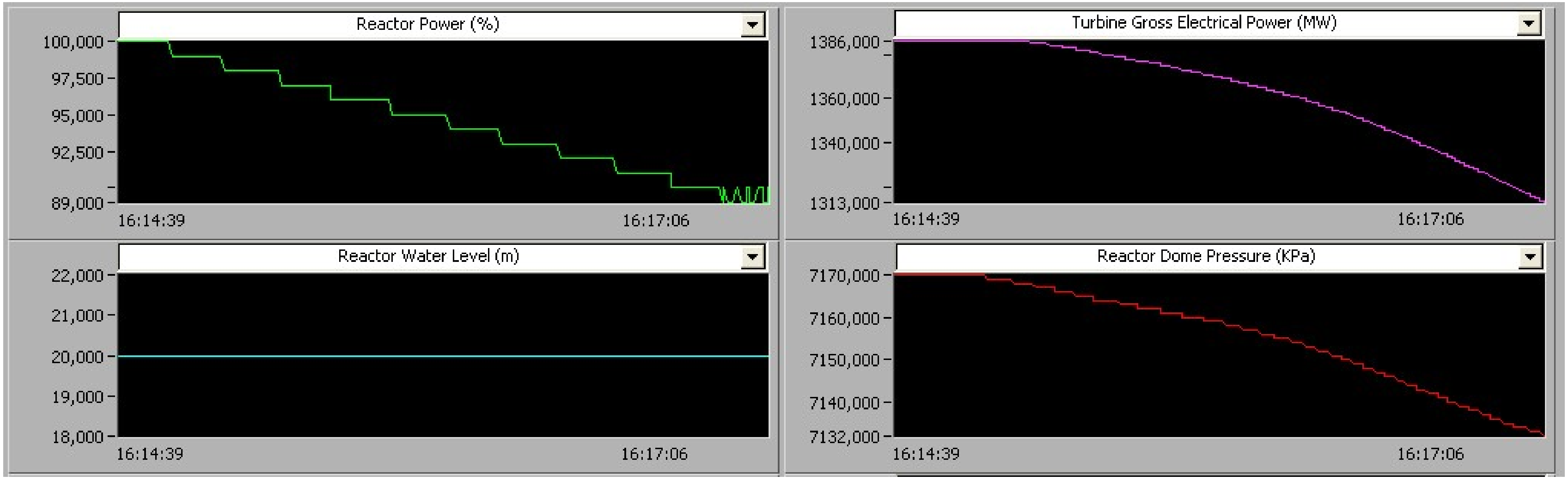
- **Part 1 – Normal/Abnormal Operation**
  - Operation at Full Power (FP)
    - Load Variations 100% - 90% - 100%
    - Load Variations 100% - 0% - 100%
  - Reactor shutdown cooling
- **Part 2 – Abnormal / Emergency Operation:**
  - In adverted Reactor Isolation
  - Main Steam Line Break in Drywell (LOCA)

Plant Exercises 1 - Load Variation 100% - 90% - 100%

- **Plant is at 100% power (FP) and load dispatcher request a power reduction of 10% FP**
  - Load the FP_100.IC
  - Verify that all parameters are consistent with full power operation.
  - Go to “Reactivity & Setpoint” Screen
  - Press RCTR PWR SETPOINT button
  - In pop-up menu lower ‘target’ to 90.00% at a ‘Rate’ of 0.5% FP/sec
- **Observe and describe the evolution of the following parameters**
  - Core Flow Rate
  - Coolant Temperature,
  - Coolant Quality at core exit
  - Reactor Water Level
  - Reactor Steam Pressure
  - Reactor Steam Flow
  - Feed water Flow
  - Turbine-Generator Power
  - Average position change of Control rods

Plant Exercises 1 - Load Variation 100% - 90% - 100%

- **Plant is at 100% power (FP) and load dispatcher request a power reduction of 10% FP**



Plant Exercises 1 - Load Variation 100% - 90% - 100%

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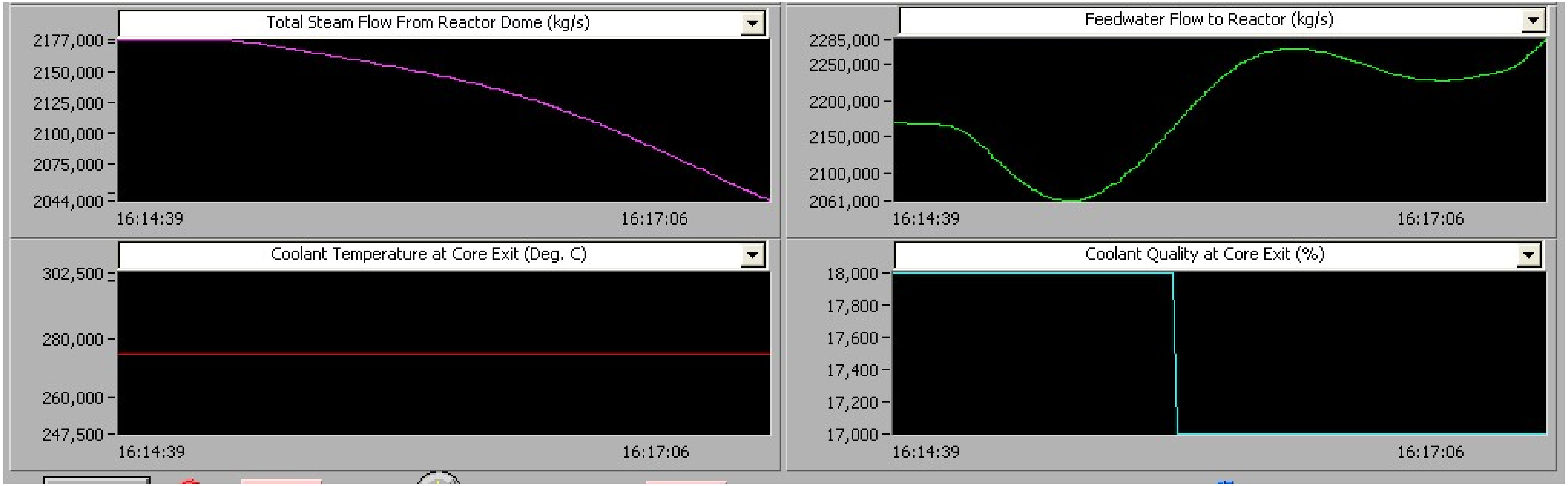

Plant Exercises 1 - Load Variation 100% - 90% - 100%

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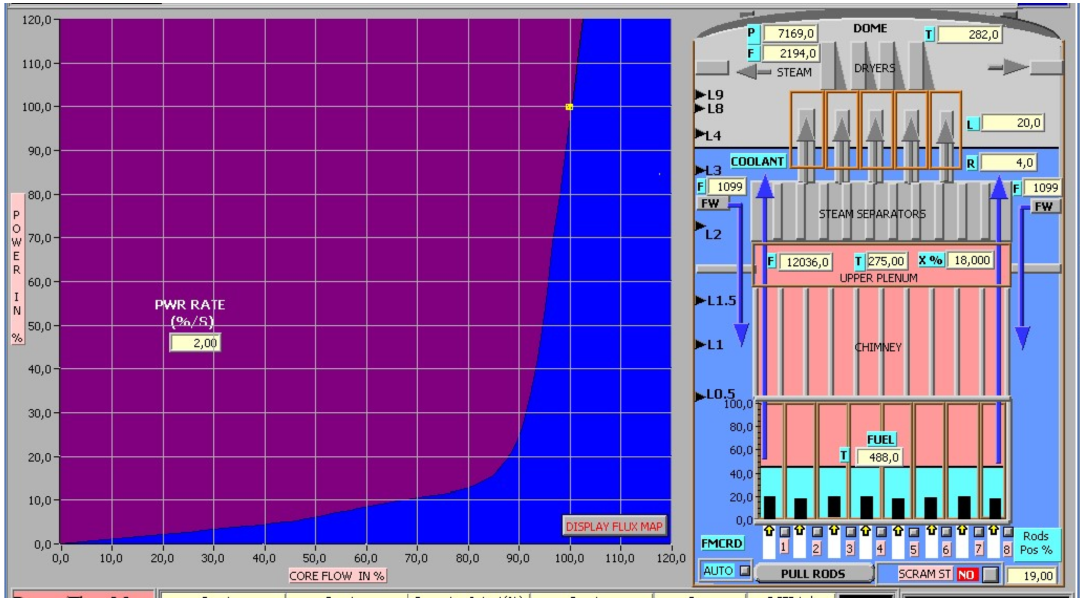
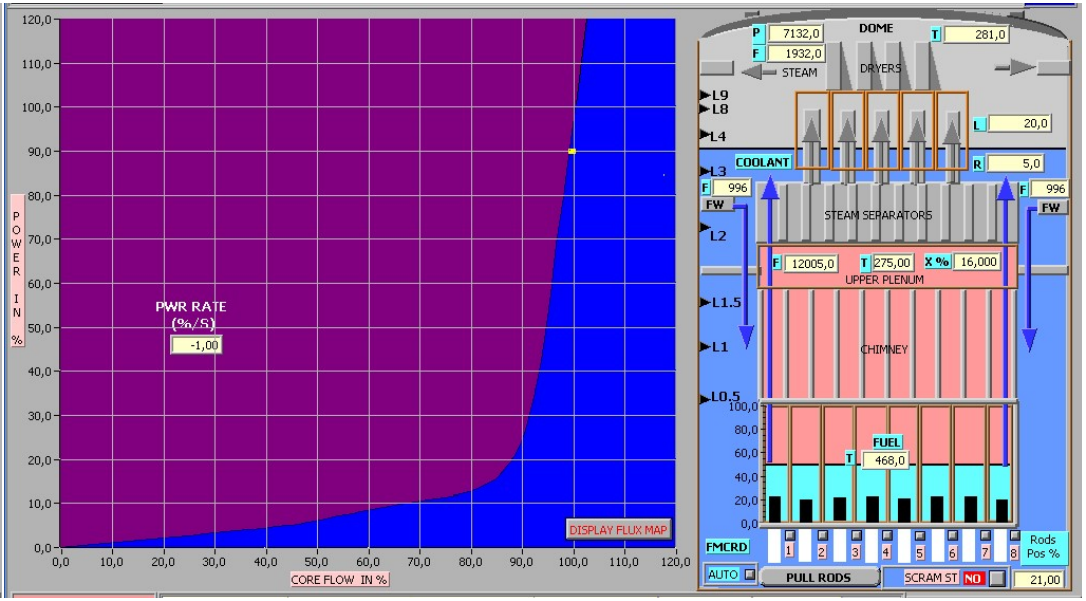
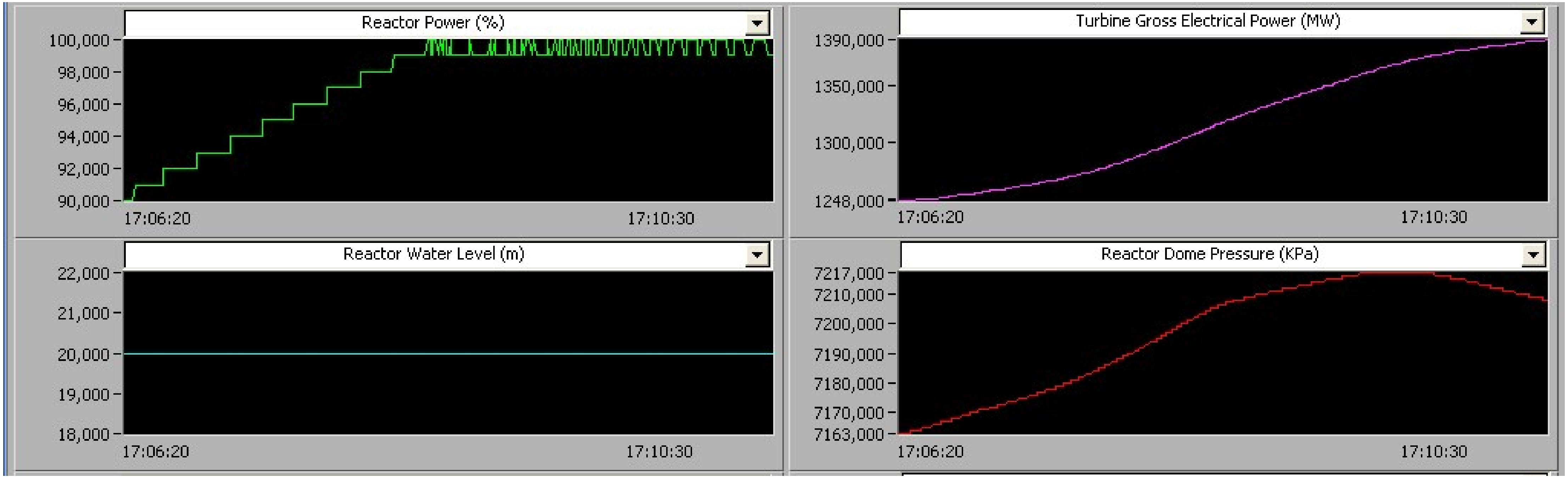




Plant Exercises 1 - Load Variation 100% - 90% - 100%

► **Plant is at 90% power (FP) and load dispatcher request a power increase of 10% to 100%**



Plant Exercises 1 - Load Variation 100% - 90% - 100%

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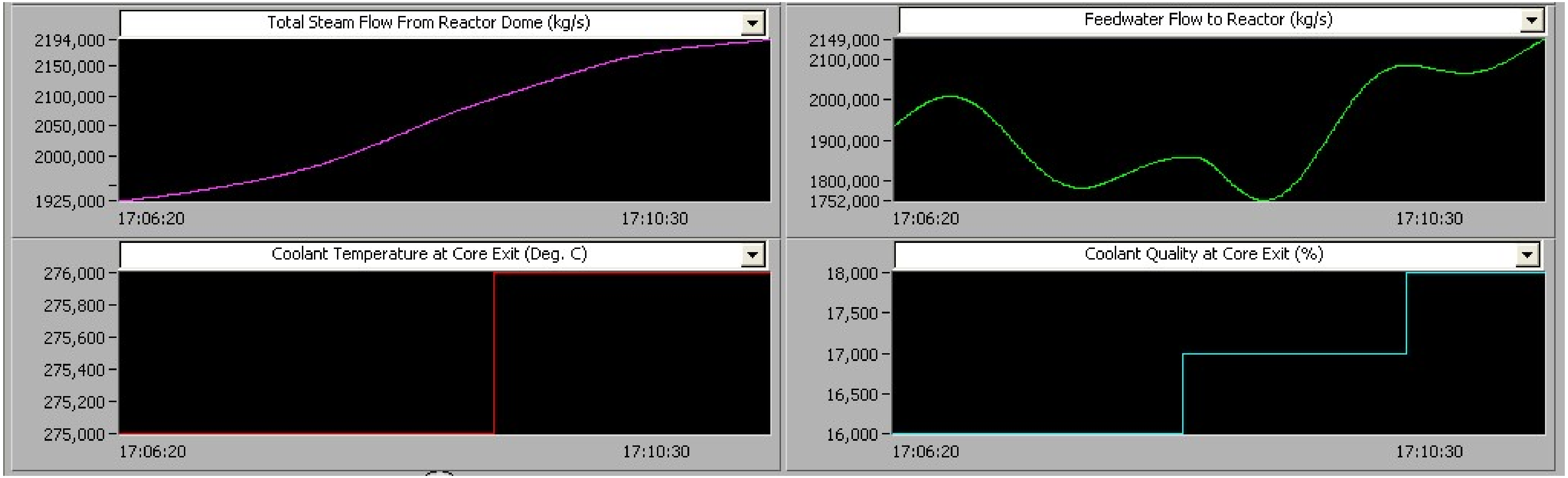

Plant Exercises 1 - Load Variation 100% - 90% - 100%

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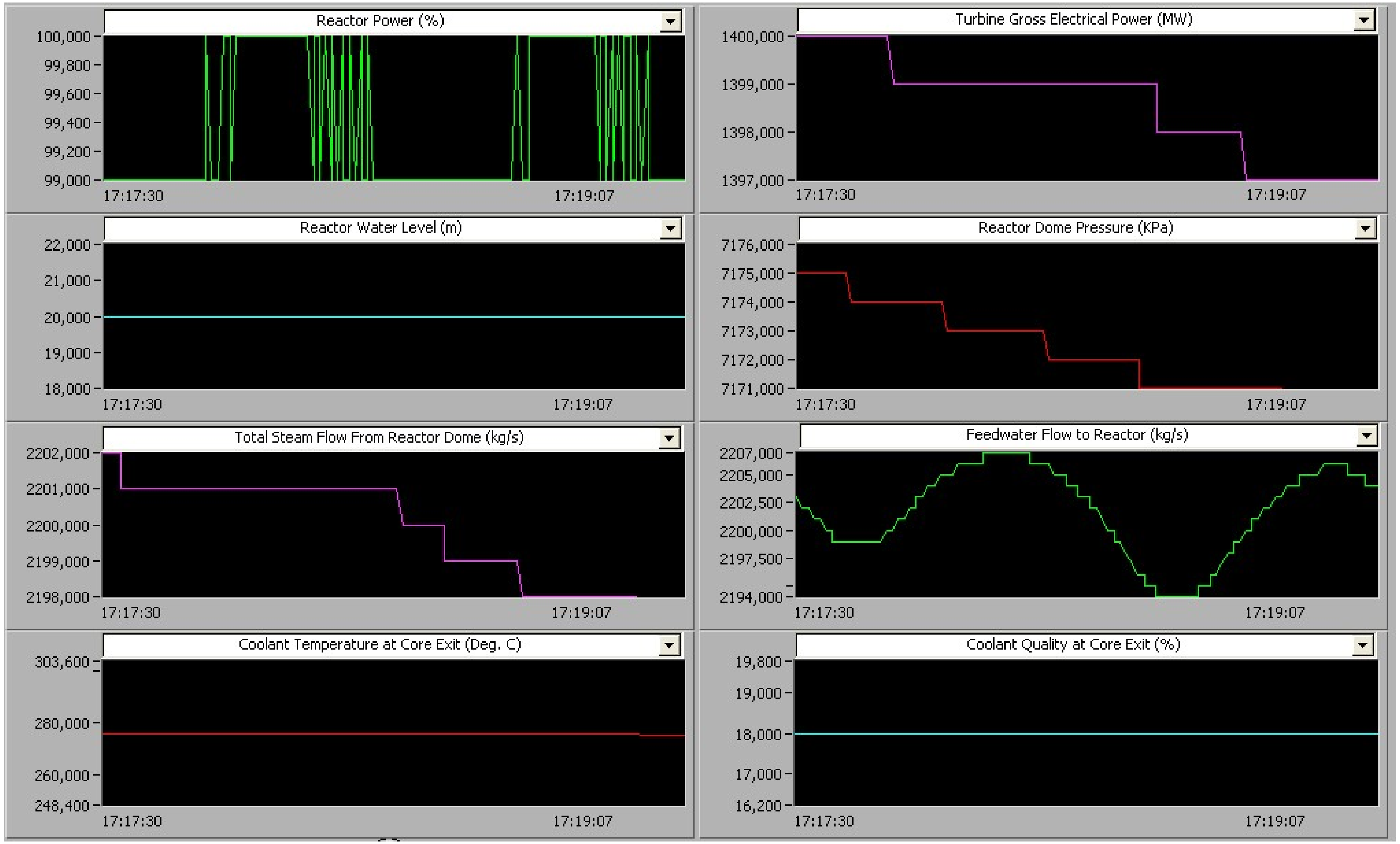


Plant Exercises 1 - Load Variation 100% - 0% - 100%

- **Plant is at 100% power (FP) and shall be shut down (Hot Shut down) for a short stop to make perform some repair work at the turbine.**
  - Initialize the simulator to 100 %FP, reduce power using 25% steps at 0.5% FP/sec from
  - 100 % to 65 %. Monitor the Reactor Water Level at all times
  - From 65 % to 20 %, use the rate of 0.5 % FP/sec
  - From 20 % to 0 %, use the rate 100 % present power (PP)/sec.
- **Observe and describe the evolution of the following parameters**

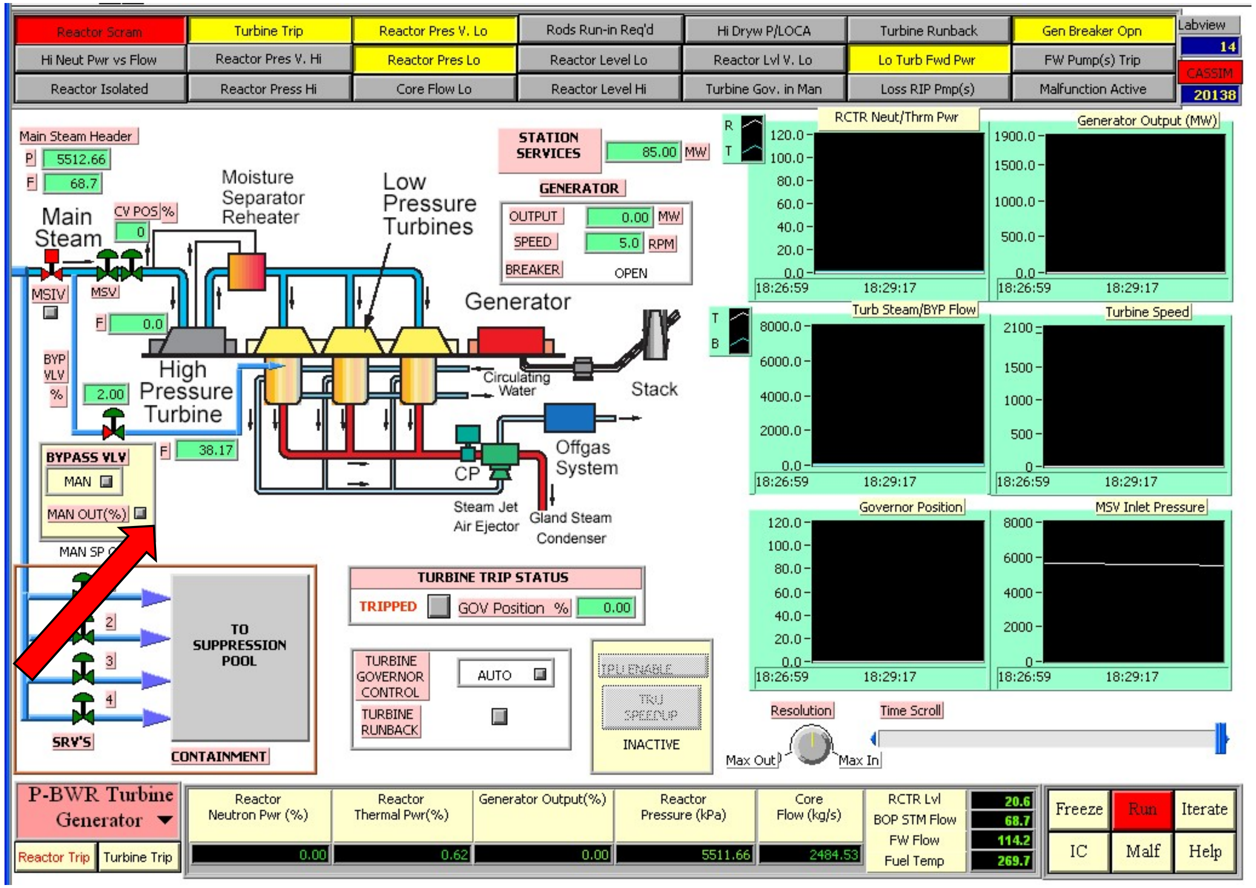
Parameter	Unit						Comments
Reactor Power	%	100%	75%	50%	25%	0%	
Core Flow Rate	Kg/s						
Coolant Temperature	°C						
Coolant Pressure at core exit	KPa						
Coolant Quality at core exit	%						
Reactor Level	m						
Reactor Steam Pressure	KPa						
Reactor Steam Flow	Kg/s						
Feedwater Flow	kg/s						
Turbine-Generator Power	%						

Plant Exercises 1 – Shutdown Cooling

- **Plant is at Hot Shut down with reactor Scrammed and Turbine Tripped – Initiate shut down cooling**
  - Confirm the reactor is scrammed, and turbine generator is tripped and on turning gear.
  - Check reactor water level. It should recover after reactor scram.
  - Go to Passive BWR Turbine Generator Screen, switch the BYPASS Valve mode to MANUAL, and use the pop-up to open the BYPASS VALVE to 2 %
  - Observe that the reactor pressure starts to decrease.
  - Go to Passive BWR RWCU/SDC Screen, use the pop-up to switch from "CLEAN-UP" to cool-down.
  - Provide explanation regarding the valving arrangement and the flow and temperature as
  - shown on the Passive BWR RWCU/SDC Screen.

Plant Exercises 1 – Shutdown Cooling

- ► **Plant is at Hot Shut down with reactor Scrammed and Turbine Tripped – Initiate shut down cooling**



Plant Exercises 1 – Shutdown Cooling

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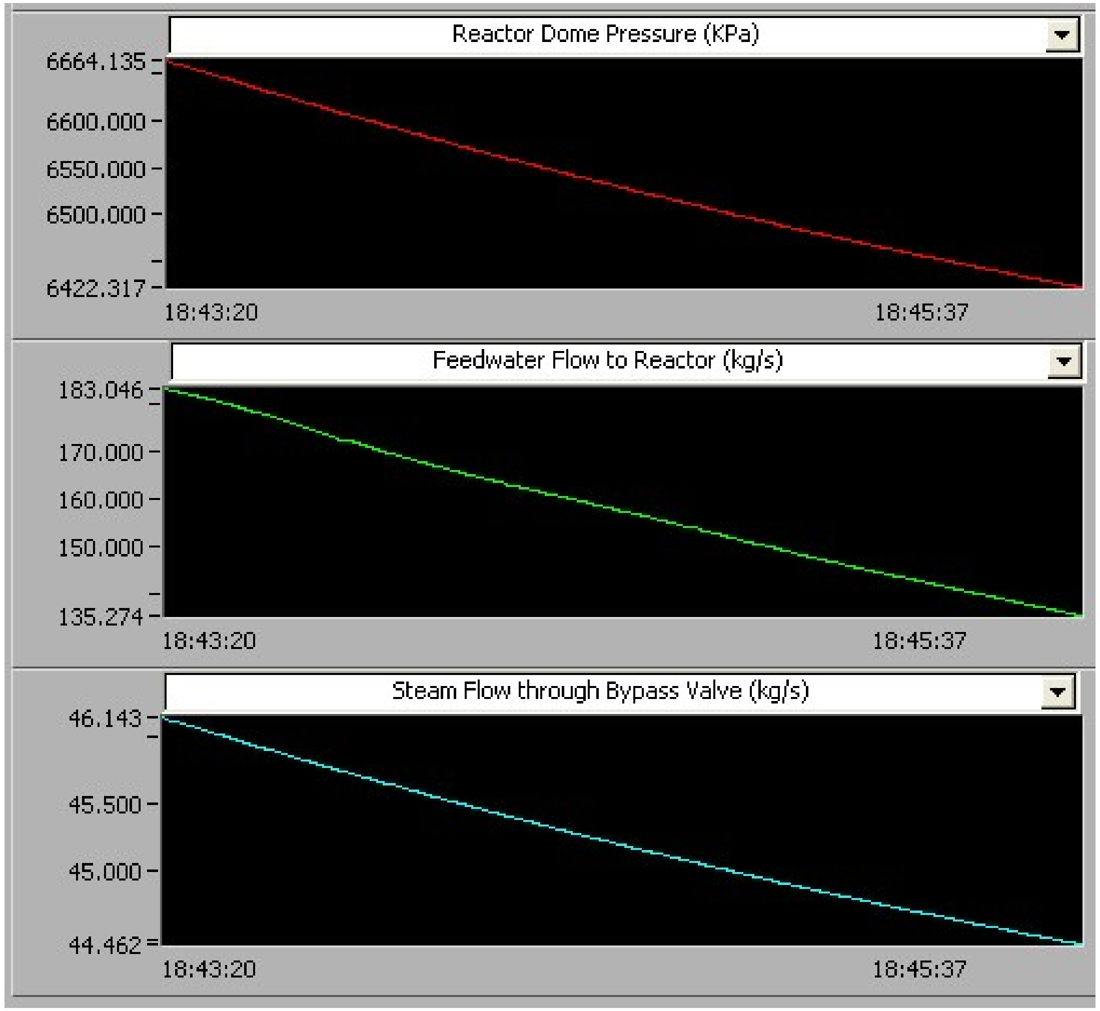

Plant Exercises 1 – Shutdown Cooling

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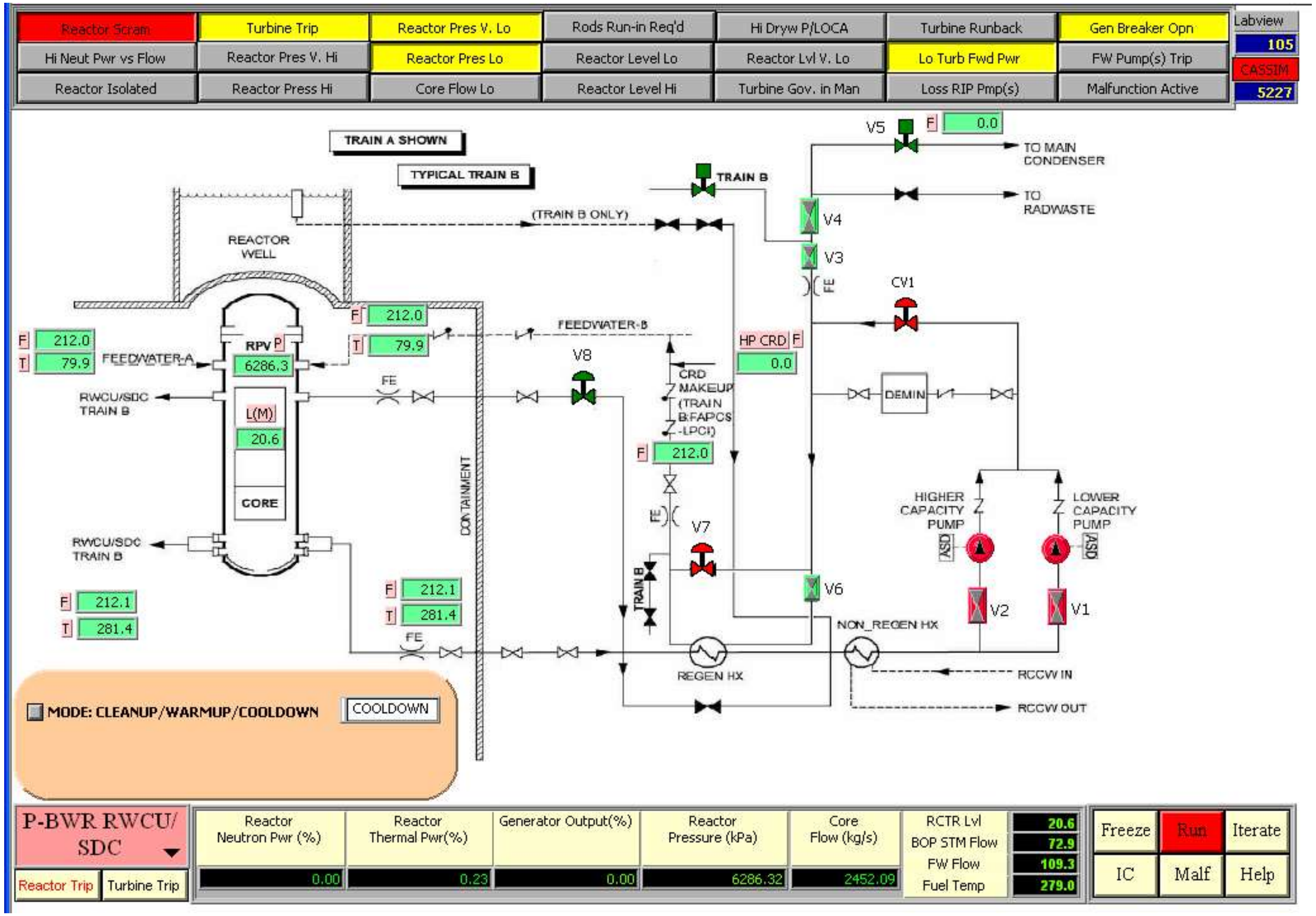

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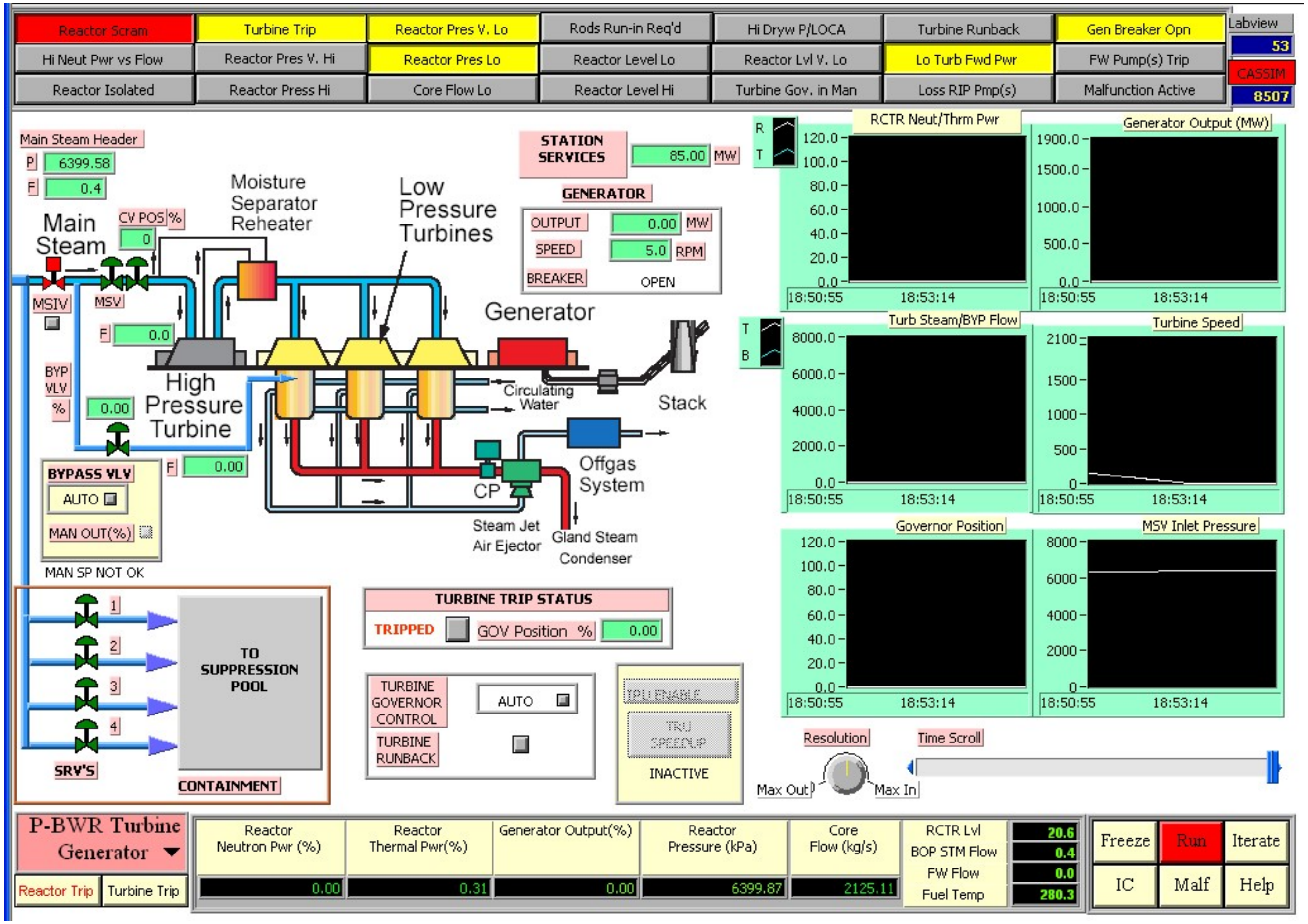
Plant Exercises 1 – Shutdown Cooling

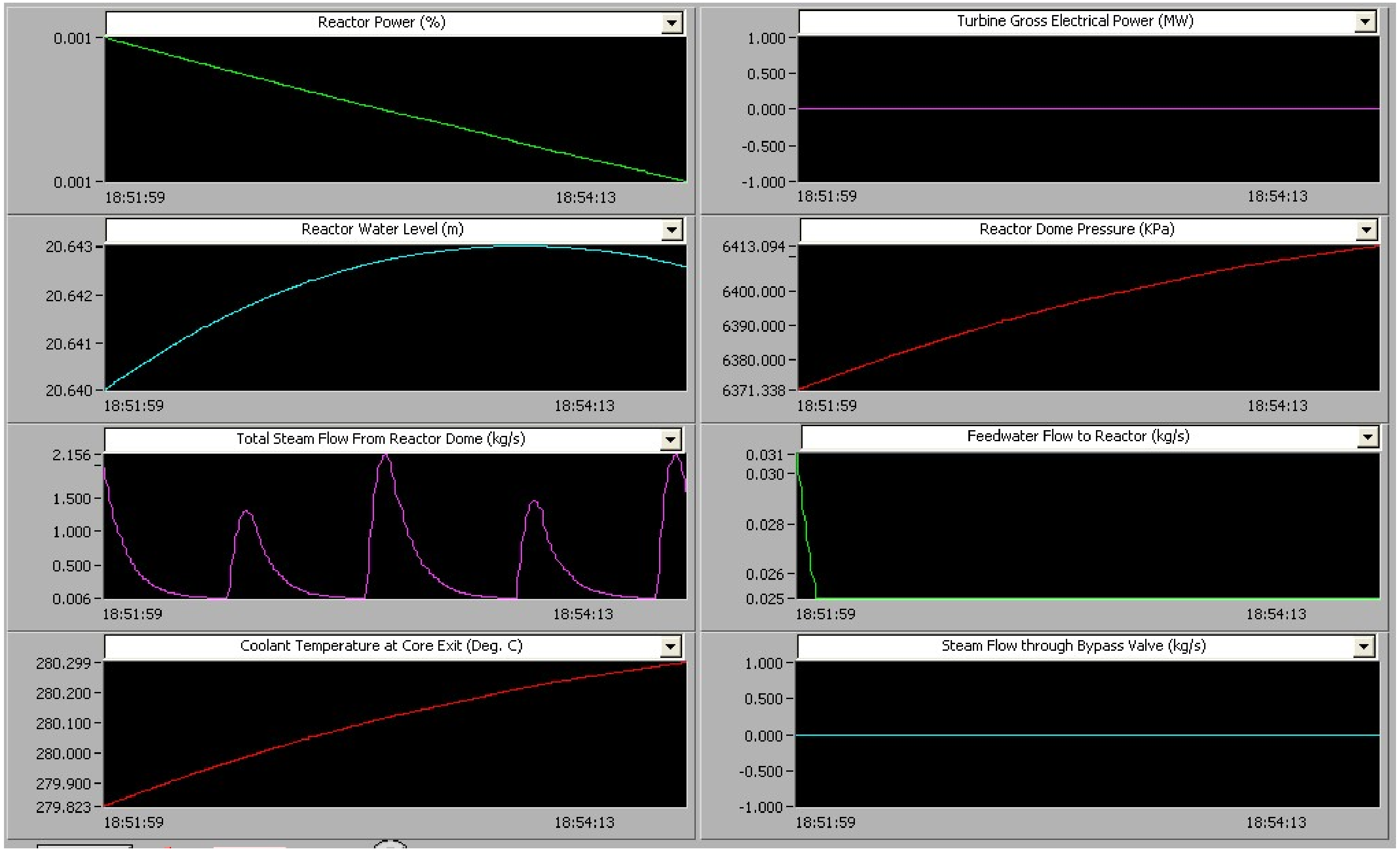
- **Plant is at Hot Shut down with reactor Scrammed and Turbine Tripped – Initiate shut down cooling**
  - Change back the Stem Bypass Valve to Auto Mode
  - What happens with:
  - the steam Bypass Flow
  - Steam Flow
  - Reactor Pressure

- Plant is at Hot Shut down with reactor Scrammed and Turbine Tripped – Initiate shut down cooling



Plant Exercises – Shutdown Cooling

► **Plant is at Hot Shut down with reactor Scrammed and Turbine Tripped – Initiate shut down cooling**

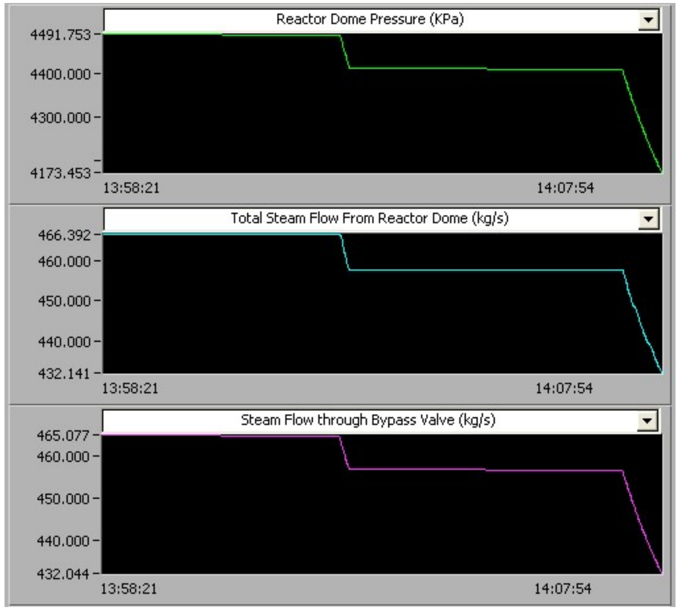


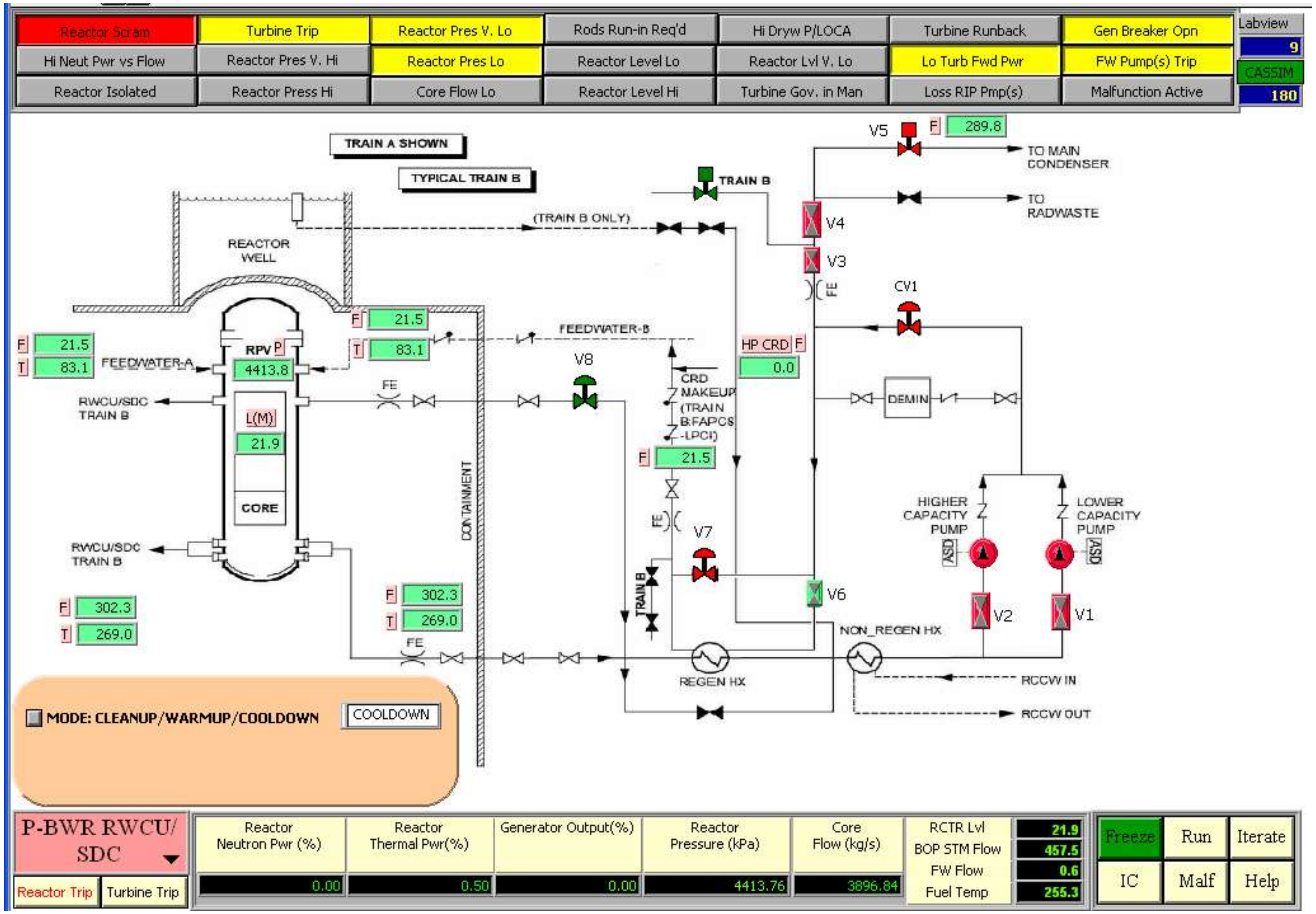
Plant is at Hot Shut down with reactor Scrammed and Turbine Tripped – Initiate shut down cooling

- Load the different IC and describe
- Changes in the RWCU/SDC Screen
- MSIV Position
- Bypass Flow
- Steam Dome Pressure
- Main Steam Flow

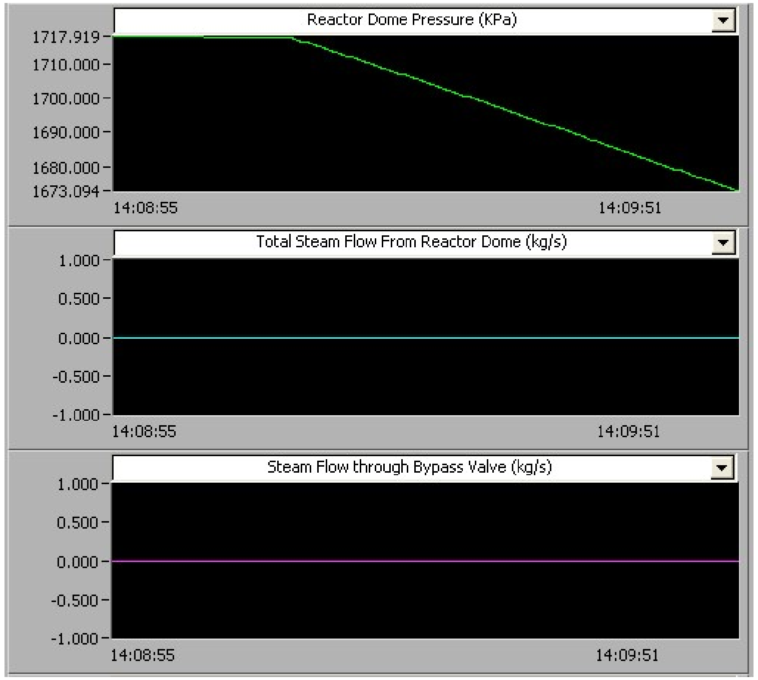
SD1_3860KPa.ic
SD2_2000KPa.ic
SD3_1280KPa.ic
SD3_1600KPa.ic
SD3_MSIV_1718KPa.ic
SD4_845KPa.ic
SD6_550KPa.ic
SD7_490KPa.ic

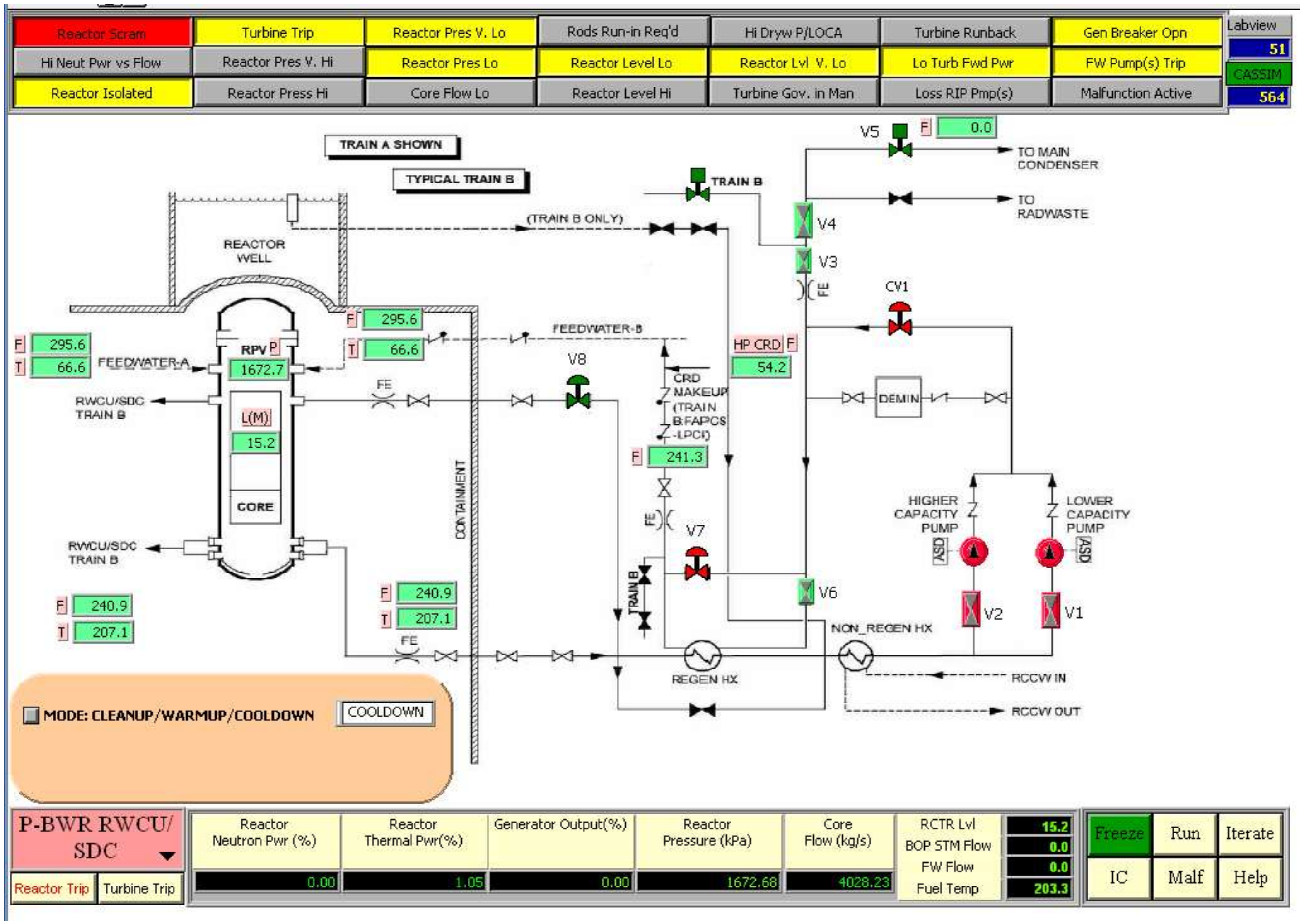
- **Plant is at Hot Shut down with reactor Scrammed and Turbine Tripped – Initiate shut down cooling**
  - IC SD_3860:
  - MSIV Position => Open





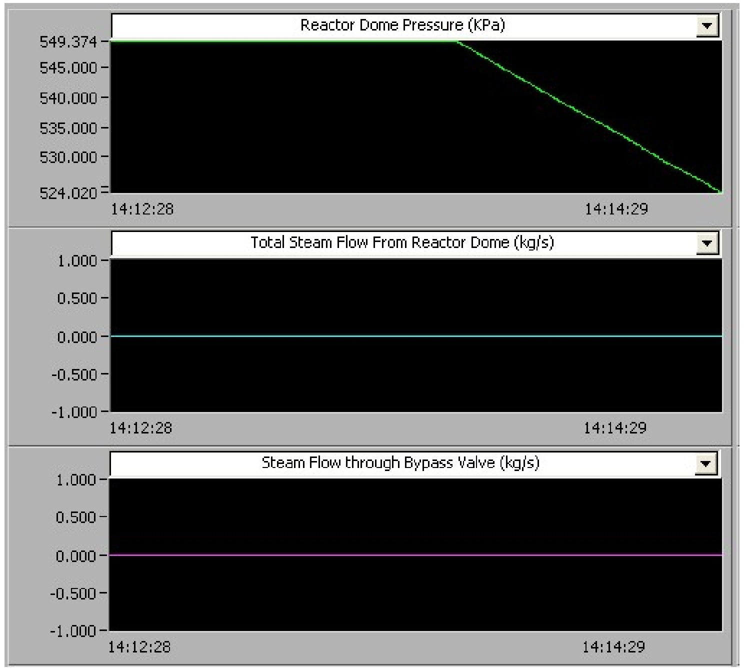
- Plant is at Hot Shut down with reactor Scrammed and Turbine Tripped – Initiate shut down cooling
  - IC SD_MSIV_1718:
  - MSIV Position => Closed

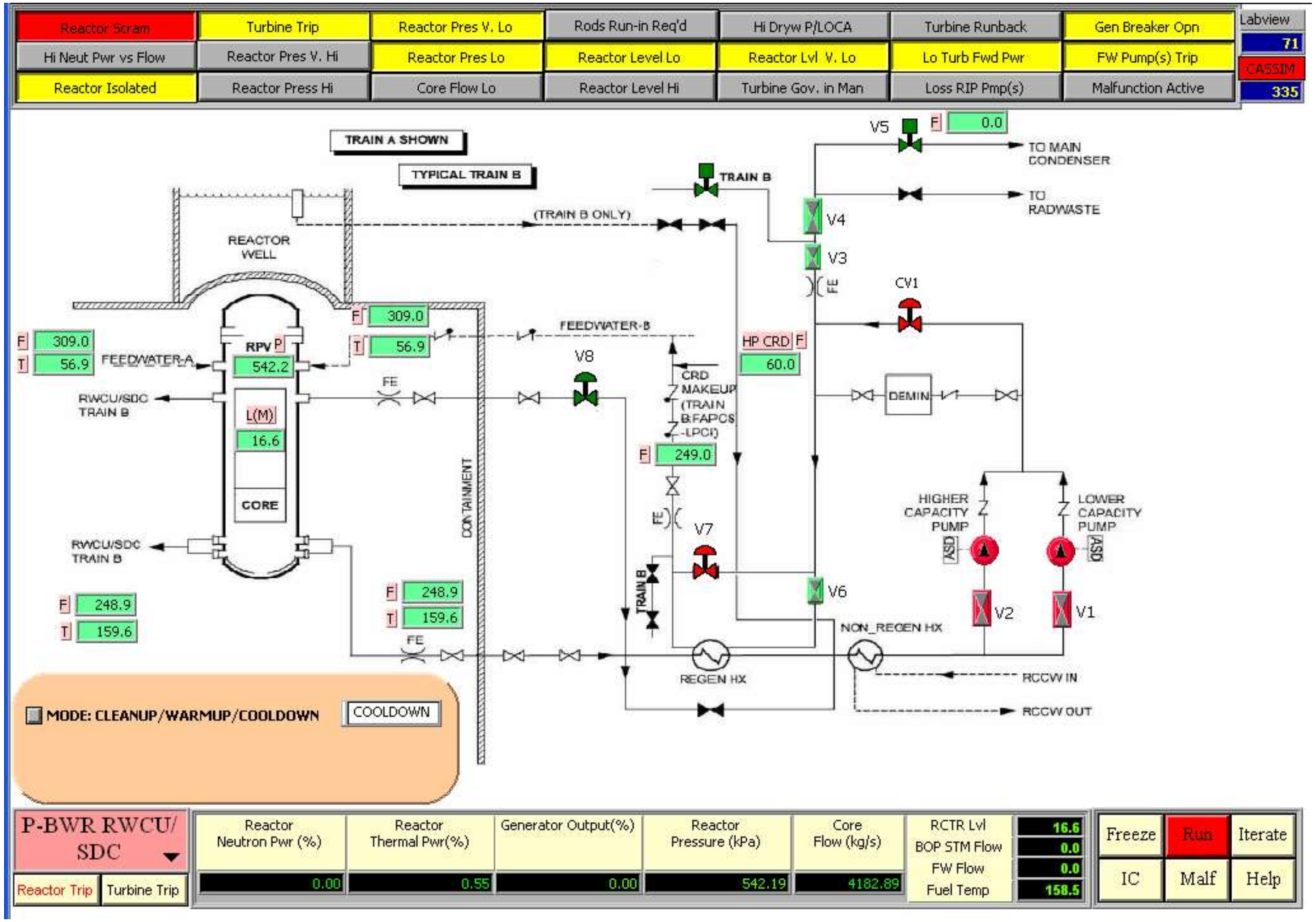




Plant Exercises 1 – Shutdown Cooling

- **Plant is at Hot Shut down with reactor Scrammed and Turbine Tripped – Initiate shut down cooling**
  - IC SD_550
  - MSIV Position => Closed



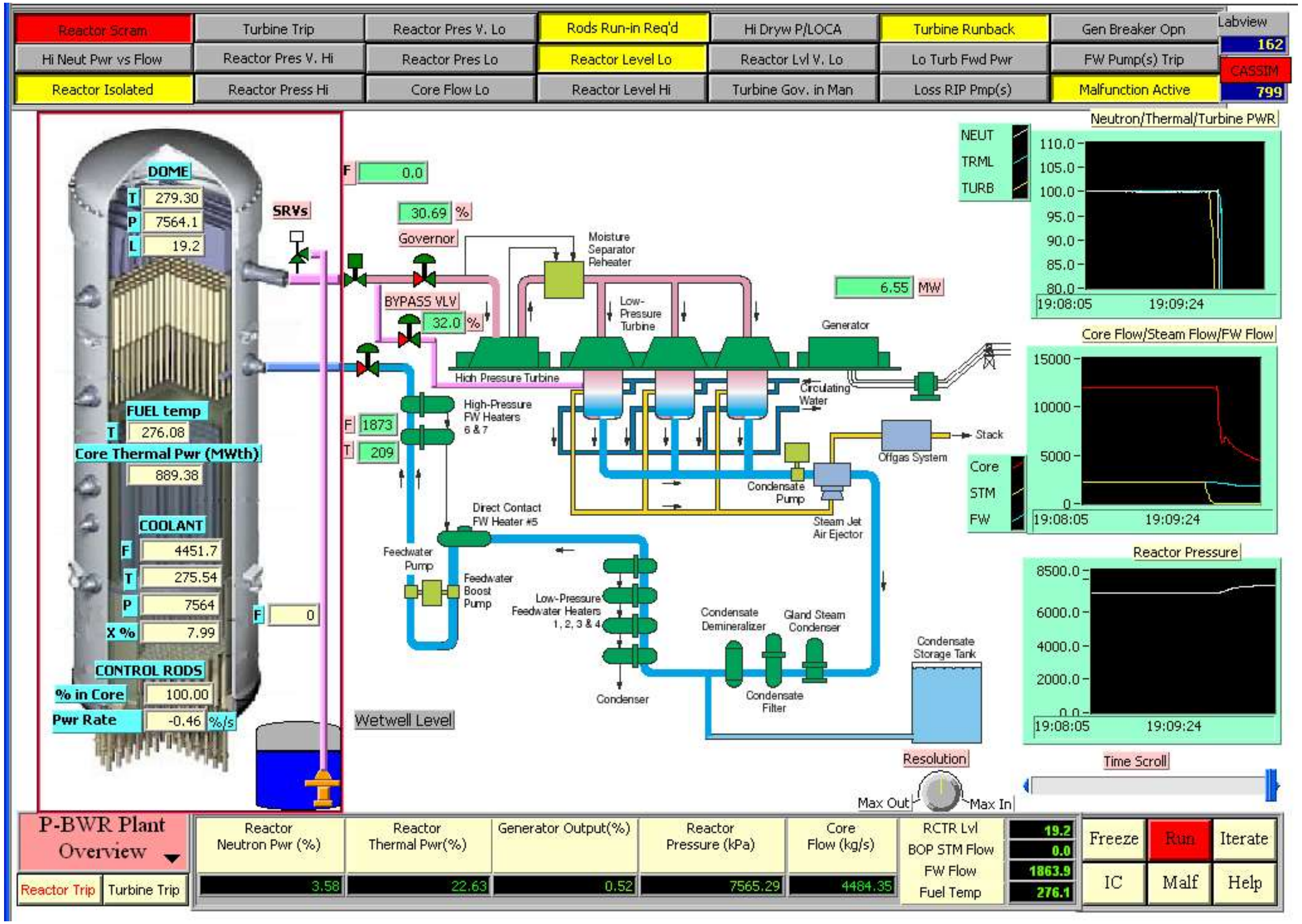


- **Various steam line and nuclear system malfunctions, or operator actions, can initiate MSIV closure.**
  - Manual action (purposely or inadvertent);
  - Spurious signals such as low pressure, low reactor water level, low condenser vacuum;
  - Equipment malfunctions, such as faulty valves or operating mechanisms.

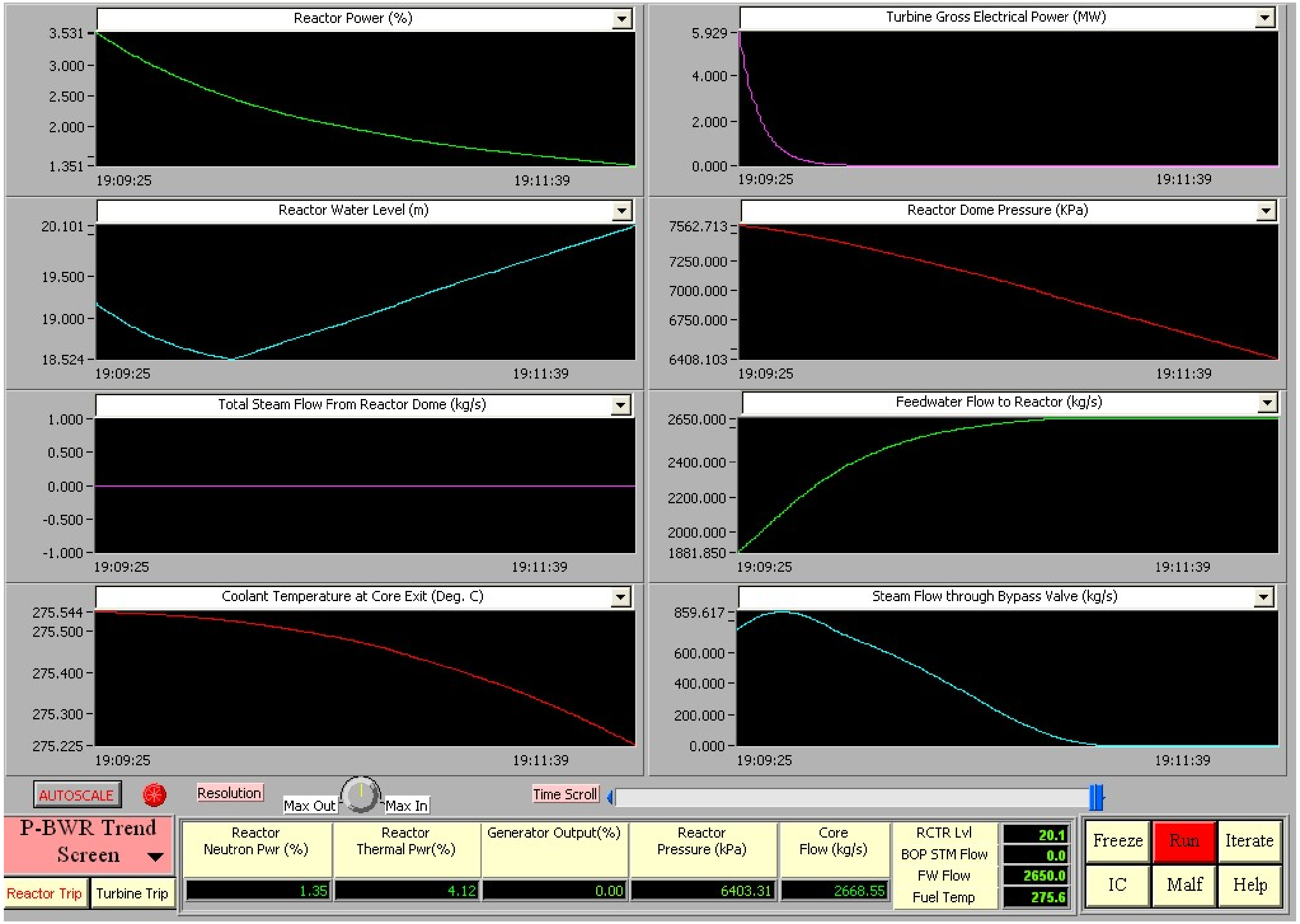
- **Practice at the Simulator**
  - Load the FP_100.IC
  - Load the Inadvertent Reactor Isolation – Closure of all MSIVs
  - On the Passive BWR Plant Overview Screen, observe the status of the MSIV
  - Note the steam flow from the reactor dome
  - Observe the status of SRV to suppression pool
  - At the bottom of the screen, note the following parameters, as the event evolves:

	10 sec.	30 sec.	1 minute	5 minutes
Reactor Power				
Generator Output				
Reactor Pressure				
Core flow				

Plant Exercises 2 – Inadvertent Reactor Isolation

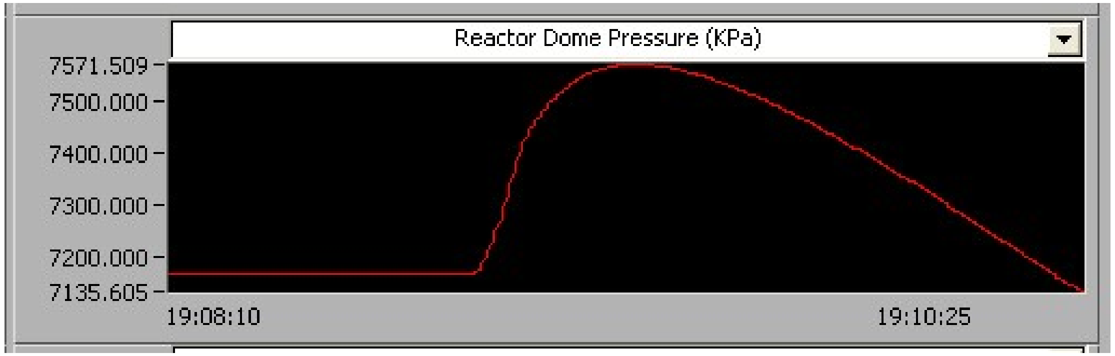


Plant Exercises 2 – Inadvertent Reactor Isolation



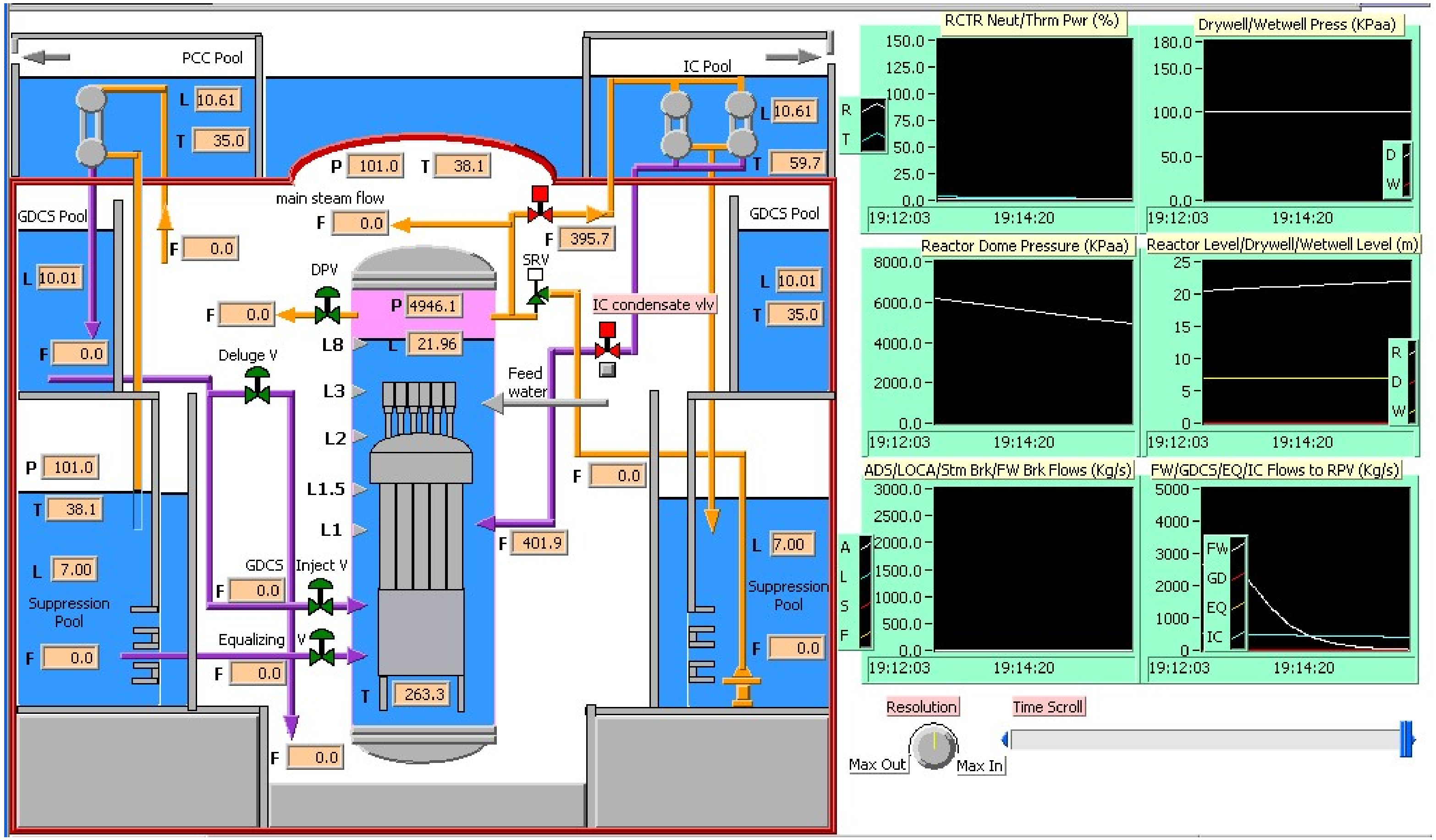
Plant Exercises 2 – Inadvertent Reactor Isolation

- **Various steam line and nuclear system malfunctions, or operator actions, can initiate MSIV closure.**
  - When the
  - Spurious signals such as low pressure, low reactor water level, low condenser vacuum;



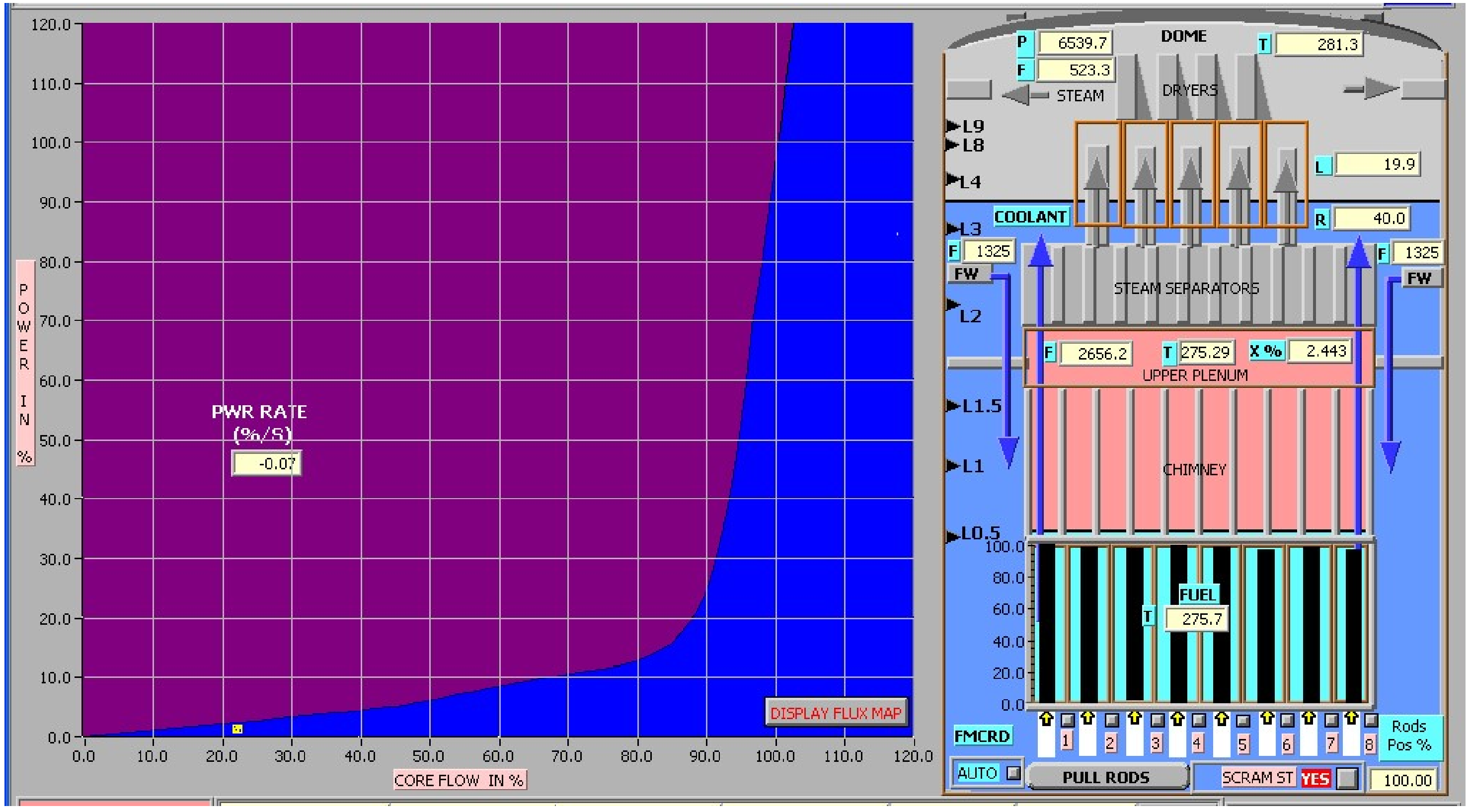
Plant Exercises 2 – Inadvertent Reactor Isolation

► **Various steam line and nuclear system malfunctions, or operator actions, can initiate MSIV closure.**



Plant Exercises 2 – Inadverted Reactor Isolation

- ► **Various steam line and nuclear system malfunctions, or operator actions, can initiate MSIV closure.**



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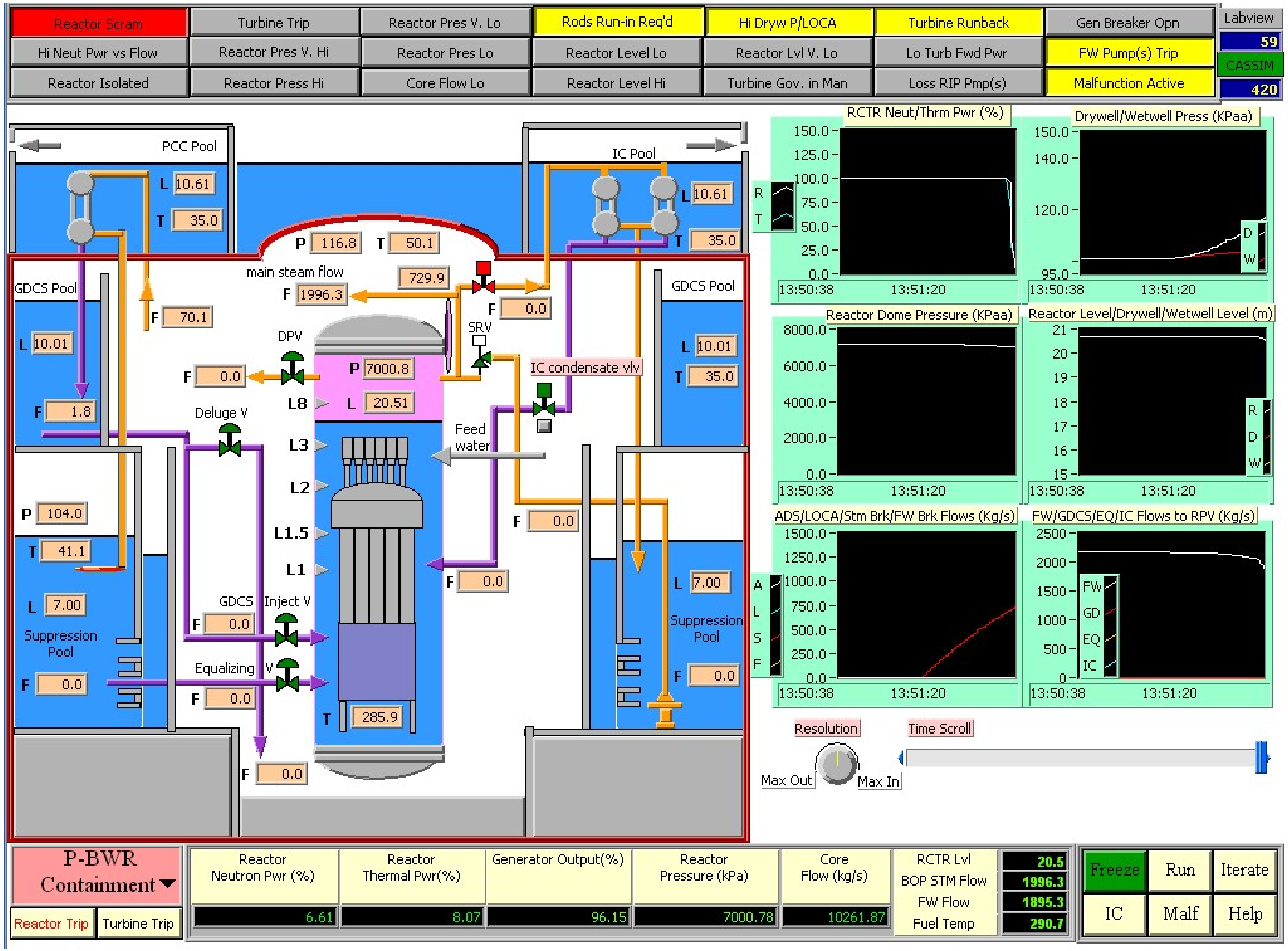
Plant Exercises 2 – Inadvertent Reactor Isolation

- **Various steam line and nuclear system malfunctions, or operator actions, can initiate MSIV closure.**
- **Sequence of Events**
  - MSIV closure initiates a reactor scram via position signals to the RPS.
  - The same signal also initiates the operation of isolation condensers, which prevent the lifting of SRVs.
  - Closure of MSIV causes the dome pressure to increase.
  - The isolation condenser operation terminates the pressure increase.
  - The anticipatory scram prevents any change in the thermal margins.

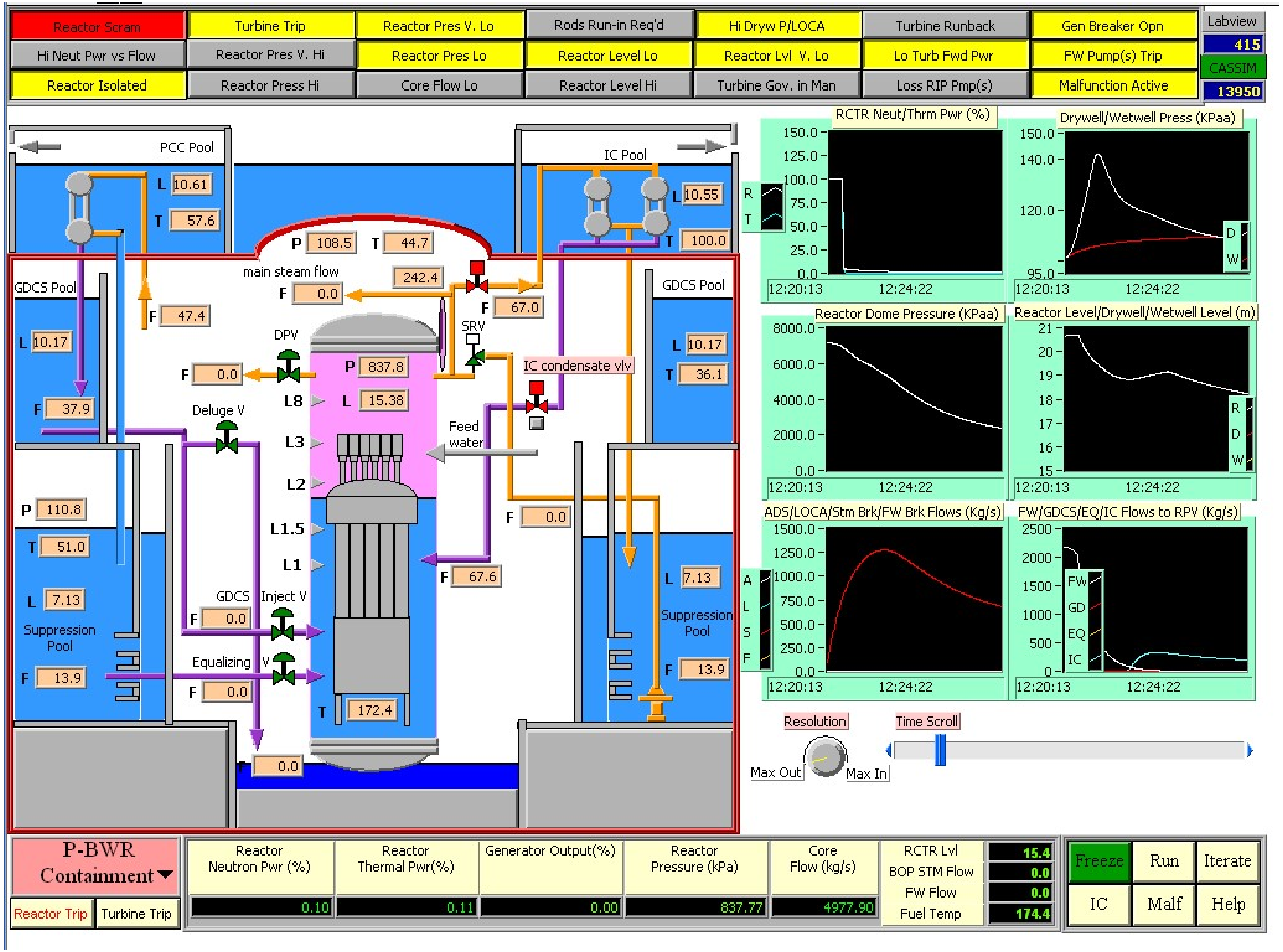
Plant Exercises 2 – Steam line break inside drywell

- **During normal operation (stable operation) suddenly a Main Steam Line Break Inside Containment (Drywell) occurs**
  - Load the FP_100.IC and start the simulator
  - Insert the Malfunction “Steam Line Break inside Drywell”
- **Describe the Event Sequence using the Containment Screen and Alarm Panel**
  - Which Safety System will be activated
  - When will the safety systems been activated
  - On which parameters depends the activation of safety systems
- **Special attention shall be paid to the following Parameters**
  - Steam Flow to Drywell
  - Drywell Pressure
  - Steam Flow from Drywell to Wet Well
  - Reactor Water Level
- **Check and record different mass flows/balances**
  - Explain differences if there any

Plant Exercises 2 – Steam line break inside drywell

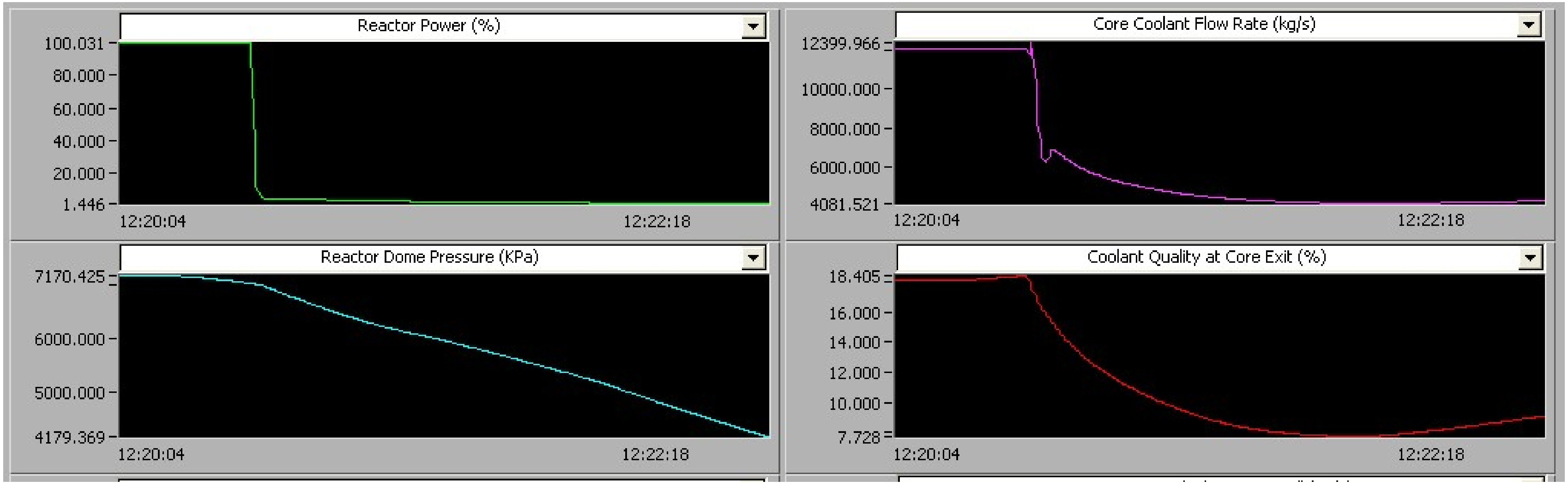


Plant Exercises 2 – Steam line break inside drywell



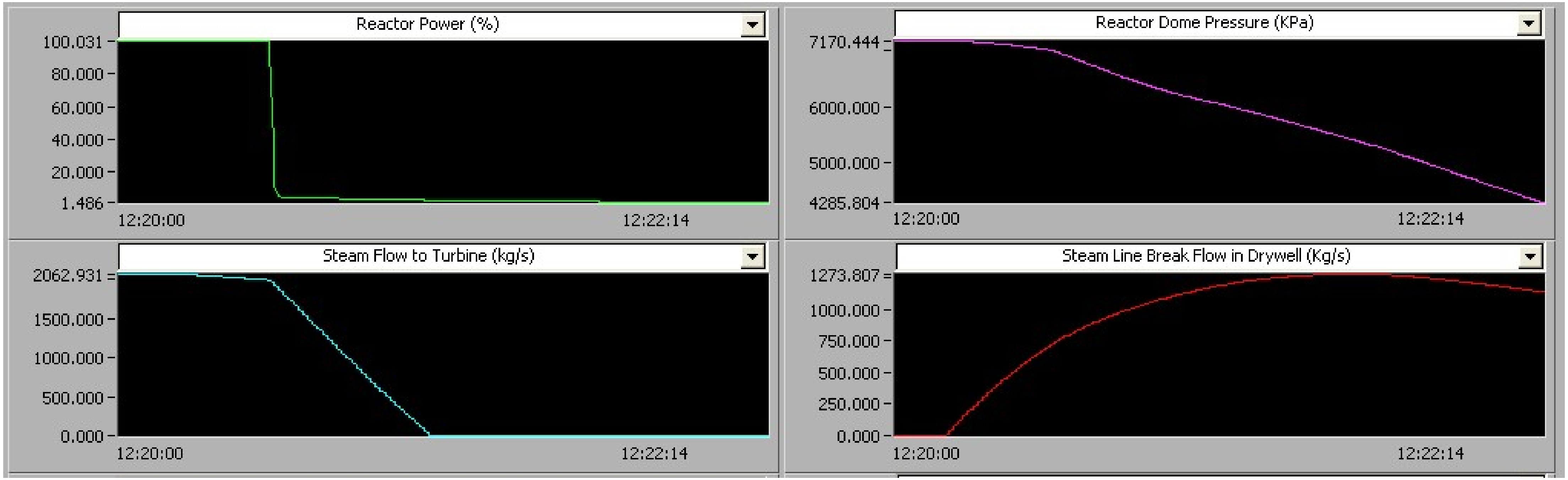
Plant Exercises 2 – Steam line break inside drywell

- Drywell Pressurization due to Break Flow
- SCRAM Activation at High Drywell Pressure
- RPV De- pressurization
- Increased Void



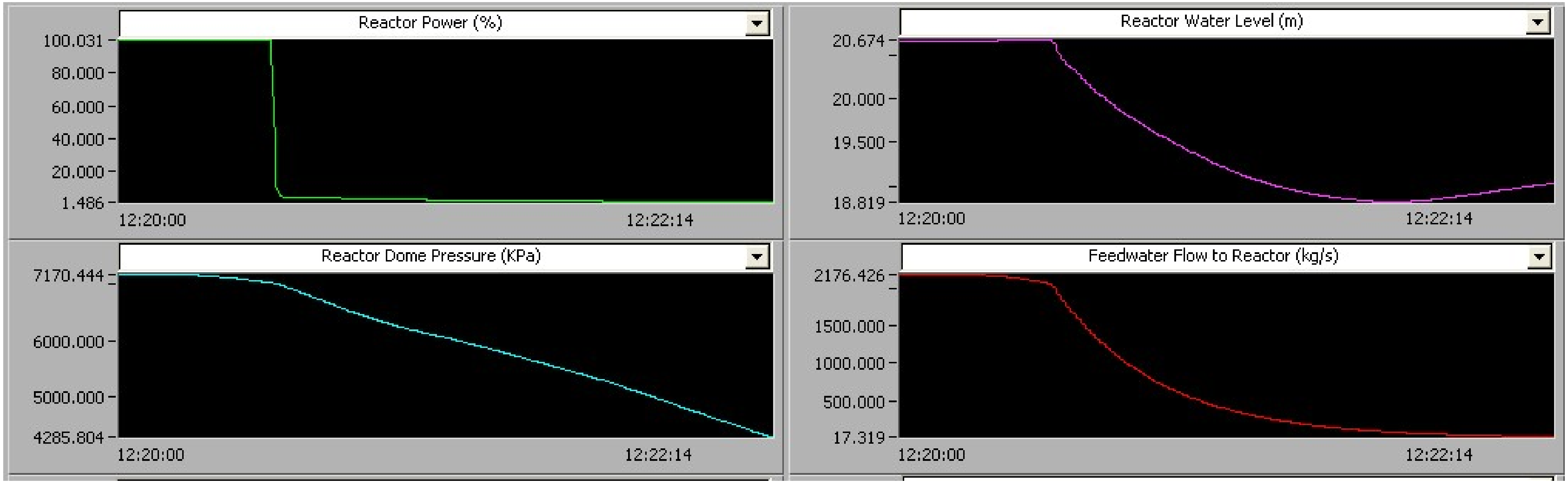
Plant Exercises 2 – Steam line break inside drywell

- ► MSIV Closure at Lo Steam Line Pressure (Reactor Isolated)
- ► IC condenser will be activated due to MSIV closure
- ► RPV De- pressurization continues

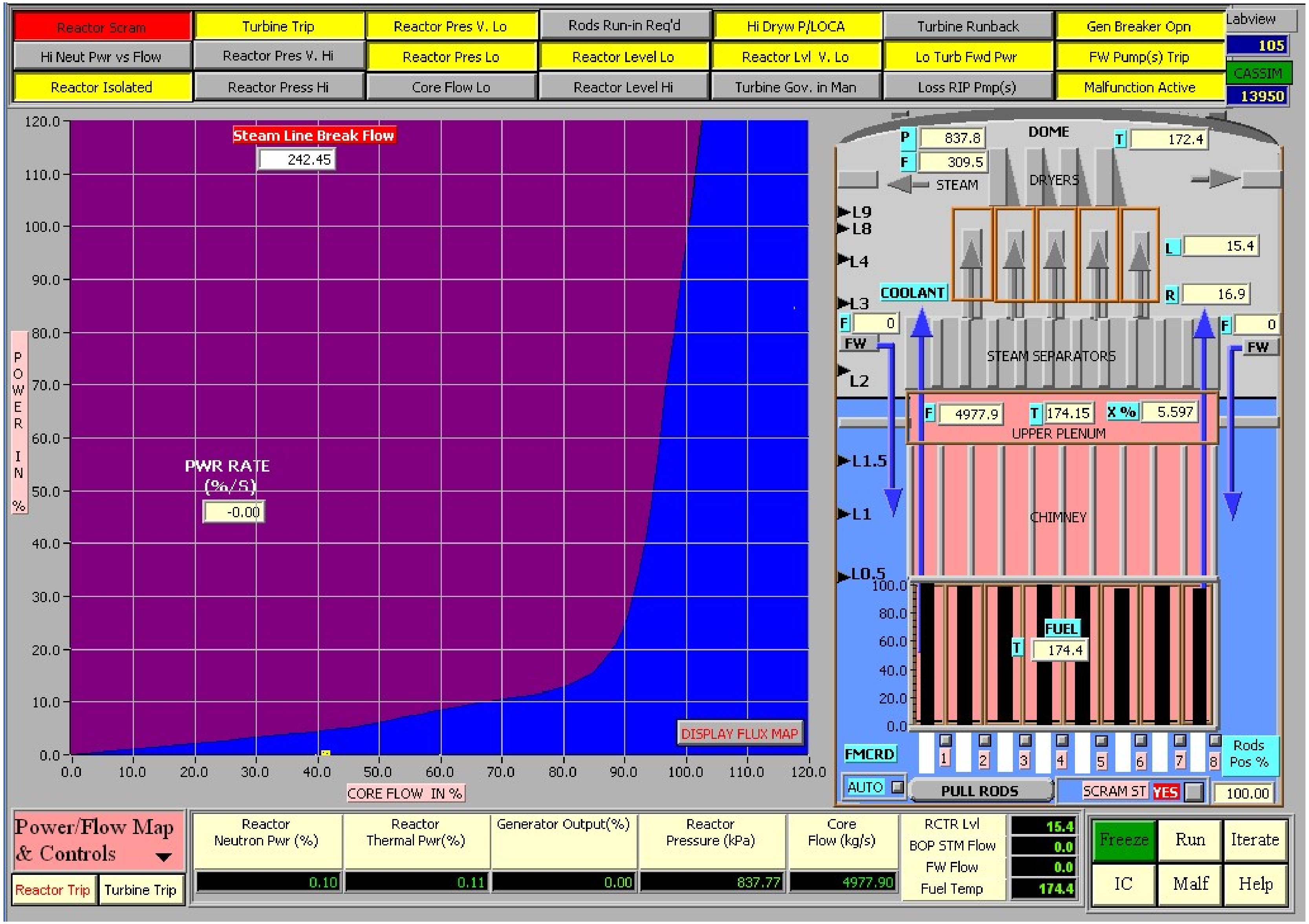


Plant Exercises 2 – Steam line break inside drywell

- ► Reactor Water Level Reaches L3 < 19 m
- ► Feed water flow stops
- ► RPV De- pressurization continues



Plant Exercises 2 – Steam line break inside drywell



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Joint ICTP IAEA Training course on Physics and Technology of Water Cooled Reactors through the Use of PC-based Simulators

Thank you for your attention!

Further Questions?

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