Analysis of Operator Response to Station BlackOut

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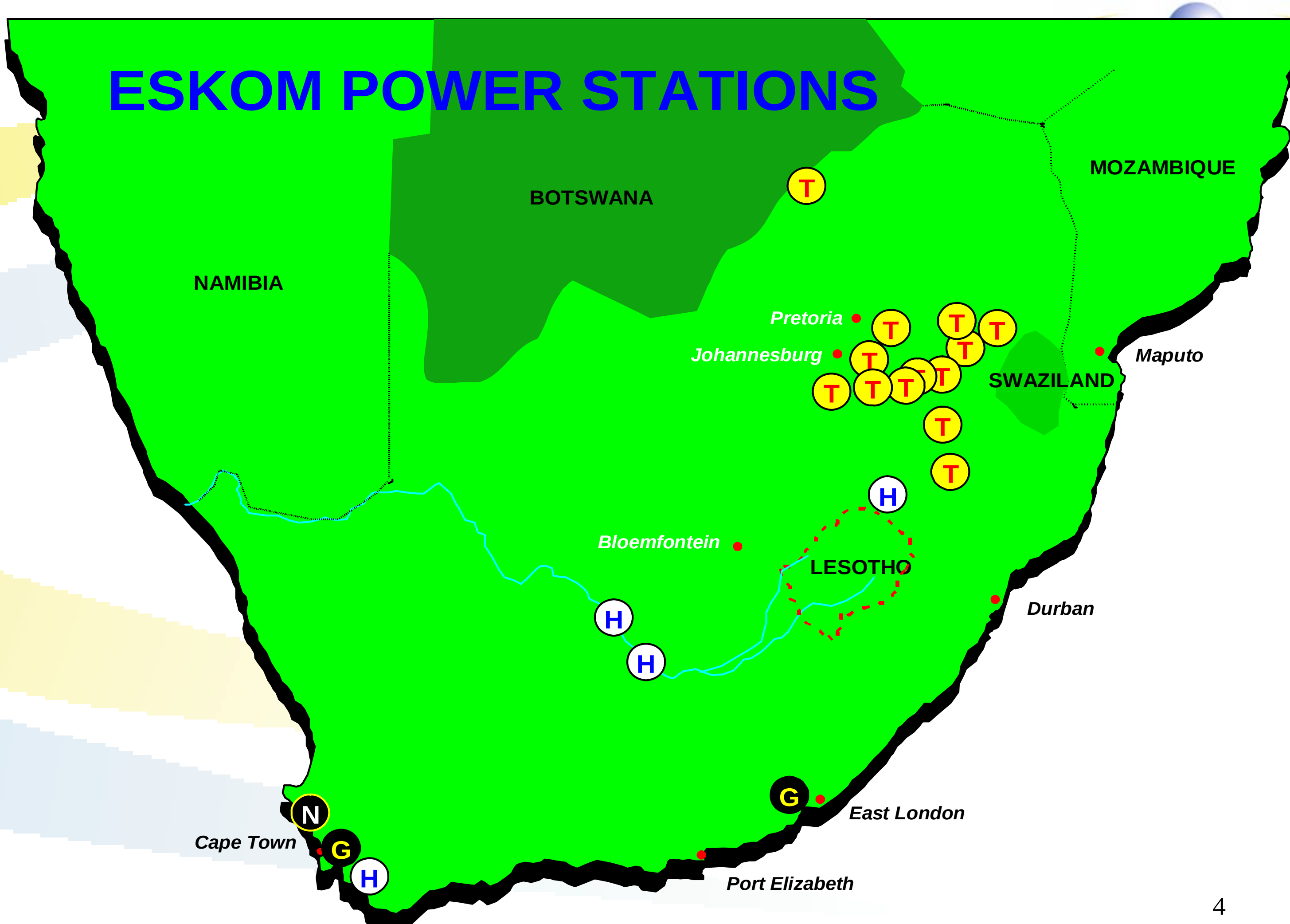
Introduction



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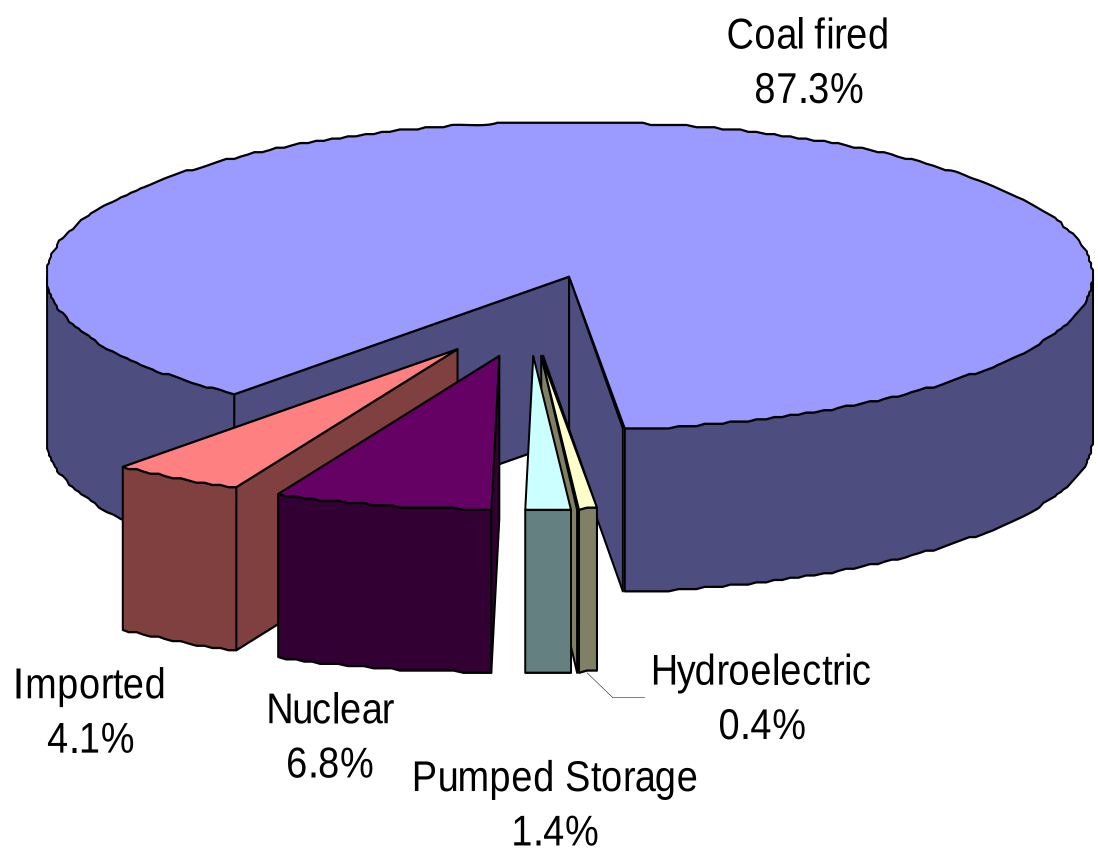
Introduction



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Koeberg Nuclear Power Station Site

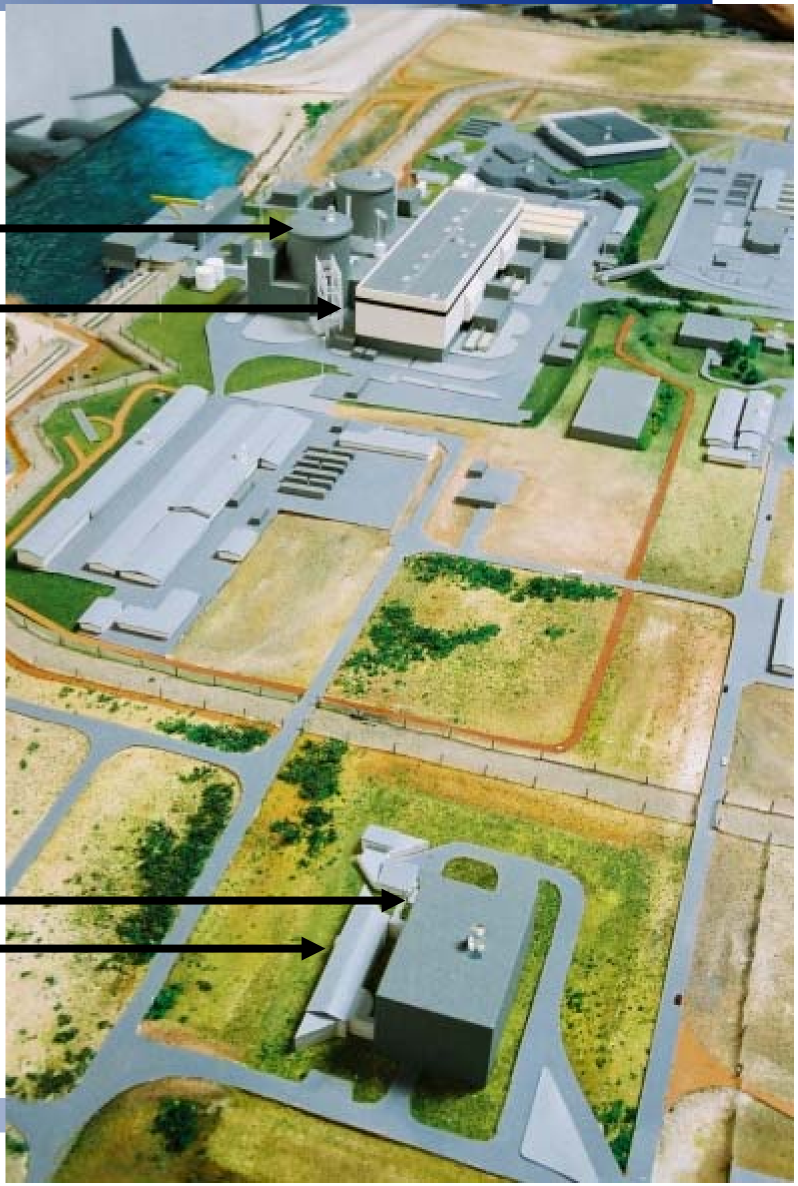
Koeberg Nuclear Power Station Site

Unit 1 & 2 Nuclear Reactor Containment

Turbine Hall

PBMR

PBMR Module Control Buiding



Introduction

Station BlackOut (SBO):

Simultaneous loss of all offsite and onsite AC power sources

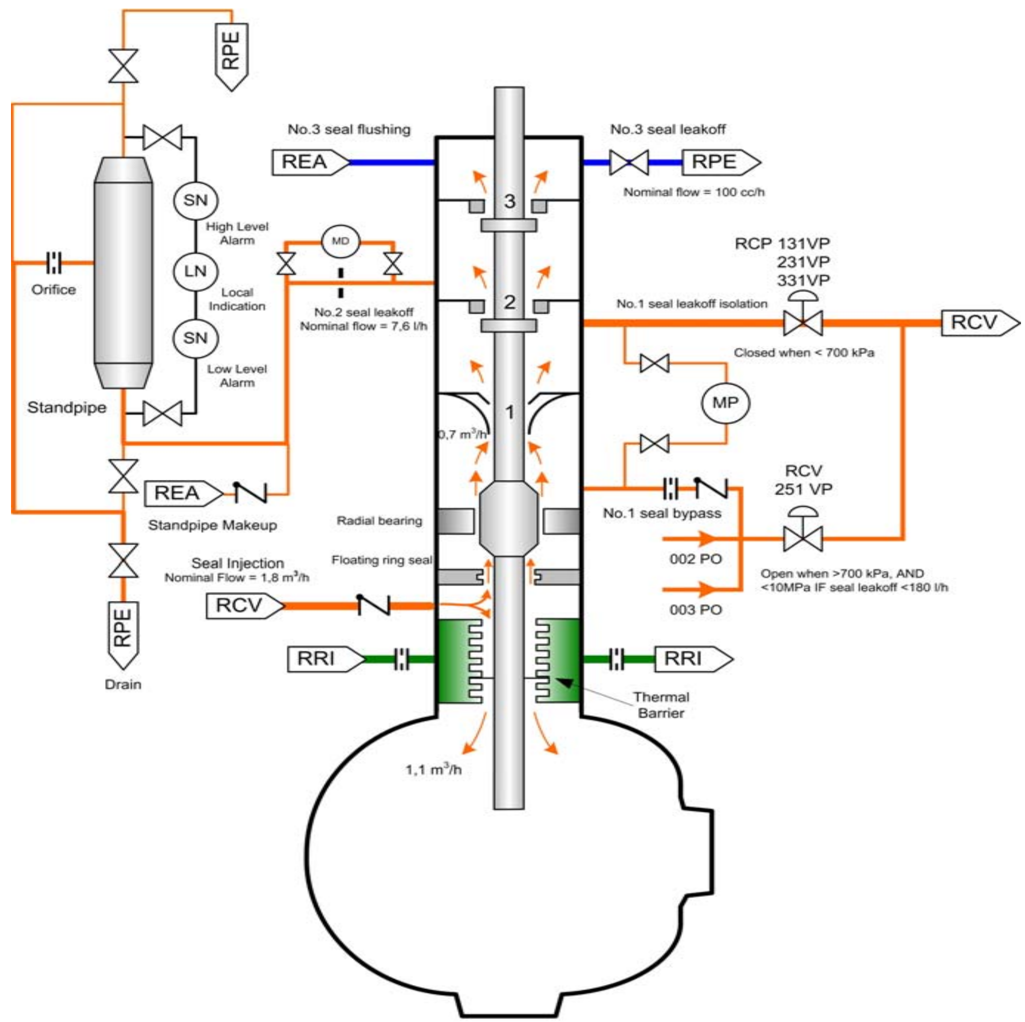
SBO results in:

- Loss of primary charging pumps providing RCP sealing water
- Loss of Component Cooling Water causes loss of RCP thermal shield cooling

Safety concern:

- Failure of RCP seals due to their overheating
- Safety Injection unavailability due to SBO
- Unmitigated LOCA, inadequate core cooling, fuel failure

Reactor Coolant Pumps' Seals Design



RCP pump seal injection and seal leakoff flows

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RCP Seals Design

Seal #1 - Main seal

- Designed for pressure drop of nominal RCS pressure
- Leakage within 0.68 - 1.02 [m^3/h]: most to leak-off line, rest to seal #2
- Leak-off from No.1 seal is returned to charging pumps suction side.

Seal #2 – To provide backpressure on seal #1

- Designed for full RCS pressure when Seal #1 fails; limits then RCS leakage within 1.8 to 2.7 [m^3/h]
- Normal leakage about 11 [dm^3/h]: most to leak-off line, rest to #3 seal.

Seal #3 – To provide backpressure on seal #2

- Designed to limit leakage to the containment
- Leakage directed to containment sump
- **<u>Not a pressure boundary seal, does not play a role in limiting RCS leakage following SBO</u>**

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RCP Seals' Cooling

Normal Operating Conditions:

1) RCP seal injection flow (from RCS charging pumps)

- Seal injection flow acts as a buffer to prevent reactor coolant from entering the pump seal and bearing section.
- A portion of the seal injection flows down the pump shaft and into RCS, the remainder flows up through the seals system

2) RCP thermal barrier cooled by Component Cooling Water

- Heat exchanger to cool the incoming reactor coolant before it enters the RCP bearing and seals
- Reservoir of cool water: When sealing flow lost, it takes several minutes to leak cool water through RCP seals before hot reactor coolant fills the volume and approaches bearing and seal #1

Abnormal Operating Conditions:

At least one cooling system should be restored within several minutes

RCP Seals Leakage Models

RCP seal leakage rate:
Dependent on RCS pressure and seals' material temperature

Timing After Loss of All RCP Seal Cooling							
0 – 13 minutes		13 – 120 minutes		Greater than 120 minutes			
				RCS Pressure less than 11.8 MPa		RCS Pressure less than 11.8 MPa	
Probability	Flow [m^3/h]	Probability	Flow [m^3/h]	Probability	Flow [m^3/h]	Probability	Flow [m^3/h]
1.0	4.769	0.79	4.769	0.79	4.769	0.396	4.769
		0.01	17.26	0.01	17.26	0.005	17.26
		0.1975	41.33	0.1975	41.33	0.099	41.33
		0.0025	109	0.0025	109	0.50	109

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RCP Seals Leakage Models

Average RCP Seals Leakage Flow Rates as Function of Time

Time interval after SBO	Average leakage flow rate per Reactor Coolant Pump
0 – 13 minutes	4.769 [m^3/h]
13 – 120 minutes	12.375 [m^3/h]
Greater than 120 minutes, with RCS pressure < 11.8 MPa	12.375 [m^3/h]
Greater than 120 minutes, with RCS pressure > 11.8 MPa	60.566 [m^3/h]

Note: Above RCP seals' leakage rates correspond to primary coolant conditions at cold leg, RCP discharge side, at nominal reactor power (T=277 ^oC, P=16 MPa

Operator Response to Station Black Out

Plant recovery from SBO:

- Only possible by restoring AC power
- In the meantime: Minimize RCS inventory loss

Objective (as defined by US NRC):

Ensure SBO Coping Time of 4 to 8 hours

Operator actions:

1) Limit loss of RCS coolant:
   Close primary PORV, letdown
2) Limit loss of SG coolant:
   Isolate SG normal feed water, SG blow-down, close Main Steam Isolation Valves (MSIVs)
3) Use turbine-driven AFW pump to restore level in SG
4) Open SG relief valves to establish P=1.3 MPa

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RCS Cooldown Benefits and Constraints

Benefits:

- **Reduced rate of RCS coolant leakage through RCP seals postpones fuel overheating**
- **Cooler fluid leaking through RCP seals reduces heat load on seals**
- **Discharge of borated coolant from hydro-accumulators into RCS increases shutdown margin (SDM)**

Constraints:

1) Possible purging of hydro-accumulators nitrogen into RCS:

To prevent it, keep RCS pressure above 0.6 MPa by closing SG steam relief valve

2) Deep cooldown can cause core recriticality:

Possible when low ShutDown Margin (e.g. fail to insert rods, little Xe^{135})

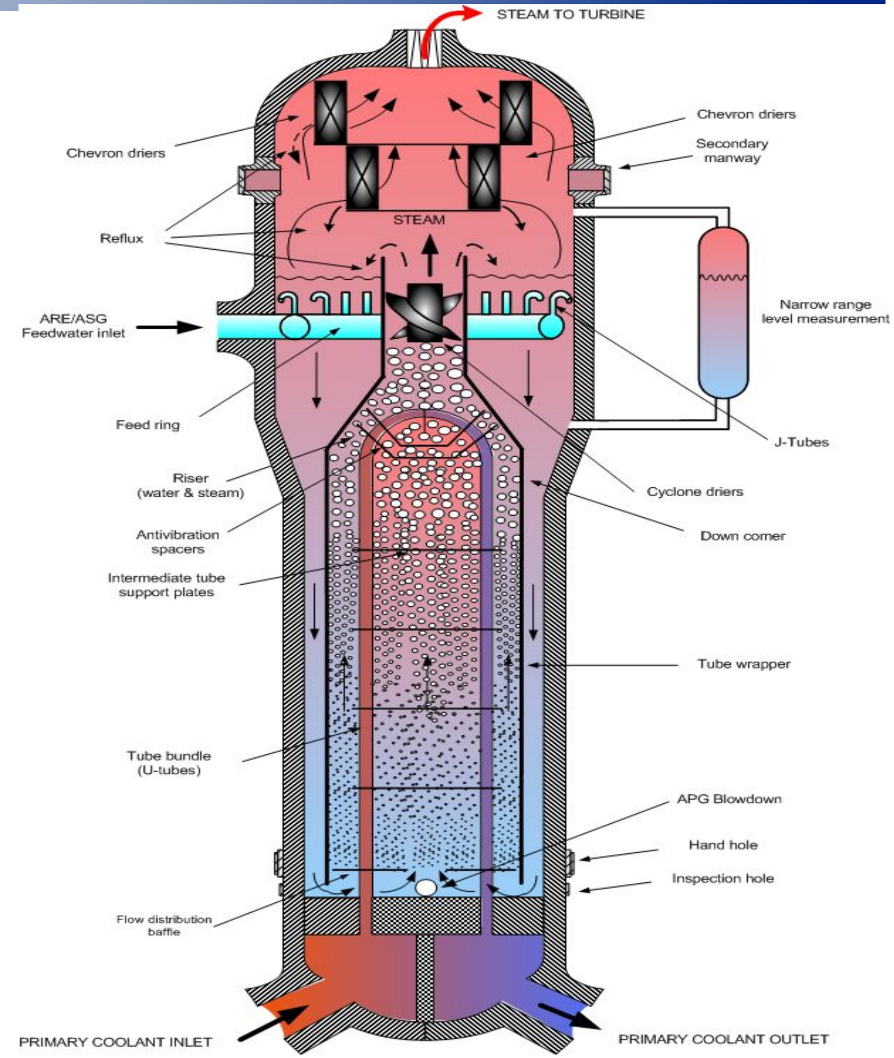
RCS Cooldown Benefits and Constraints

Constraints (CONT'D):

3) Maintain SG level:

Close SG steam relief valve if level too low

Stop feedwater to SG if level too high



Steam Generator

Simulation Results

Case #0: SBO without SG Depressurization

Assumptions:

- Initial plant state: Nominal full power
- Only SG#1 available for depressurization
- Turbine-driven AFW pump flow only to SG#1: 80 [m^3/h] when secondary side pressure P=7.03 [MPa] or higher
- Steam dump to atmosphere only via SG safety valves (P_{OPEN}=7.4 [MPa]
- All MSIVs closed at time $T=T_{SBO}$+10 min
- Operator controls secondary coolant level in SG#1 by opening AFW valve at SG level < -0.9 [m] and closing it at level > 0.2 [m]

Simulation Results

Cases #1 to #3: SBO With SG Depressurization

Assumptions:

- Initial plant state: Nominal full power
- Only SG#1 available for depressurization
- Turbine-driven AFW pump flow only to SG#1:

Case Number	SG pressure 7.45 MPa	SG pressure 1.5 MPa	SG pressure 1.1 MPa
No. 1	80 [m^3/h]	60 [m^3/h]	60 [m^3/h]
No. 2	80 [m^3/h]	50 [m^3/h]	50 [m^3/h]
No. 3	80 [m^3/h]	40 [m^3/h]	40 [m^3/h]

Note: For SG steam pressures in between above values, pump affinity laws used to determine AFW flow as function of SG steam pressure

Simulation Results - Assumptions

Cases #1 to #3: SBO With SG Depressurization

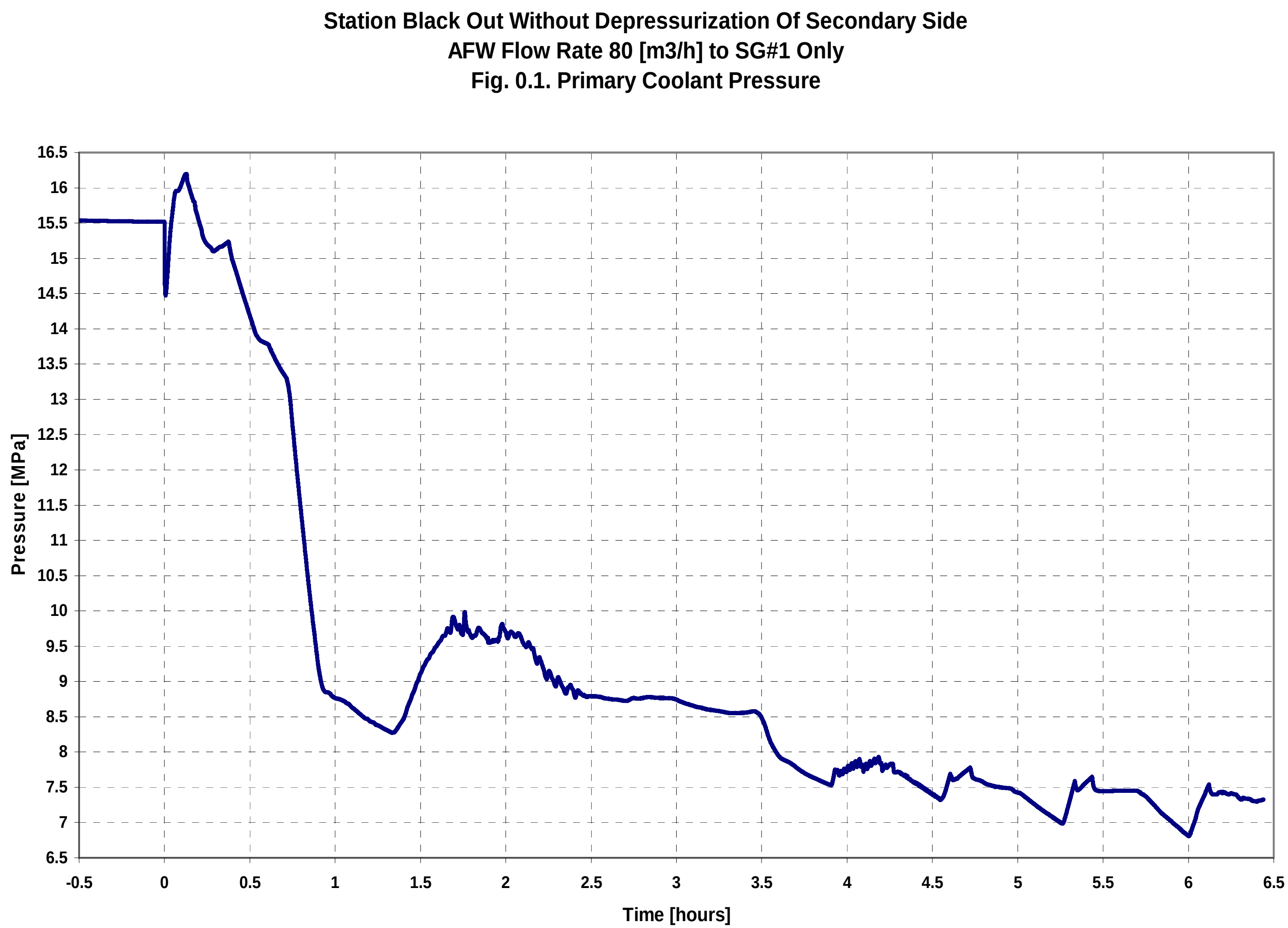
Assumptions:

All MSIVs closed at time $T=T_{SBO}+10$ min

- Steam dump to atmosphere only via SG safety valves ($P_{OPEN}=7.4$ [MPa] until time $T=T_{SBO}+15$ min
- Operator opens at time $T=T_{SBO}+15$ min SG#1 relief valve and dumps steam to establish SG secondary side steam pressure

  $P_{SG}=1.3\pm0.2$ [MPa]
- Operator closes SG#1 relief valve and stops steam dump every time the SG level becomes lower than -1.2 [m]
- Operator controls secondary coolant level in SG#1 by opening AFW valve at SG level < -0.9 [m] and closing it at level > 0.2 [m]

Primary Coolant Pressure



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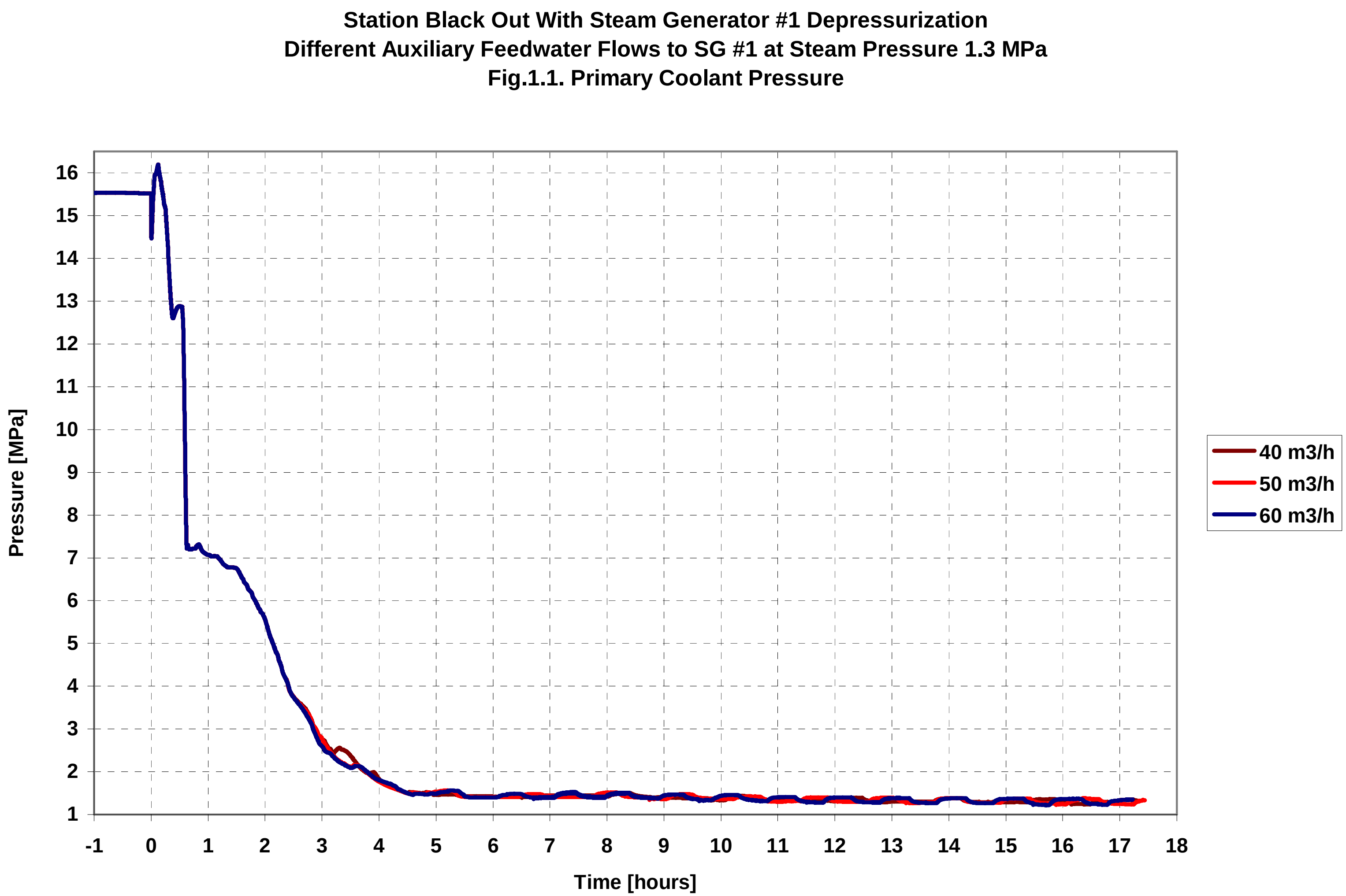
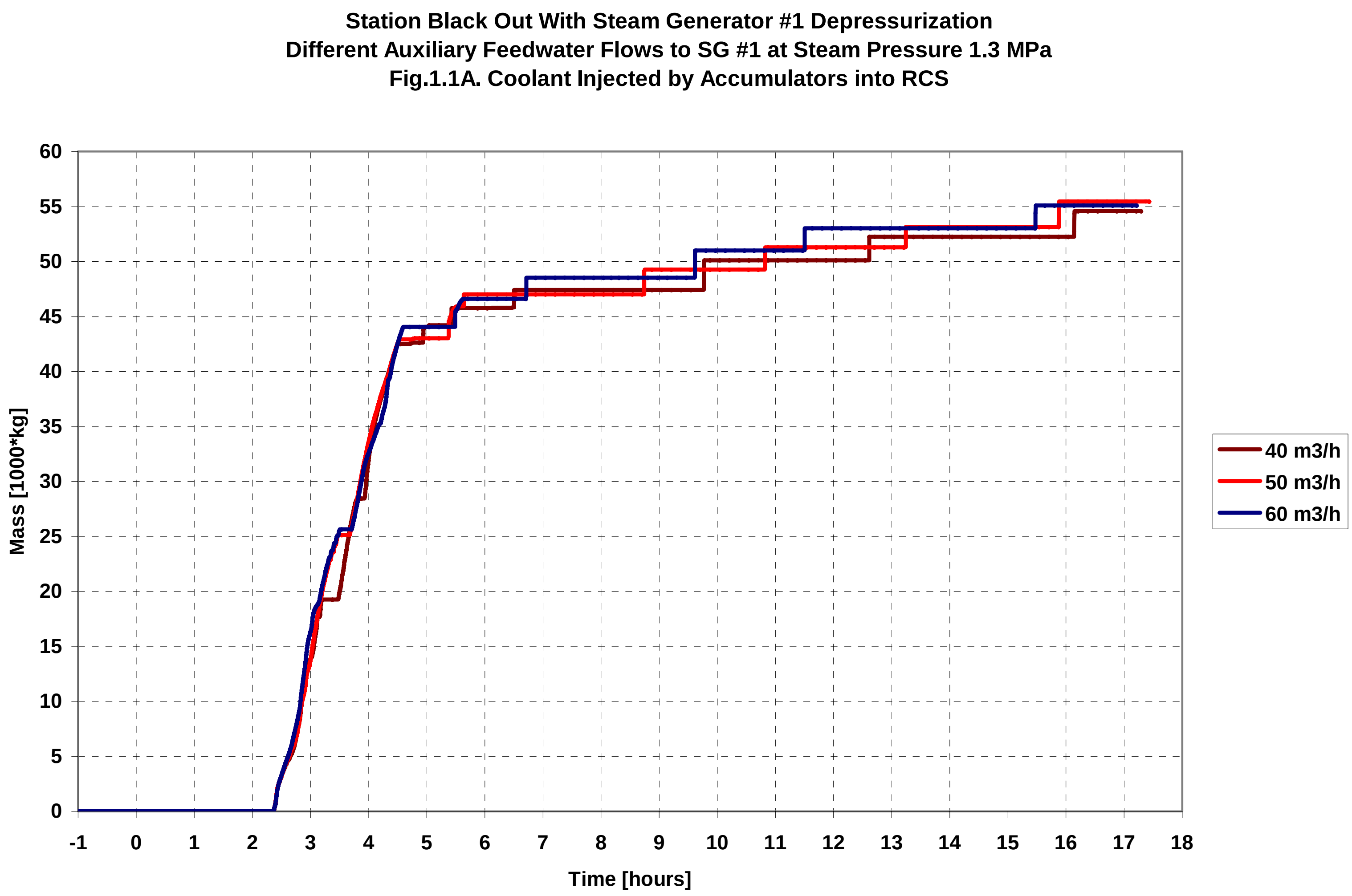
Primary Coolant Pressure



Primary Coolant Injected by Hydro-Accumulators



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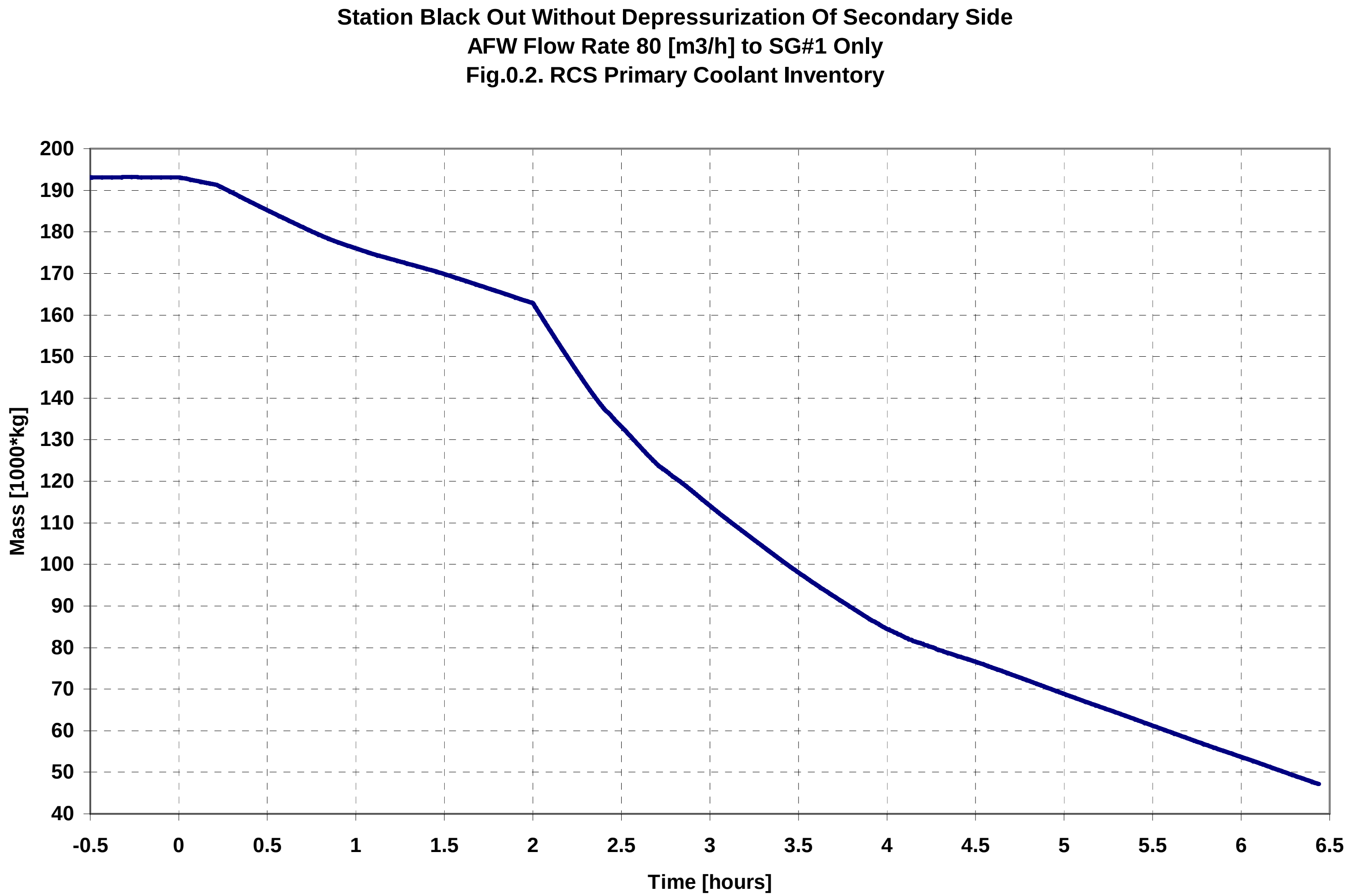
Reactor Coolant System Inventory



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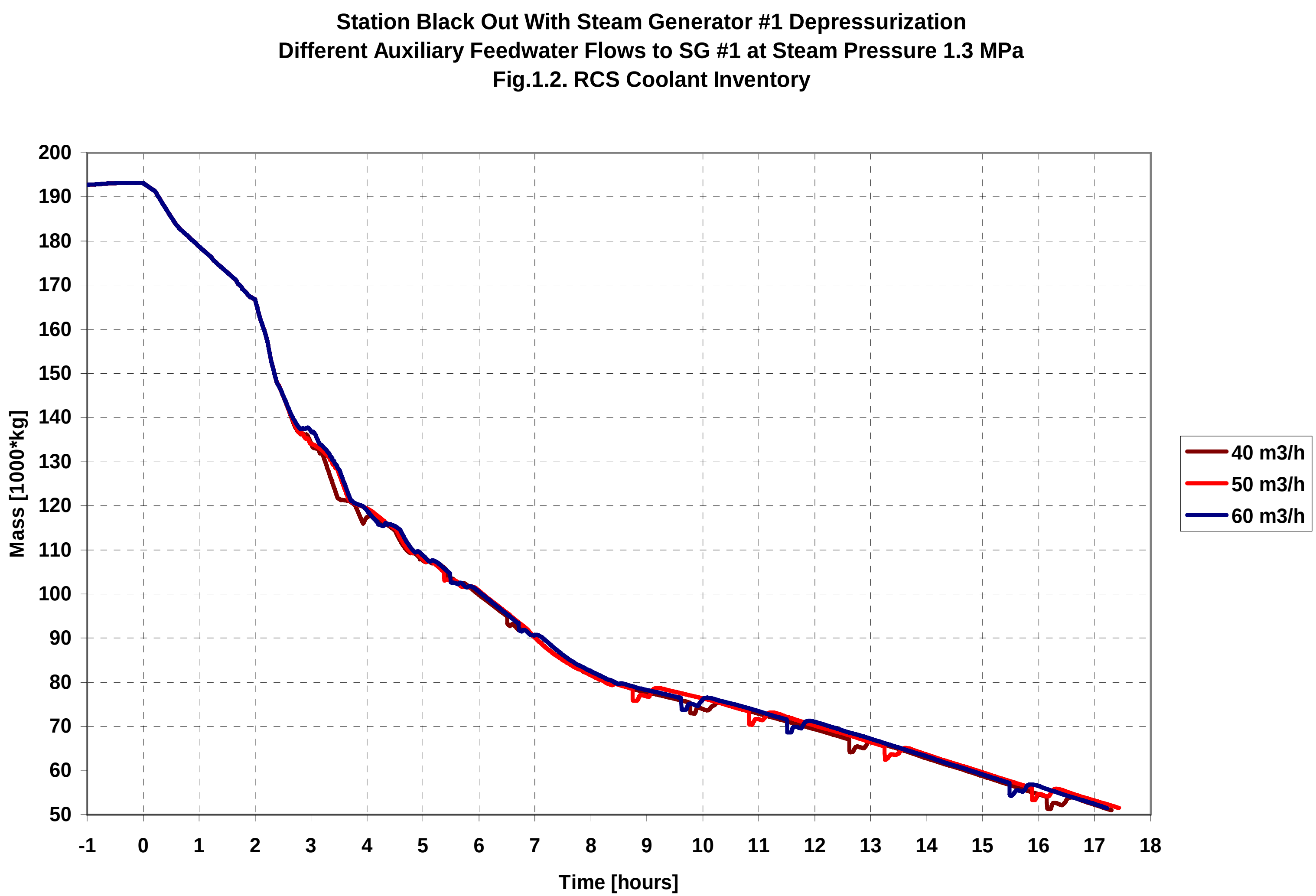
Reactor Coolant System Inventory



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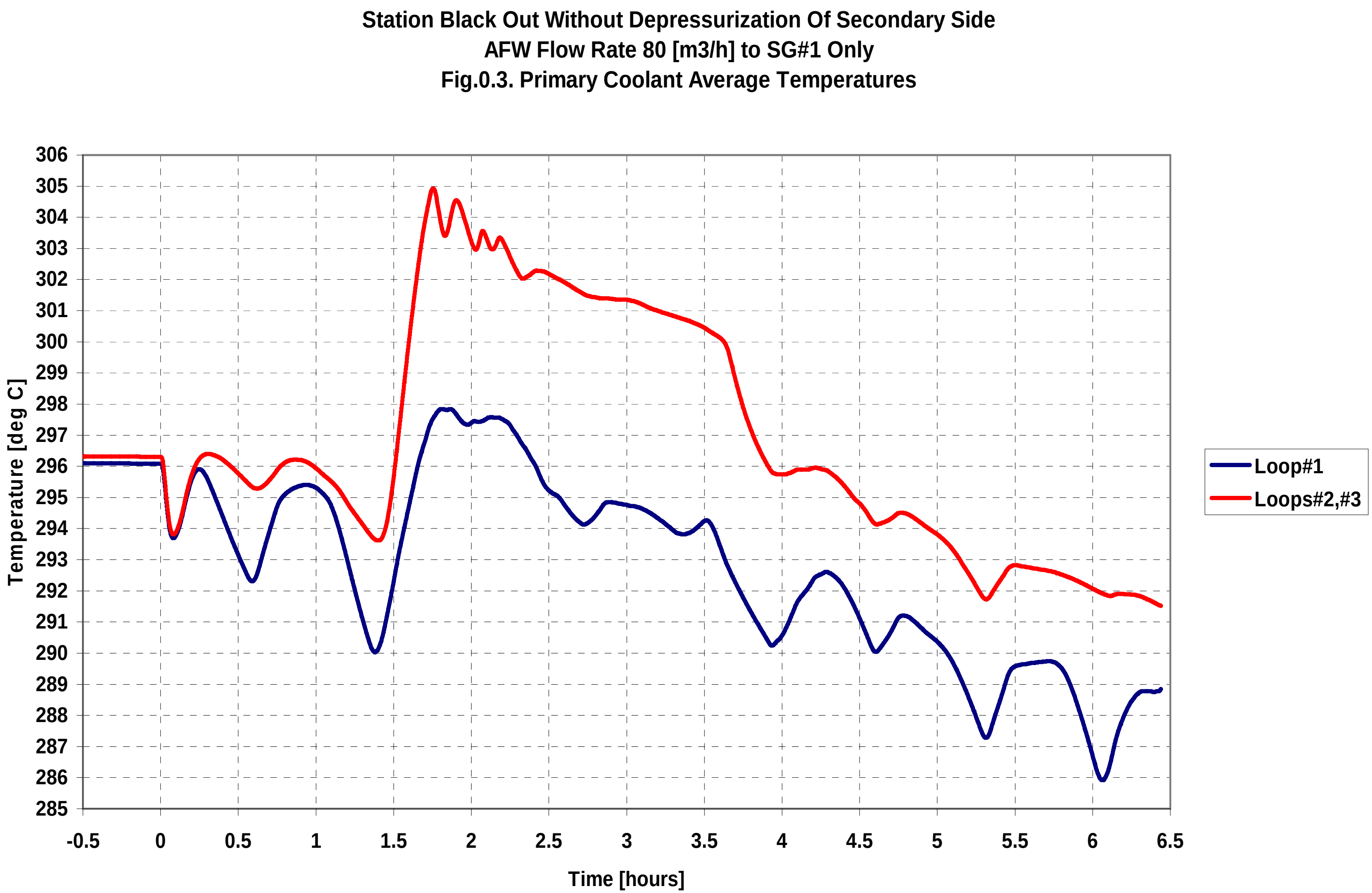
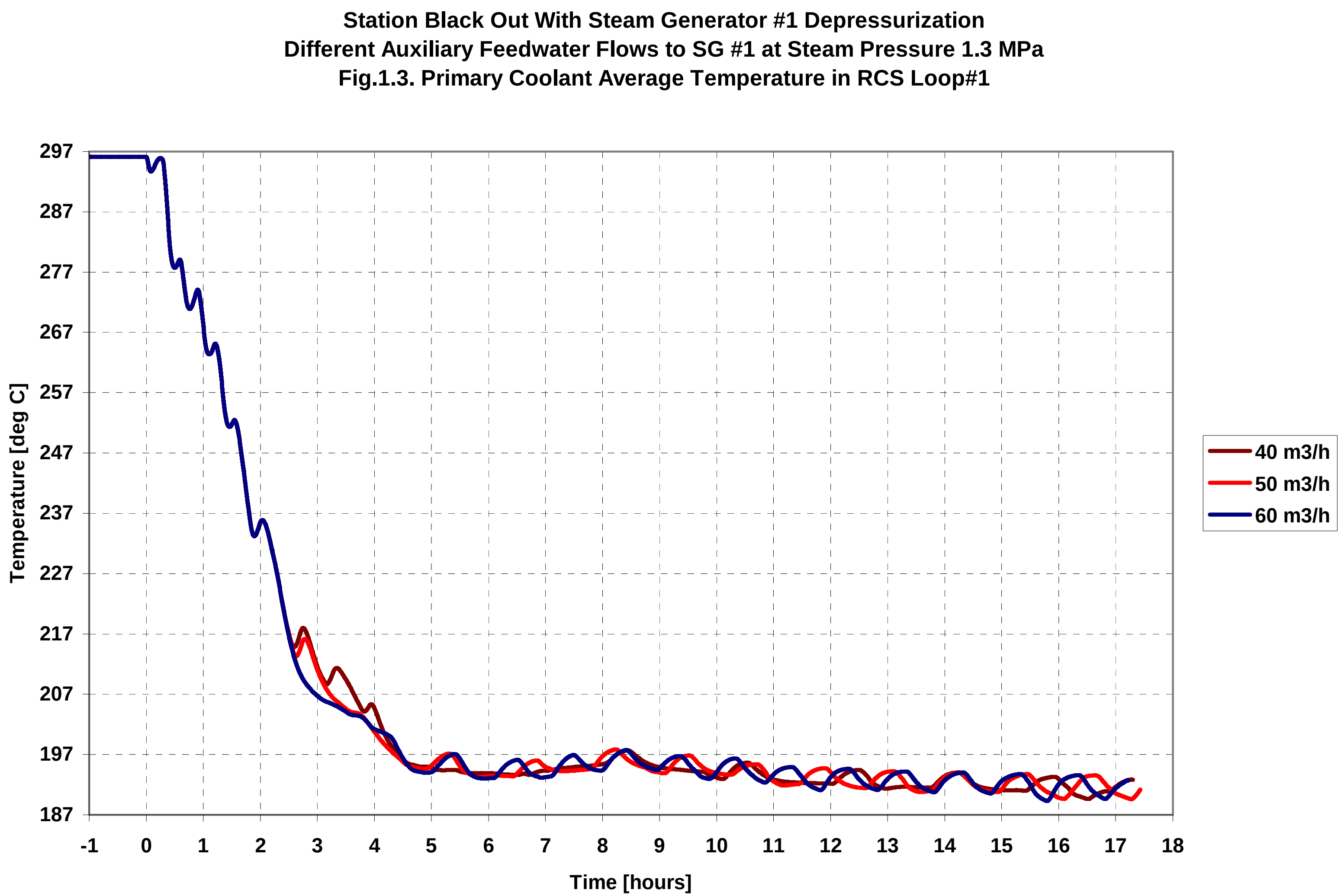
Reactor Coolant Average Temperatures in Loop#1 (SG depressurized) and Loops#2,3 (SGs not depressurized)



Reactor Coolant Average Temperatures in Loop#1 (SG depressurized)



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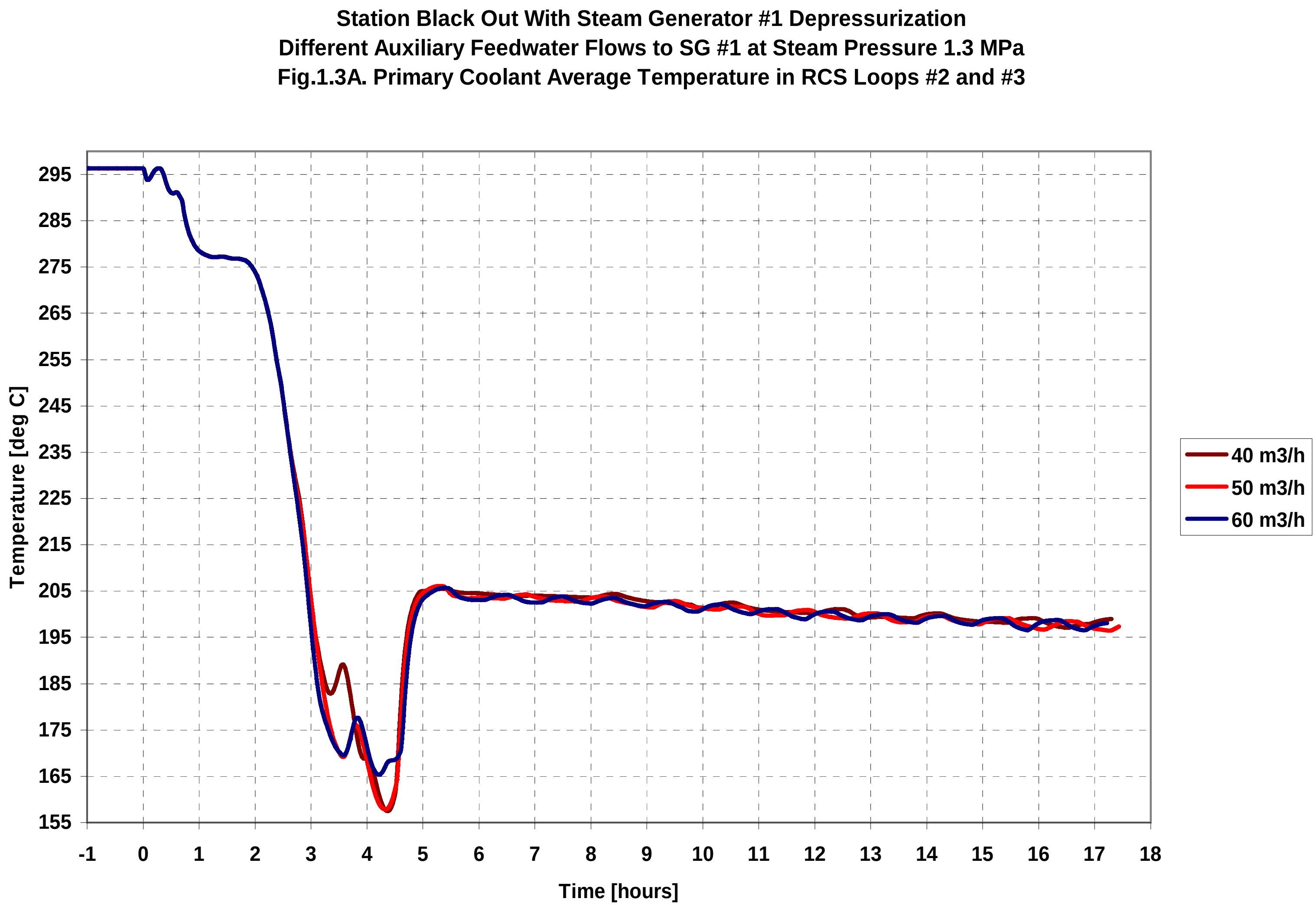
Reactor Coolant Average Temperatures in Loops#2,3 (SGs not depressurized)



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Reactor Pressure Vessel Level Measurement

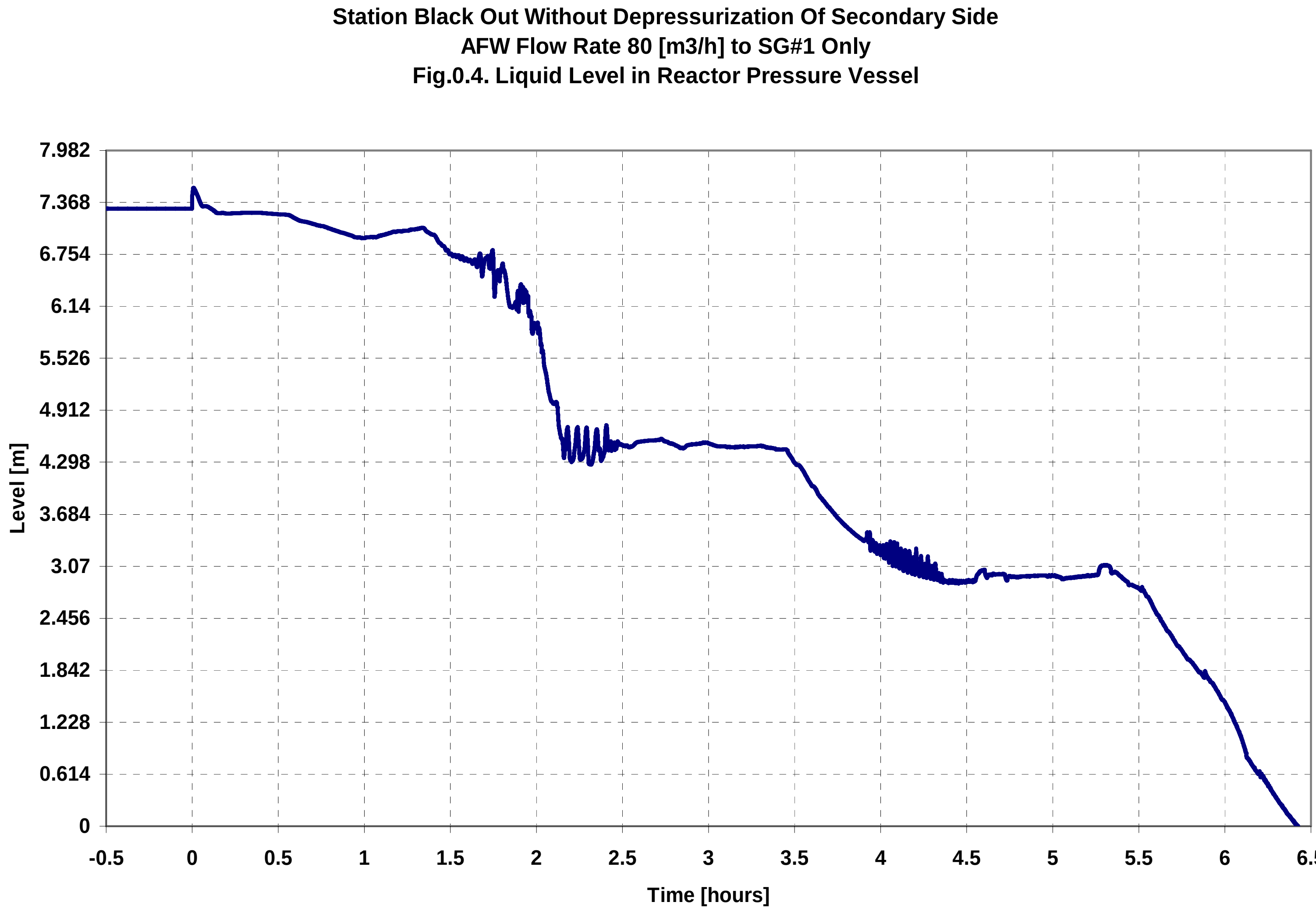
Reactor Pressure Vessel Level Measurement:

"Hot-calibrated" for normal operating conditions: Primary coolant average temperature T_{AVG} = 295.9 [^{o}C] and pressure P= 15.5 [MPa].

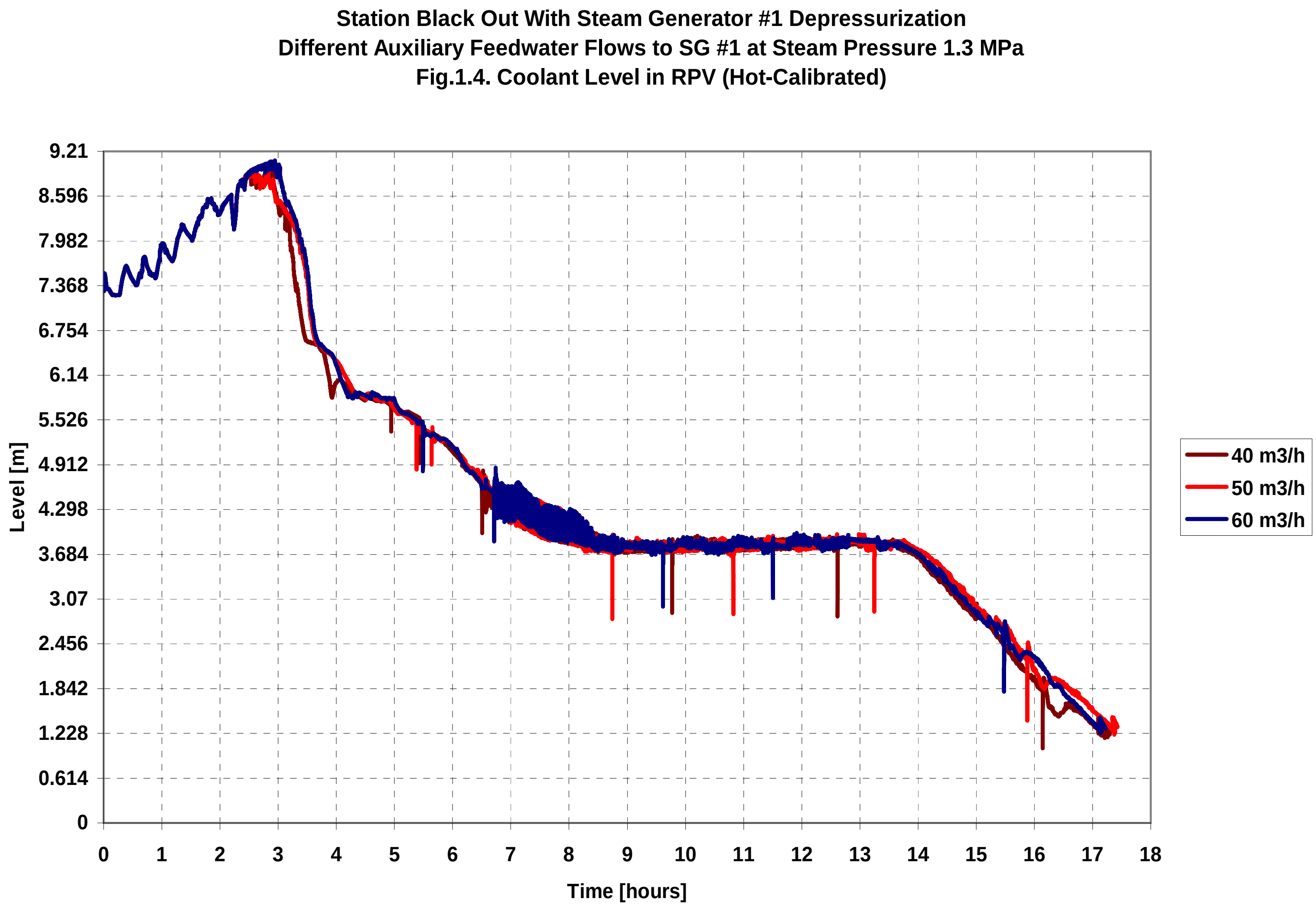
$$L_{RPV} = 10.972 * \frac{\sum_i \left[L_i * \left(\rho_i - \rho_{g,cal} \right) \right]}{L_{RPV} * \left(\rho_{f,cal} - \rho_{g,cal} \right)} - 3.681$$

Value of RPV Indicated Level	**Corresponds to**
7.291 [m]	Reactor vessel completely full of water up to the main flange
5.241 [m]	Steam-liquid mixture level at outlet nozzle centerline
3.682 [m]	Steam-liquid mixture level at top of fuel pellets stack
0.0 [m]	Steam-liquid mixture level at bottom of fuel pellets stack
-3.681 [m]	Reactor vessel completely empty of liquid

Reactor Pressure Vessel Level Measurement

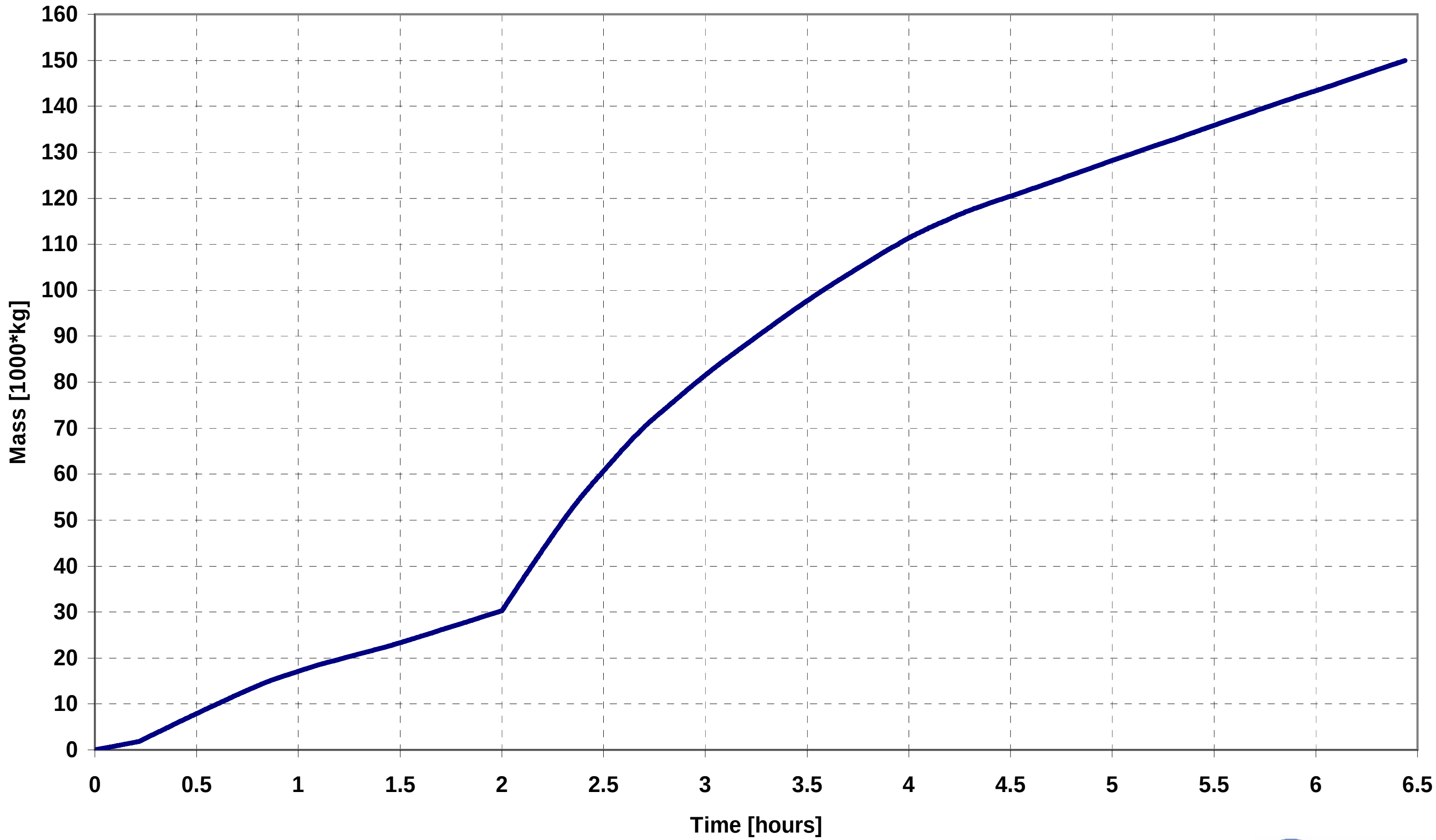


Reactor Pressure Vessel Level Measurement



Total Amount of Primary Coolant Leakage

Station Black Out Without Depressurization Of Secondary Side
AFW Flow Rate 80 [m3/h] to SG#1 Only
Fig.0.5. Total Mass of Primary Coolant Lost Through RCP Seals



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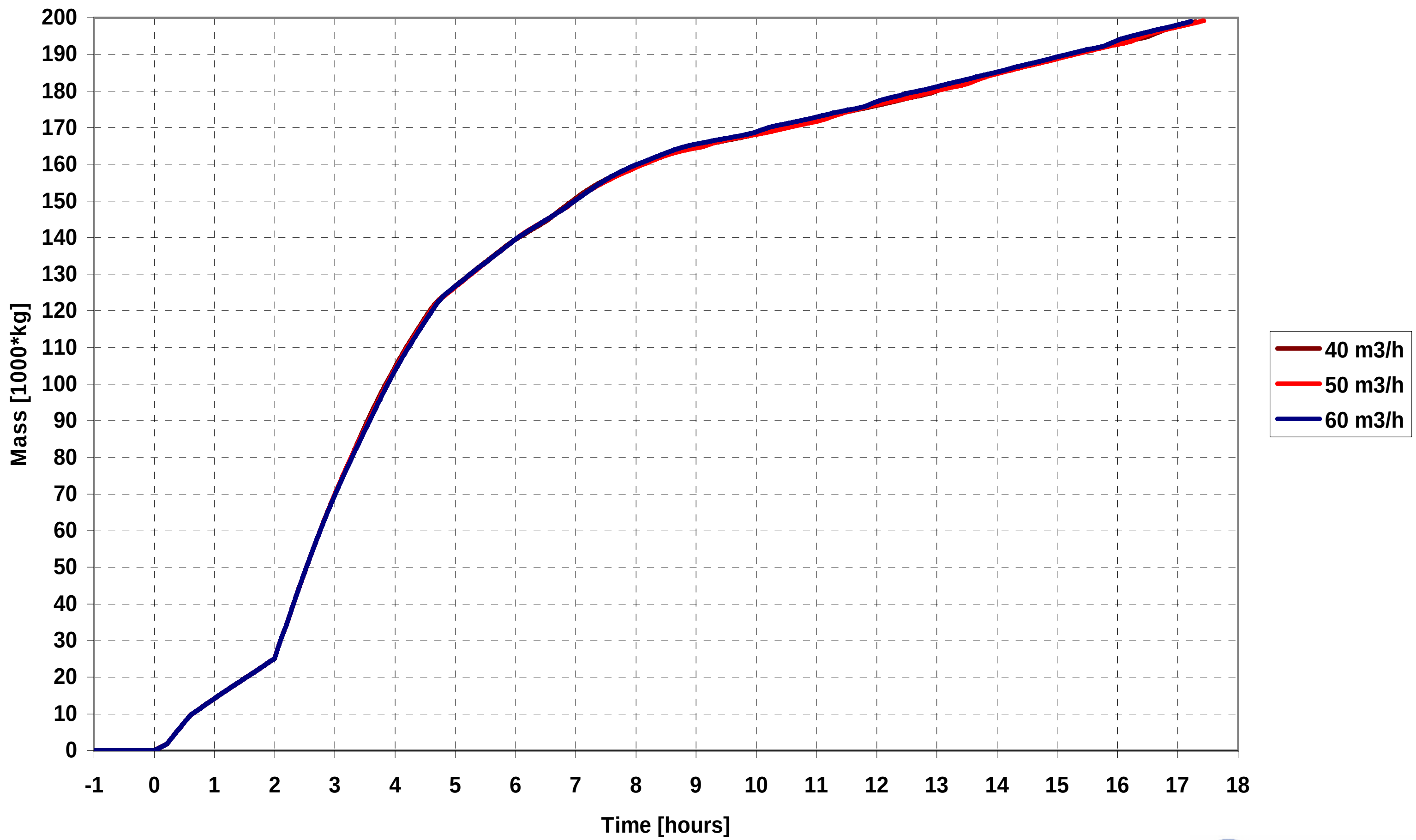
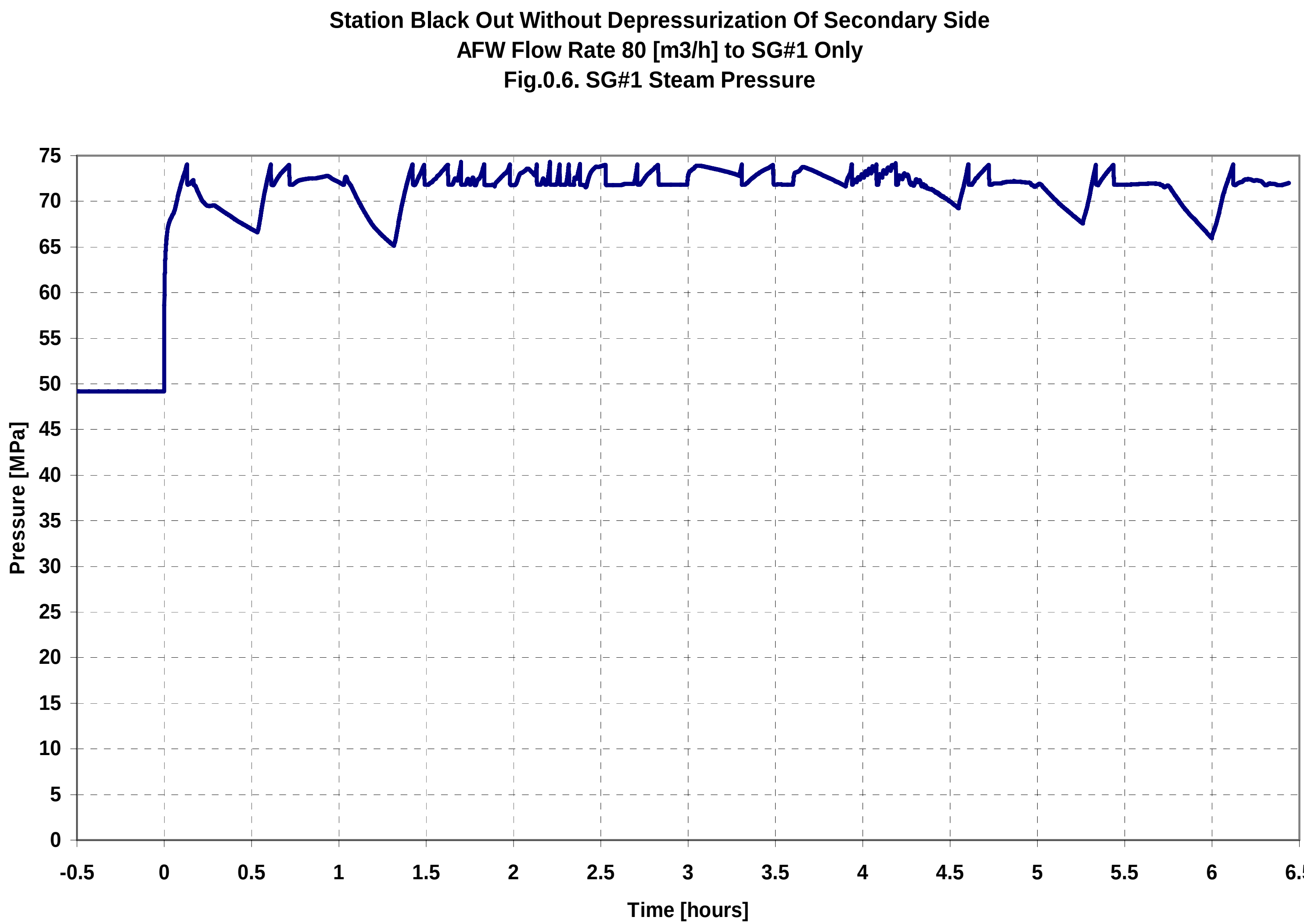
Total Amount of Primary Coolant Leakage

Station Black Out With Steam Generator #1 Depressurization
Different Auxiliary Feedwater Flows to SG #1 at Steam Pressure 1.3 MPa
Fig.1.5. Coolant Lost Through RCP Seals



Secondary Side Pressure in SG#1 (Depressurized)



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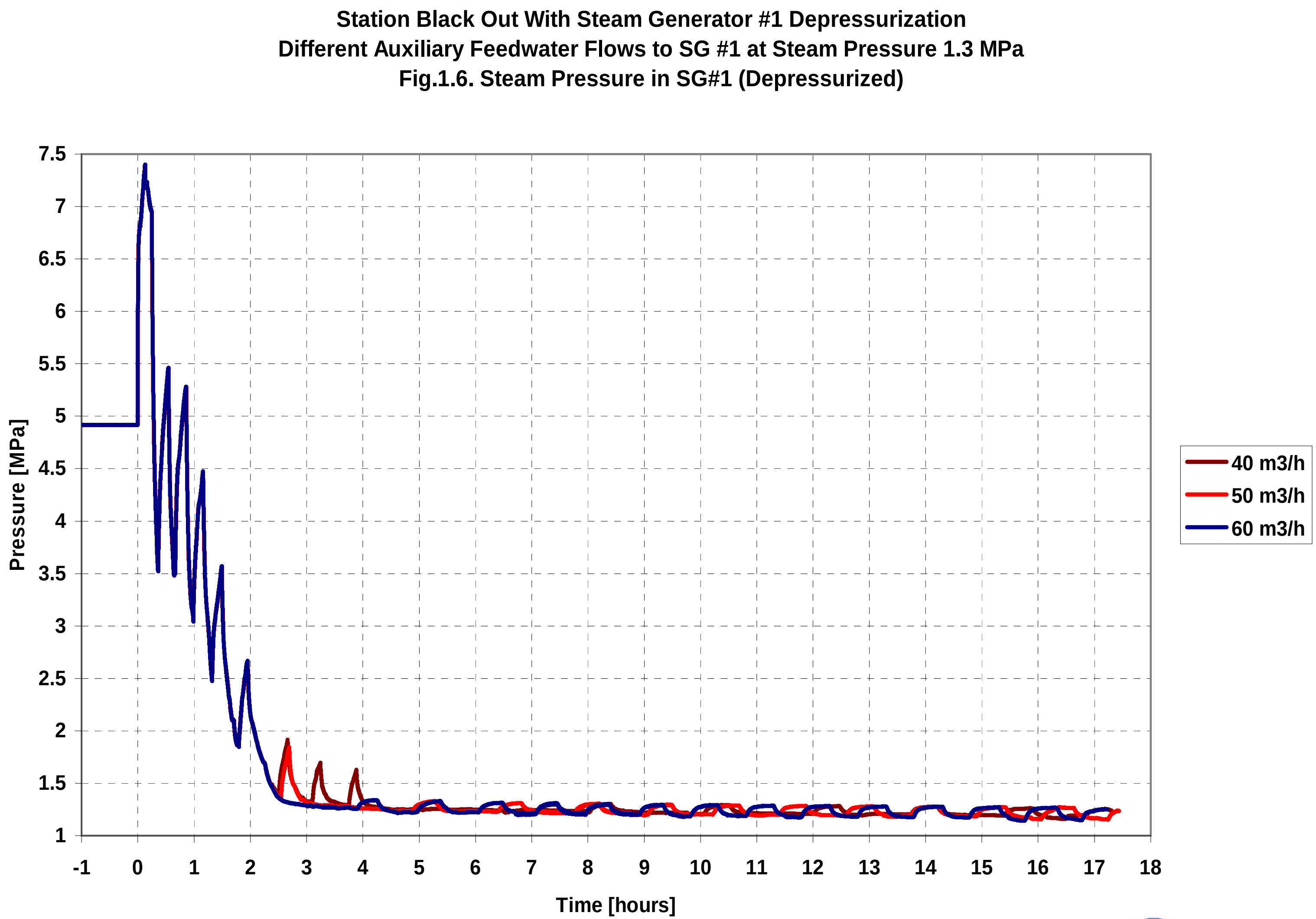
Secondary Side Pressure in SG#1 (Depressurized)



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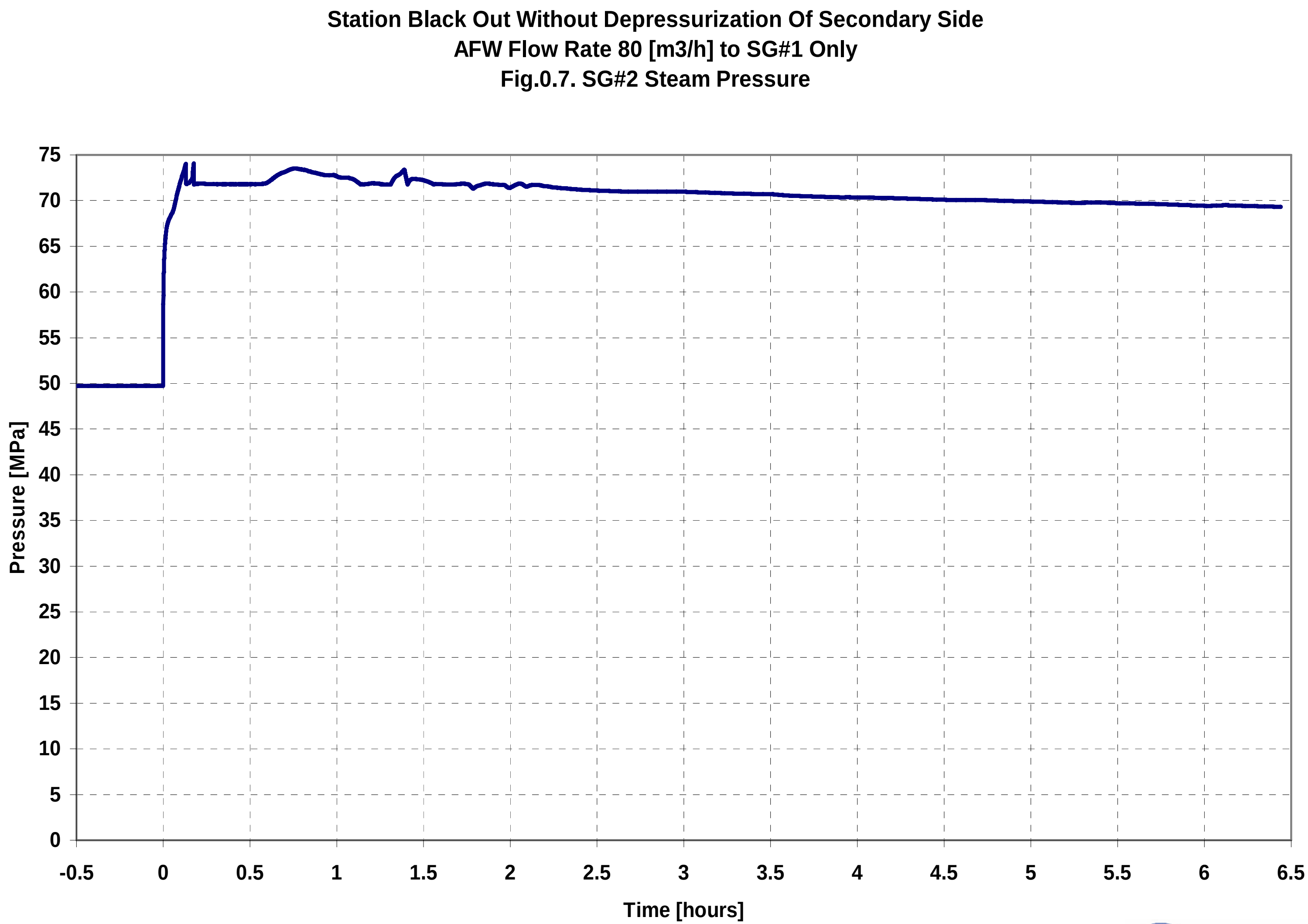
Secondary Side Pressure in SG#2,3 (Non-Depressurized)



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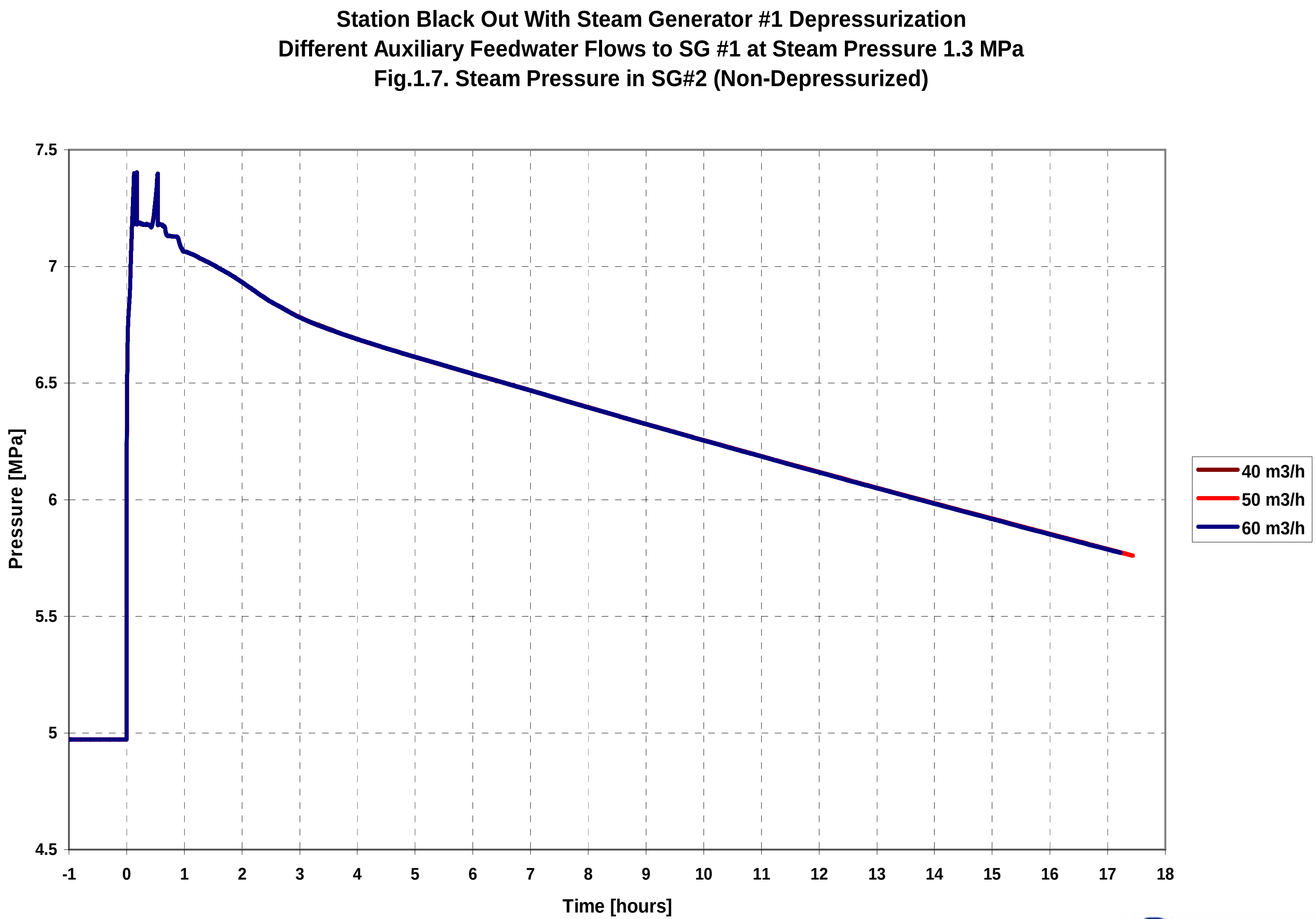
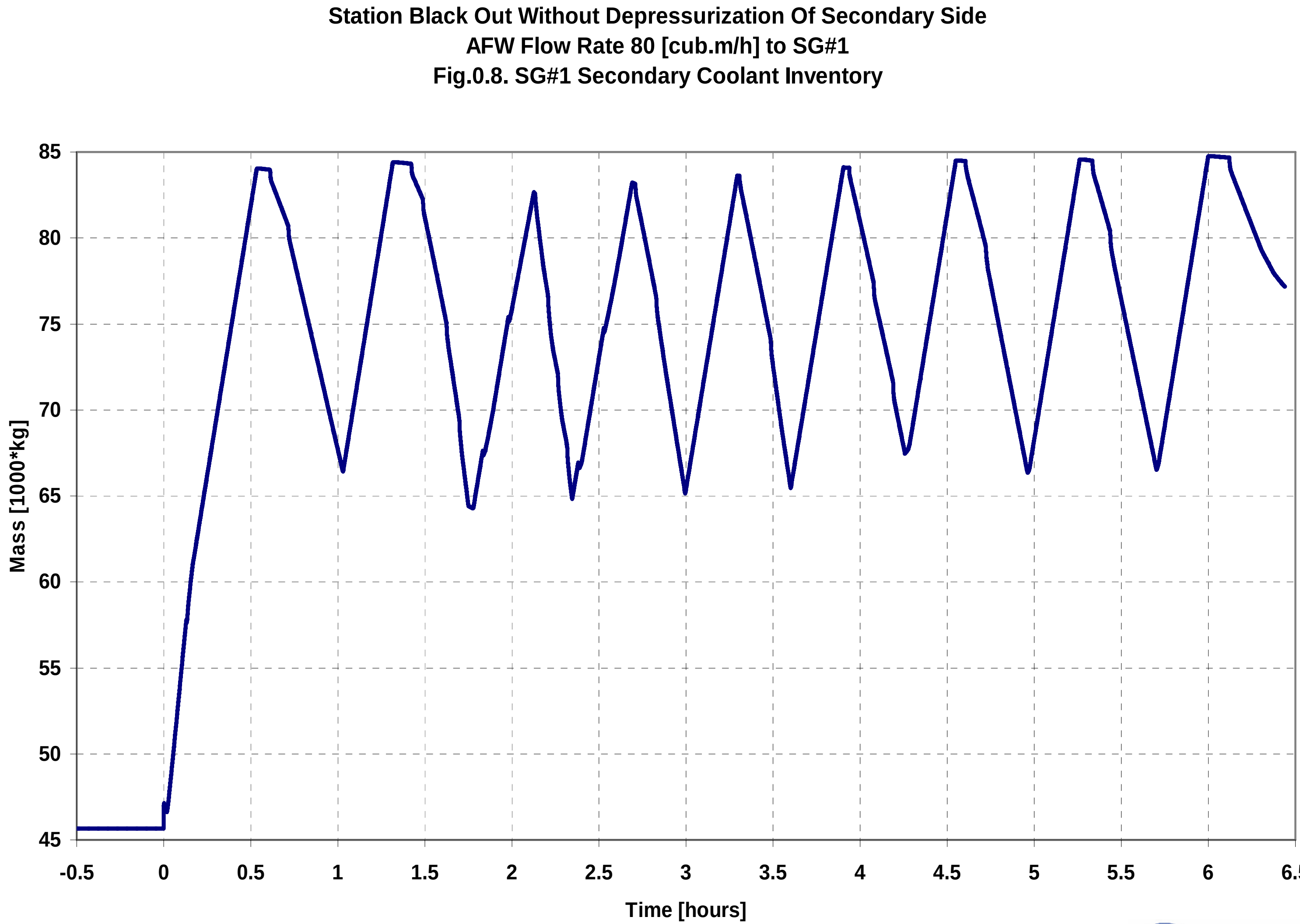
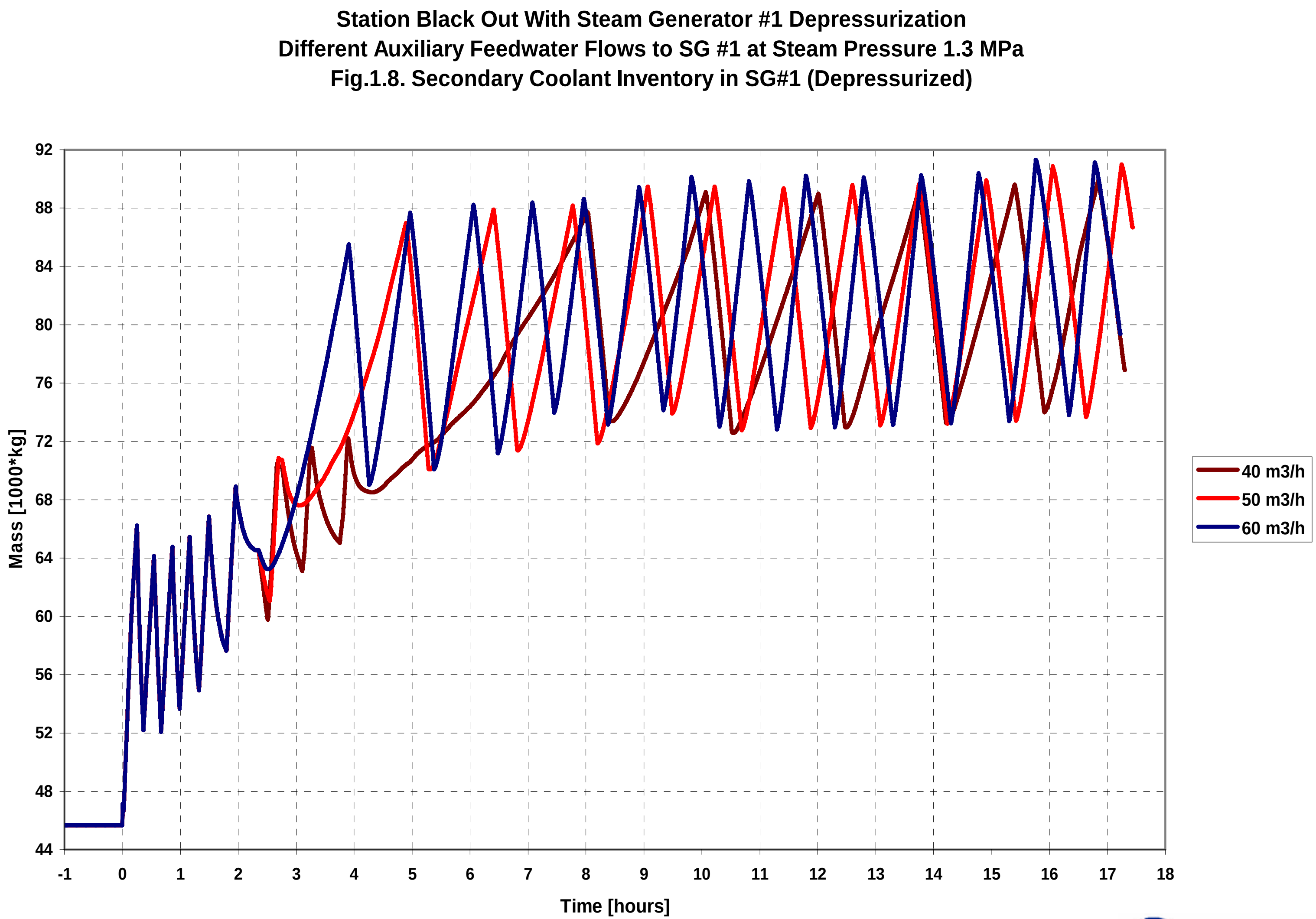
Secondary Side Pressure in SG#2,3 (Non-Depressurized)



Secondary Coolant Inventory in SG#1 (Depressurized)



Secondary Coolant Inventory in SG#1 (Depressurized)



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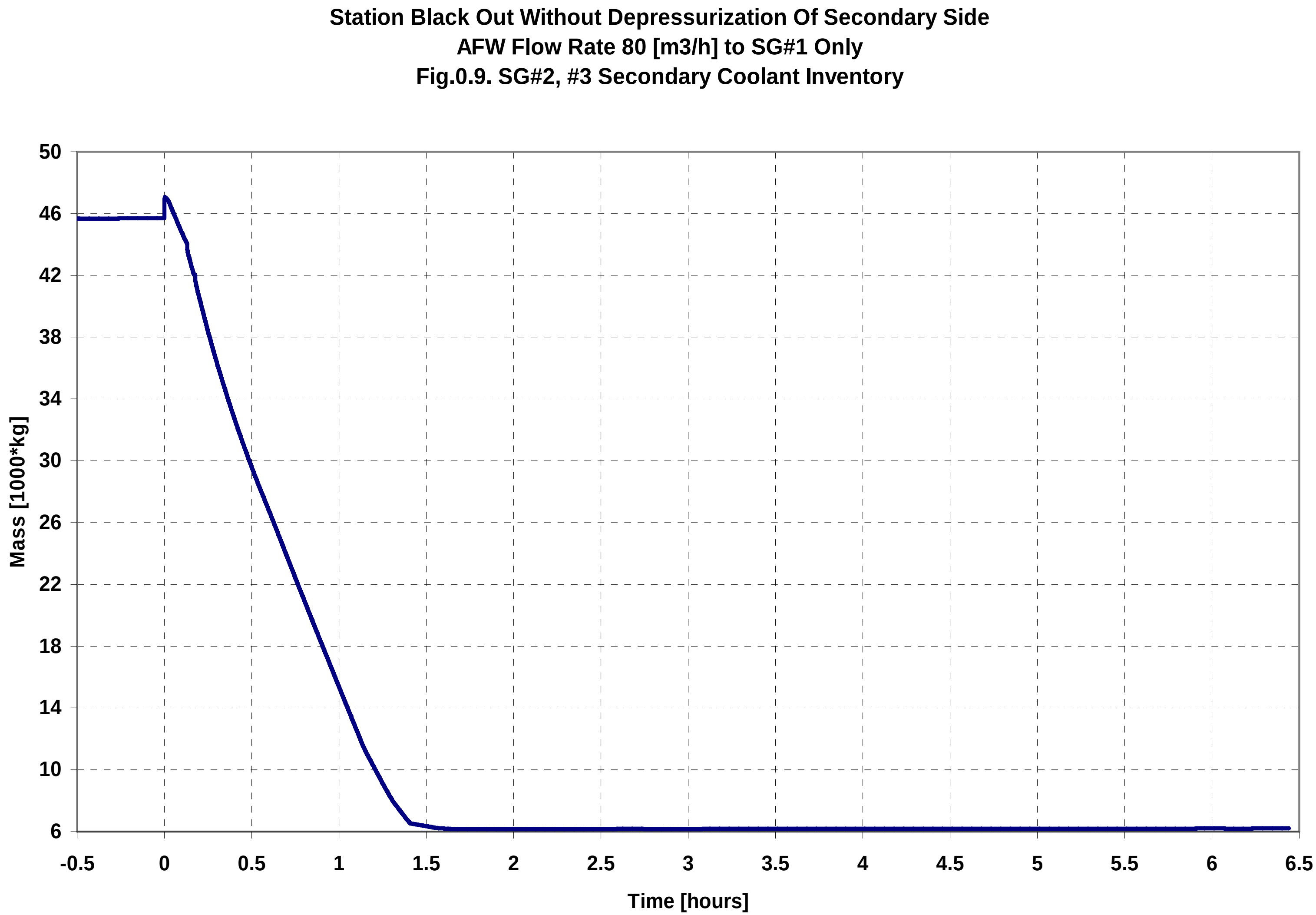
Secondary Coolant Inventory in SG#2,3 (Non-Depressurized)



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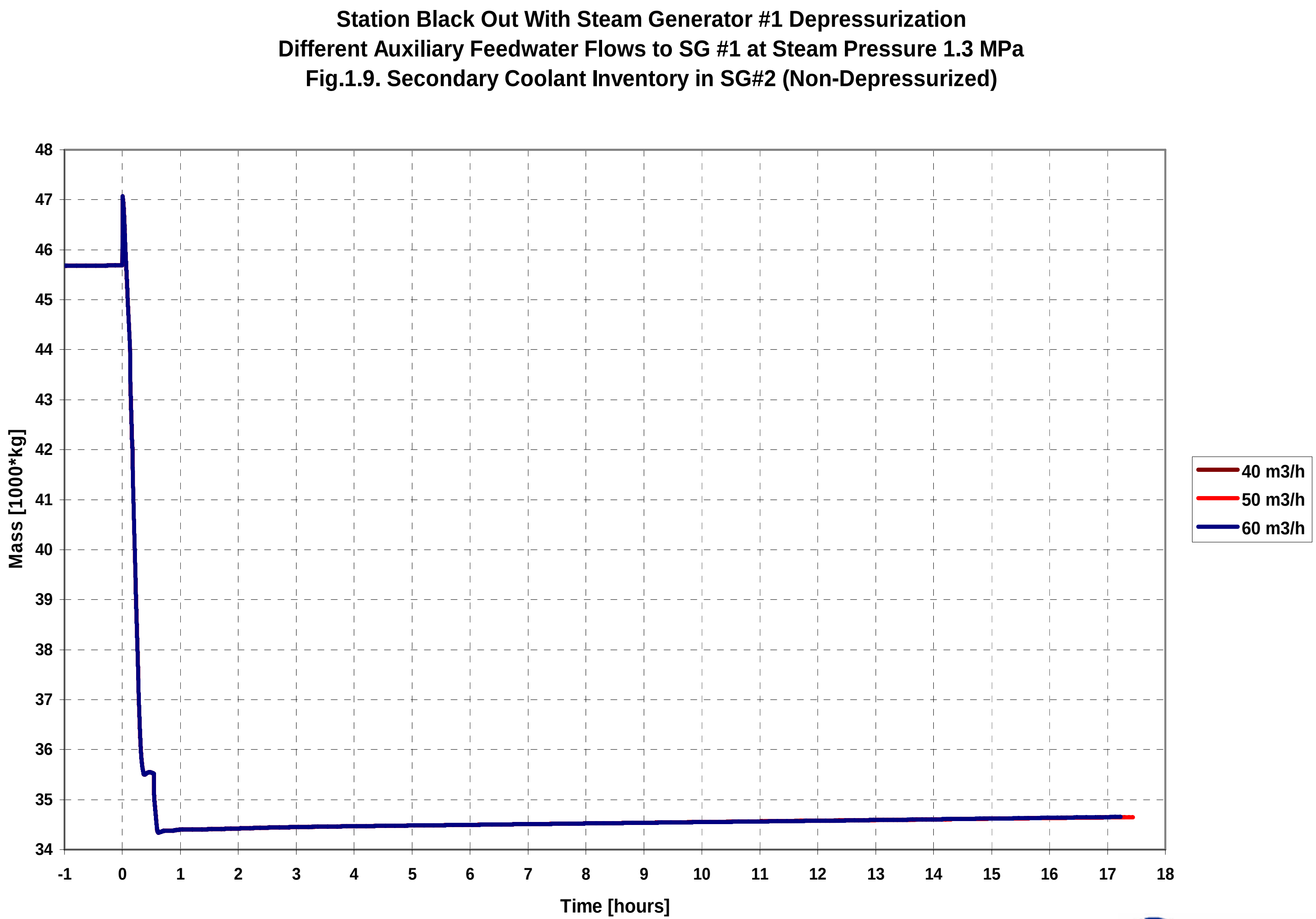
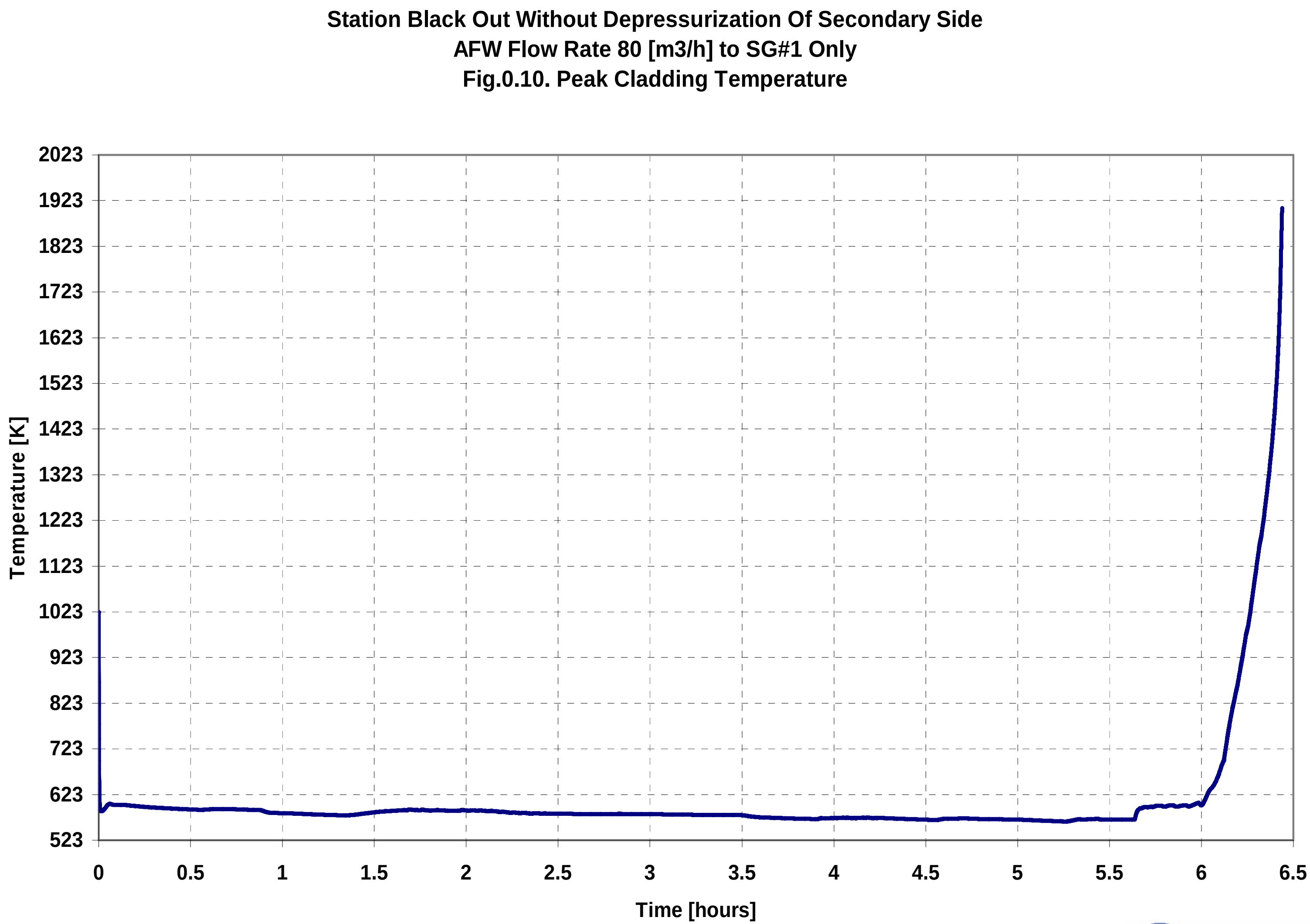
Secondary Coolant Inventory in SG#2,3 (Non-Depressurized)



Peak Fuel Cladding Temperature



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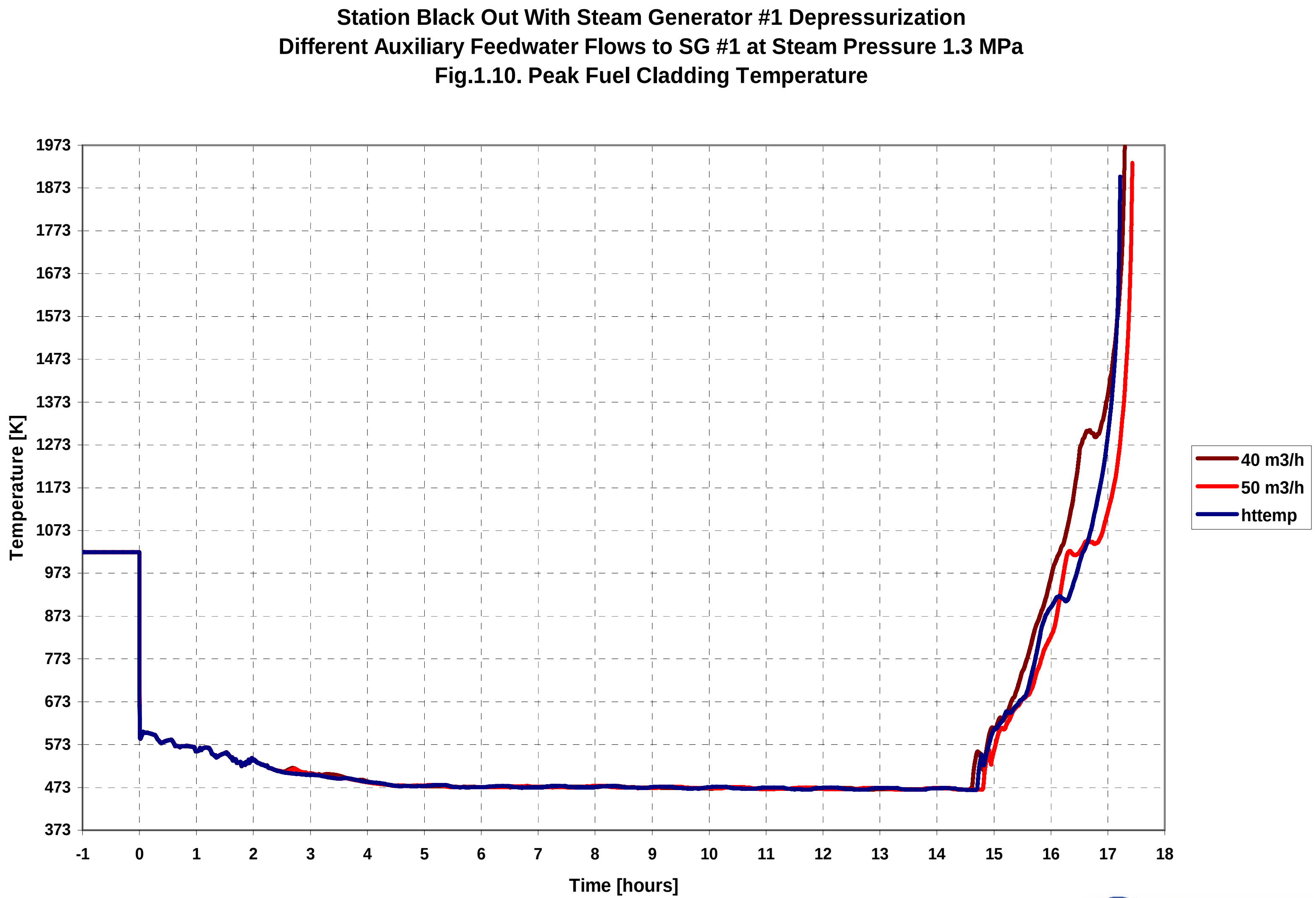
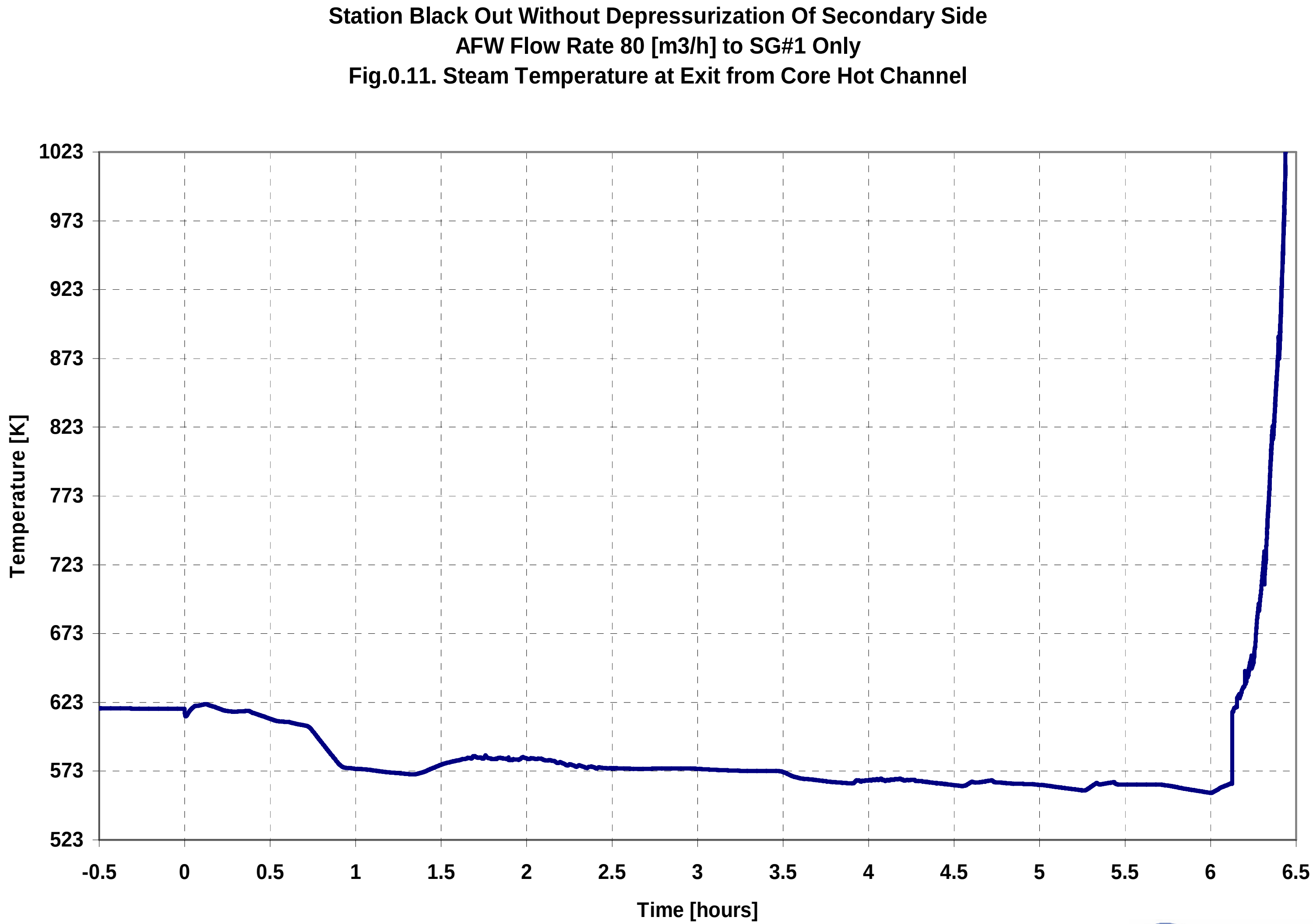
Peak Fuel Cladding Temperature



Maximum Steam Temperature at Core Exit



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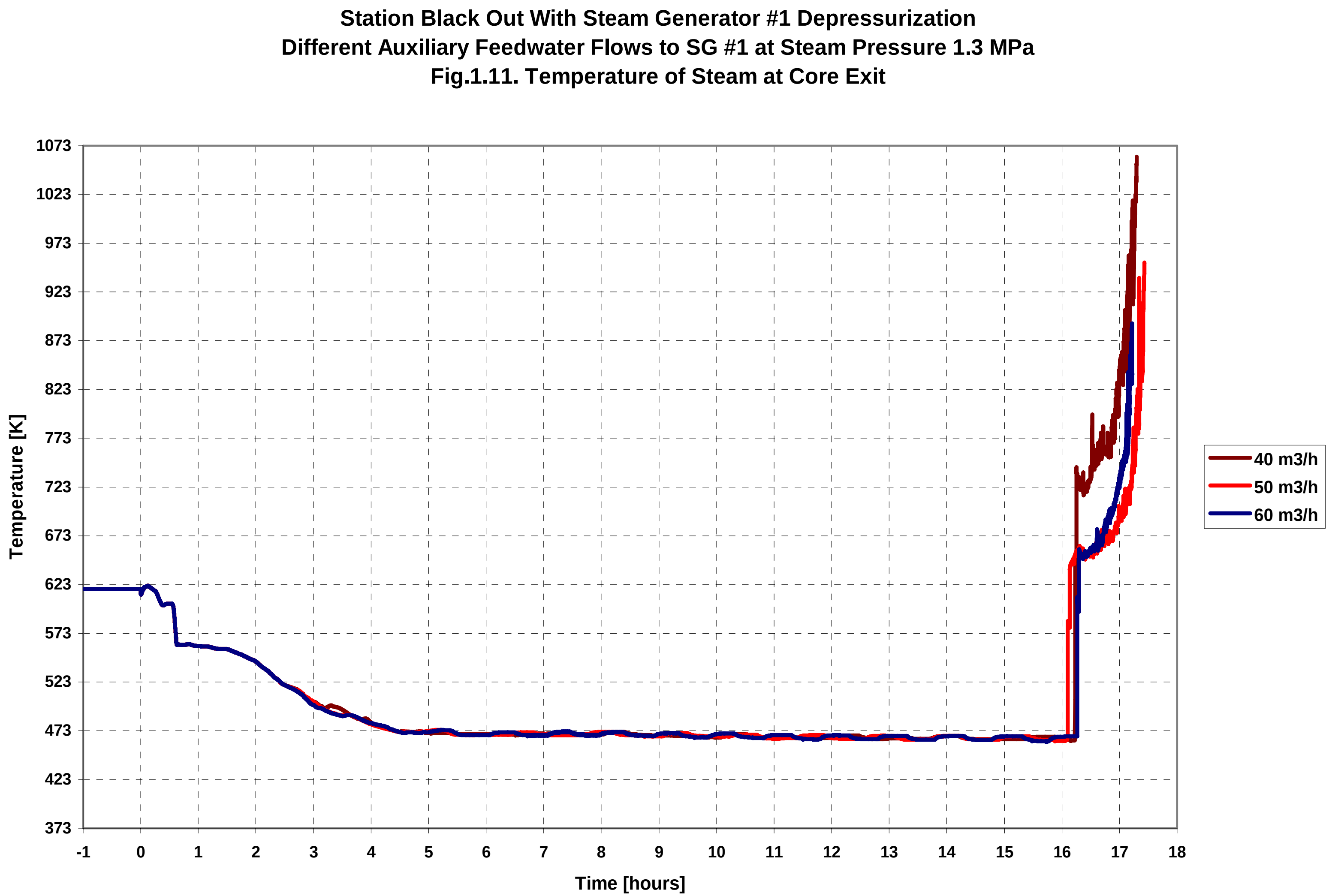
Maximum Steam Temperature at Core Exit



Conclusions

- SBO causes a loss of reactor coolant pumps' (RCP) seal injection flow and pump thermal barrier cooling.
- SBO considerably increases the risk of RCP seal failure that results in an unmitigated LOCA and large-scale fuel failure
- Any reduction of leakage through the RCP seals will extend the time to fuel damage and increase the time to restore AC power
- "SBO Coping Time" is defined as the time until the peak fuel cladding temperature exceeds 650 [^{o}C]
- Safety Objective: Achieve *"SBO Coping time at least 4 to 8 hours"*
- SBO Without SG Depressurization: *"SBO Coping Time" is 6 hours*
- SBO With SG Depressurization to cool down the reactor system – extends *"SBO Coping Time" from 6 to 16 hours*
- Parametric studies done with different AFW pump flows have shown that AFW flow of 40 [m^3/h] to only one SG kept at steam pressure of 1.3 [MPa] yields SBO Coping Time of 16 hours, i.e. it is sufficient to meet US NRC requirement: *"SBO Coping Time at least 4 to 8 hours"*