LOCA with Loss of ECC

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ACR Fuel and Fuel Channel Safety Analysis

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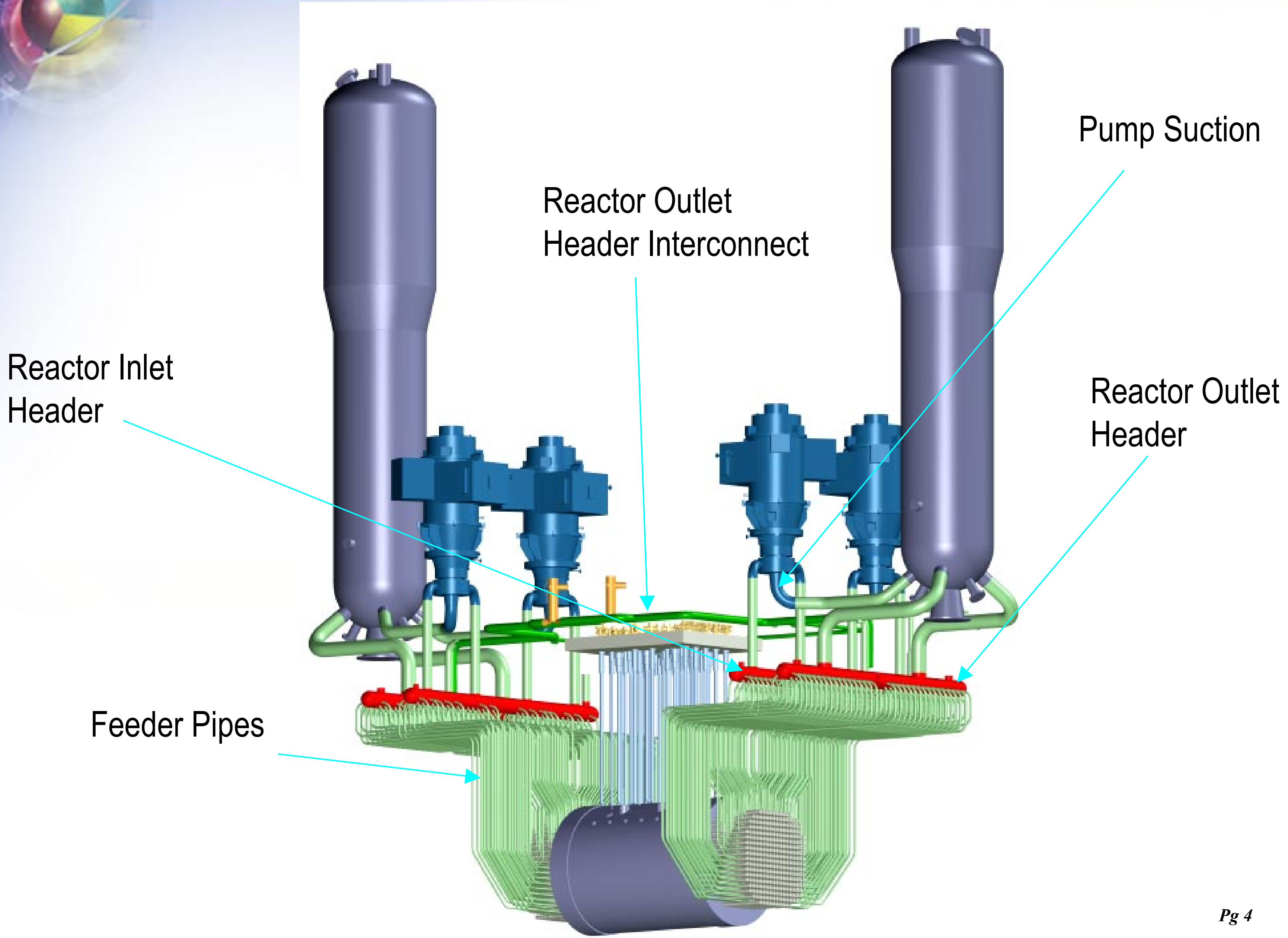
Outline

- Introduction.
- System Description.
- Sequence of Events.
- Analysis Methodology.
- Selected Results.
- Summary and Conclusions.

Introduction

- LOCA with LOECC is a key limited core damage event that affects the entire core.
- LOCA/LOECC leads to fission product release from multiple channels.
- This event provides the highest fission product source term to containment.
- This event tests the robustness of various engineered heat sinks (reserve water and moderator system) and the containment system.

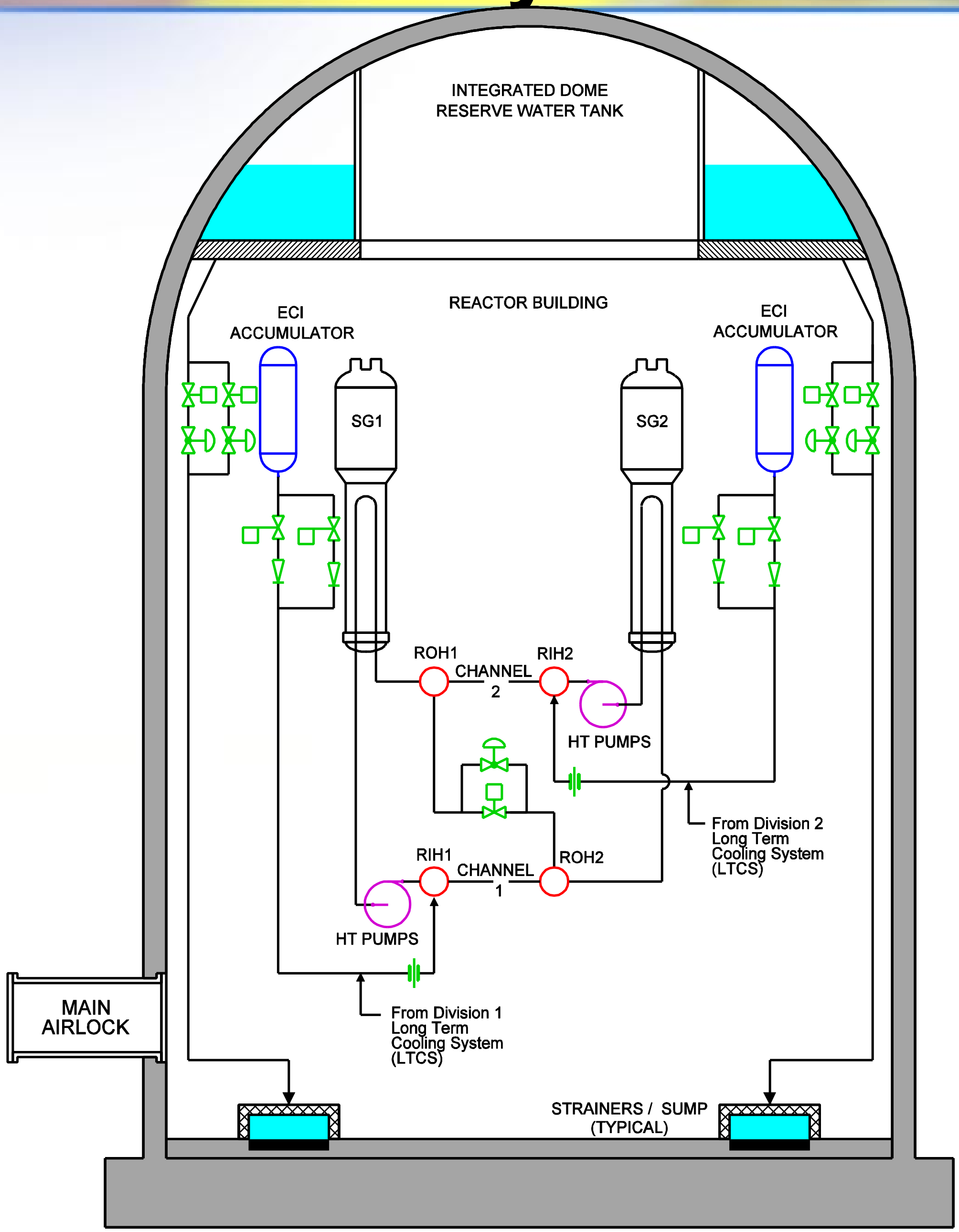
Reactor Cooling System



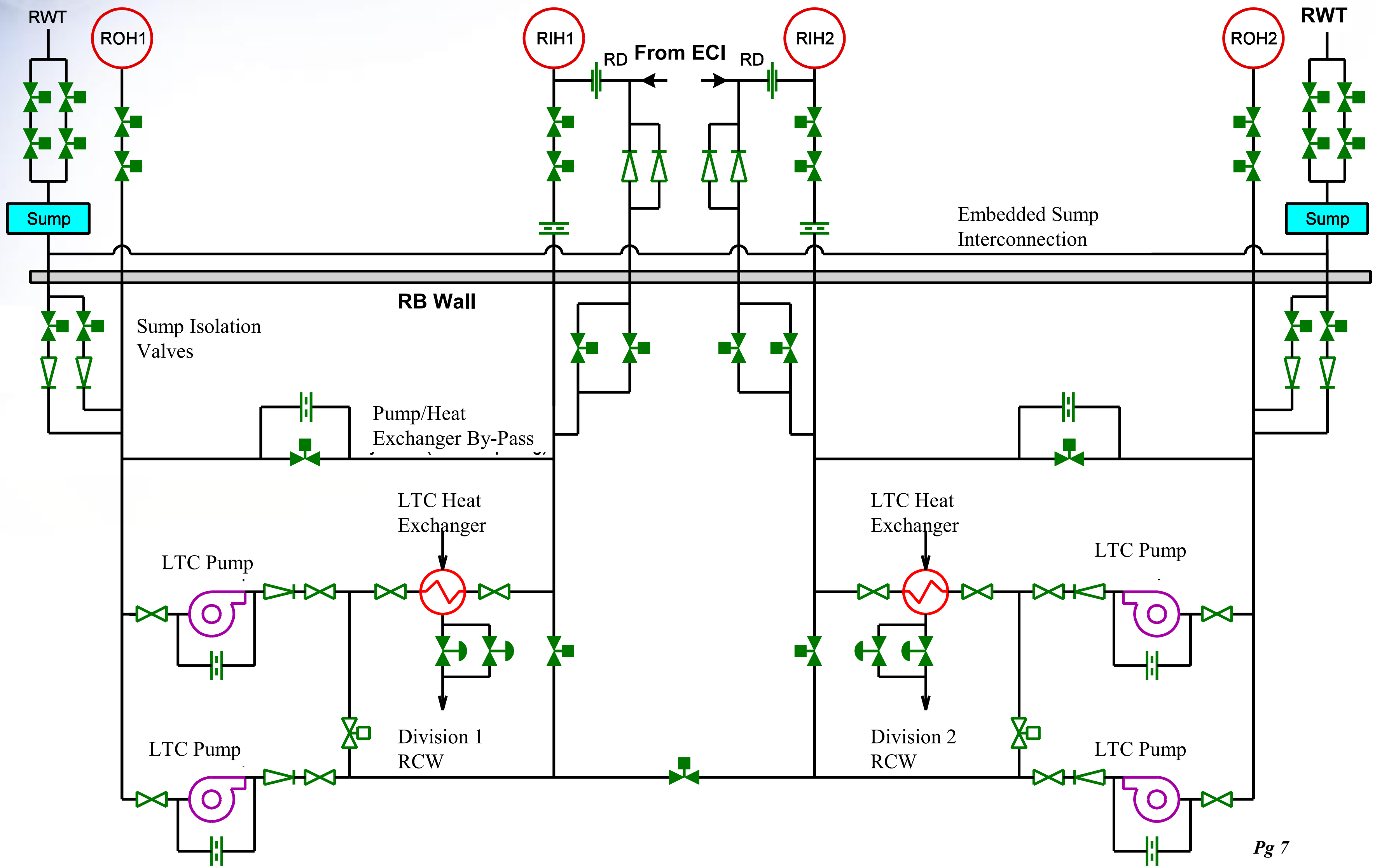
Emergency Core Cooling (ECC) System

- **The system consists of:**
  - **High pressure injection Emergency Coolant Injection (ECI) system;**
  - **Medium pressure Long Term Cooling (LTC) system; and**

ECI System


INTEGRATED DOME
RESERVE WATER TANK
REACTOR BUILDING
ECI
ACCUMULATOR
ECI
ACCUMULATOR
SG1
SG2
ROH1
CHANNEL
2
RIH2
HT PUMPS
From Division 2
Long Term
Cooling System
(LTCS)
RIH1
CHANNEL
1
ROH2
HT PUMPS
MAIN
AIRLOCK
From Division 1
Long Term
Cooling System
(LTCS)
STRAINERS / SUMP
(TYPICAL)

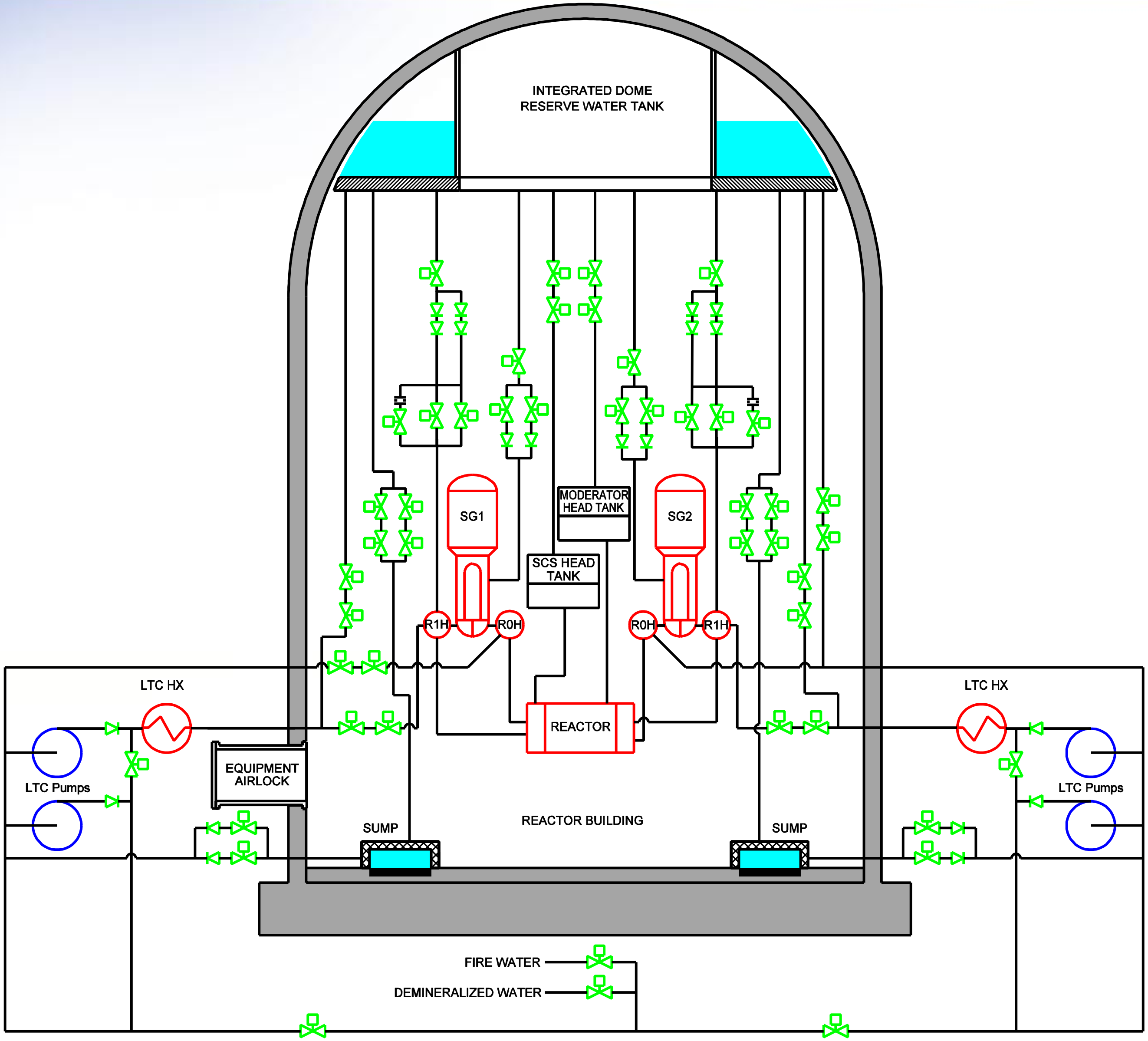
Long Term Cooling (LTC) System



Additional System

- **Low pressure Reserve Water System (RWS):**
  - **Initiated on ECI signal and second crash cool signal.**

Reserve Water System (RWS)



Sequence of Events

1) After a loss of primary coolant, the RCS depressurizes:
   - mass and energy discharge into containment reaching low RCS pressure trip setpoint,
   - high containment pressure conditioning setpoint and generating the signal to begin ECC operation.
2) Valves on the interconnect line between the reactor outlet headers open.

Sequence of Events

3) Second crash cooldown is initiated by a low RCS pressure signal accompanied by a conditioning signal (sustained low RCS pressure, high RB pressure), resulting in the following actions:
   - All main steam safety valves open,
   - Reserve water tank valves to the RIH open, and
   - Reserve water tank valves to the reactor building sump open.

Sequence of Events

4) As the inventory decreases, the heat transport pumps become less and less effective until they trip automatically. Thus, flow decreases; fuel and pressure tube temperatures increase.
5) When the RCS pressure falls to the point where the ECI rupture disc differential pressure is less than 0.52 MPa, ECI is initiated (if assumed available).

Sequence of Events

6) After the ECI phase is over (injection of 120m^3 of water from each of the two tanks), the RCS will continue to depressurize.
7) The RCS pressure falls below the RWT static pressure, the reserve water system also provides a backup supply of demineralized light water for the RCS (injected into the RIH).

Sequence of Events

8) Once the available amount of water for this application from the RWT is depleted (up to 1500m^3), and if the LTC cannot be brought into operation by operator action, the fuel will begin to slowly heat up:

- Additional fuel clad failures begin to occur, releasing fission products from the fuel-clad gap;
- Fission products begin to diffuse out of the fuel and are released to the RCS.
- Transient release of fission products from the fuel matrix begins.

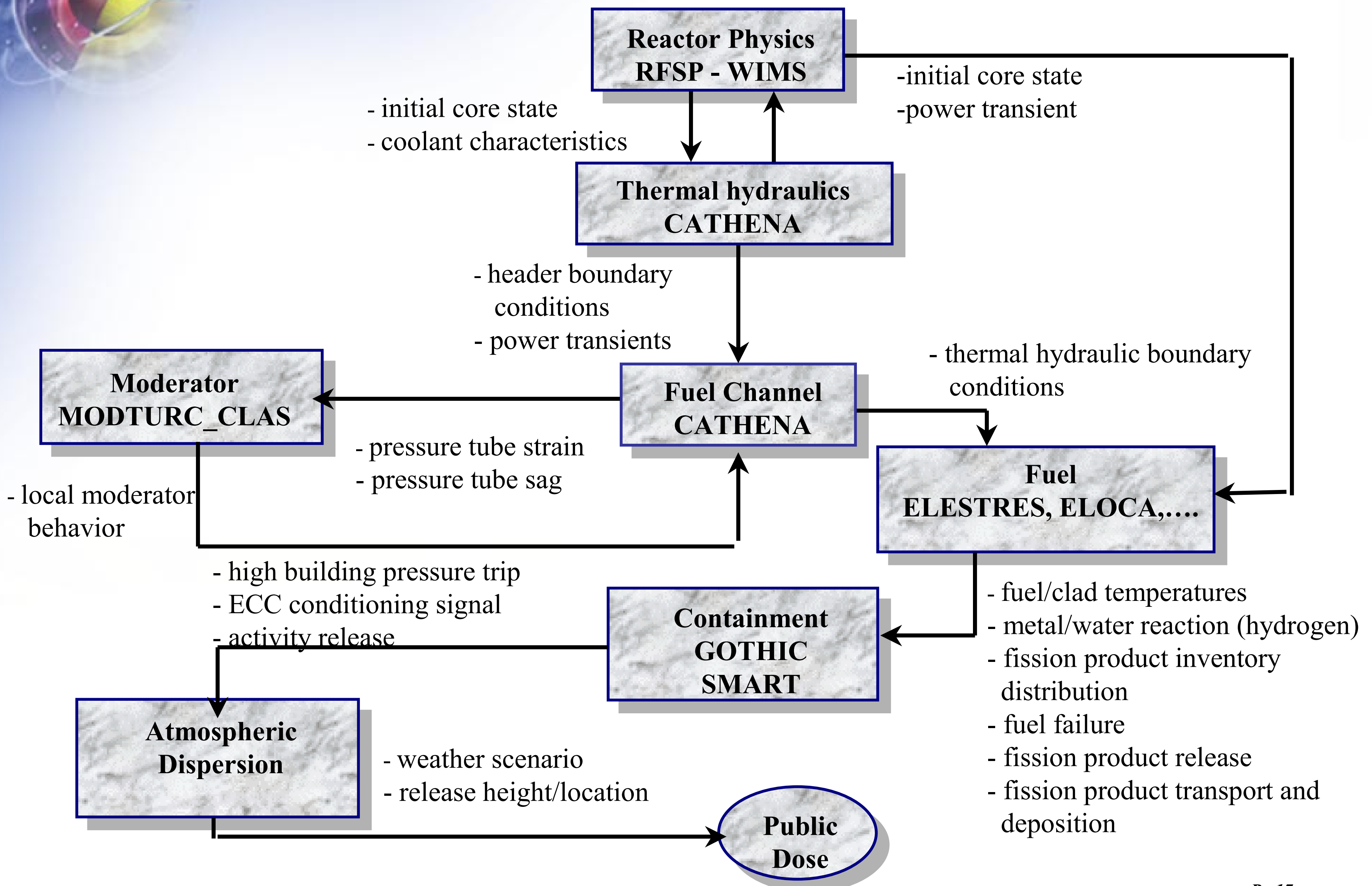
Sequence of Events

9) The pressure tubes may get hot enough to deform:
   - The RCS pressure is too low to drive pressure tube creep.
   - Any subsequent pressure tube heat up may result in sag contact with the calandria tube.
   - That portion of the pressure tube in contact with the cold calandria tube drops in temperature significantly.
   - Heat is transferred from the calandria tube to the surrounding moderator.
   - The moderator cooling system removes heat from the moderator.

Sequence of Events

10) Long-term cooling of the fuel is provided by radiation heat transfer to the pressure tube, conduction through the pressure tube and calandria tube and convective heat transfer to the moderator.

Computer Code Connections



Physics Analysis Tools

WIMS-AECL:

- **Inputs:**
  - Physical dimensions of the cell
  - The geometrical arrangement
  - The composition of the cell
  - Temperature and density of the materials in the cell
- **Outputs:**
  - Cell-averaged parameters are tabulated as functions of fuel burnup, fuel temperature, and coolant density
  - It produces 2-group cell-averaged parameters for RFSP calculations

Physics Analysis Tools

RFSP

- Inputs:
  - Cross sections from WIMS
  - Core size and mesh size
  - Device incremental cross sections
  - Coolant temperature and density, and fuel temperature from CATHENA thermal hydraulics code
- Outputs:
  - Channel and bundle power distributions within the core
  - Thermal and fast flux distributions within the core

Thermal Hydraulic Analysis Tools

CATHENA

- **Inputs:**
  - Geometry and layout of piping
  - Channel power distributions from RFSP
  - System controls and properties
  - Reactor power transients from RFSP
- **Outputs:**
  - System thermal hydraulic behavior
  - Boundary conditions for detailed single channel analyses
  - Coolant and fuel temperatures for RFSP

Thermal Hydraulic Analysis Tools

CATHENA Single Channel Analysis

- **Inputs:**
  - fuel and fuel channel geometry
  - fuel and fuel channel axial and radial power distribution
  - transient header boundary conditions from CATHENA full circuit calculations
  - power transient from RFSP calculations
- **Outputs:**
  - fuel boundary conditions (pressure, temperature, and fuel-to-coolant heat transfer coefficient) for ELOCA
  - pressure tube temperatures and strain

Fuel Analysis Tools

ELESTRES

- **Inputs:**
  - Fuel geometry and composition, and
  - Power / burnup history from RFSP
- **Outputs:**
  - Heat generation rates within the fuel pellets for input to ELOCA
  - Clad strain for input to ELOCA
  - Fuel-to-clad gap conductance for input to ELOCA
  - Distribution of fission products (grain bound, grain boundary, and fuel-to-clad gap) for input to SOURCE

Fuel Analysis Tools

ELOCA

- **Inputs:**
  - heat generation rates, clad strain, and fuel-to-clad gap conductance from ELESTRES
  - fuel boundary conditions (pressure, temperature, and fuel-to-coolant heat transfer coefficient) from CATHENA
  - power transient from RFSP calculations
- **Outputs:**
  - fuel and clad temperatures for input to SOURCE
  - fuel failure time
  - the extent of clad oxidation for input to SOURCE

Fission Product Analysis Tools

SOURCE

- **Inputs:**
  - fuel temperature transients from ELOCA
  - fuel boundary conditions (pressure, temperature, and clad-to-coolant heat transfer coefficient) from CATHENA
  - power transient from RFSP calculations
- **Outputs:**
  - fission product release transient – amounts and species

Fission Product Analysis Tools

SOPHAEROS

- **Inputs:**
  - fission product release transients from SOURCE
  - RCS boundary conditions (steam pressure and temperature, materials and temperatures) from CATHENA
- **Outputs:**
  - fission product retention within the RCS, and deposition on the RCS materials
  - the amount and species of the fission products released into containment

Moderator Analysis Tools

MODTURC-CLAS

- **Inputs:**
  - Moderator circuit geometry and conditions
  - Heat load to the moderator during normal operation and accidents conditions obtained from CATHENA
- **Outputs:**
  - Moderator temperature distribution

Containment Analysis Tools

GOTHIC

- **Inputs:**
  - break discharge and hydrogen release transients from CATHENA
  - containment geometry and heat sinks
- **Outputs:**
  - Thermal hydraulic conditions to SMART
  - Peak containment pressure and temperature

Containment Analysis Tools

SMART

- **Inputs:**
  - Thermal hydraulic conditions from GOTHIC
  - Fission product releases from SOPHAEROS
- **Outputs:**
  - Fission product releases to atmosphere to be used in dose assessment

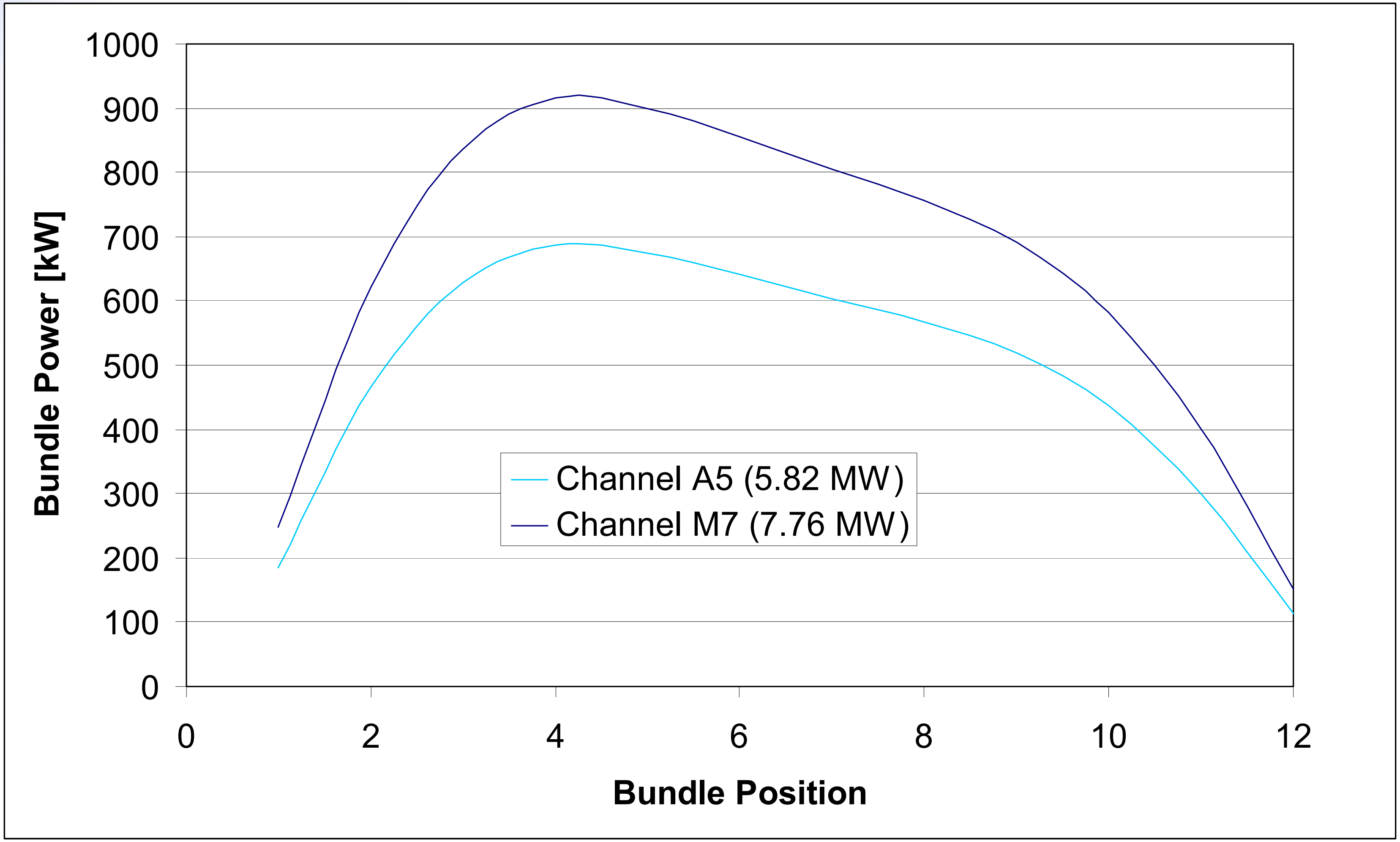
Core Inventory Calculations

- Calculated using ELESTRES for each element in the fuel bundle:
  - Core power distribution;
  - Channel powers;
  - Power Burnup history;

Channel Power Map

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
A					5816	6649	7140	7109	6822	6953	7083	6883	6645	6084				
B			6005	6396	6592	7173	6699	6561	6565	6495	6560	6822	7276	6571	6309	6058		
C		6099	6403	6803	6874	7115	6998	6877	6503	6627	7029	7066	7207	6688	6993	6371	6128	
D		6405	6675	7153	6837	7456	7340	7456	7131	6786	7396	7548	7151	7211	7019	6318	6622	
E	6084	6767	6714	7315	7397	7209	7577	7094	7110	7290	7171	7516	7372	7566	6871	6869	6646	6306
F	6563	6517	6873	7143	7420	7041	7326	7563	7358	7215	7638	7240	7037	7161	7320	7022	6351	6440
G	6845	6278	6741	7498	7694	7195	7440	7710	7124	6992	7456	7634	7332	7373	7501	6713	6276	6813
H	6944	6486	7131	7339	7148	7496	7642	7458	6980	7237	7643	7100	7533	7608	7362	6866	6709	6914
J	6787	6594	6870	6945	7211	7514	7091	7206	7225	7055	7443	7169	7340	7057	6931	6942	6480	6768
K	6967	6439	6929	7346	7001	7320	7116	7473	7135	7188	7080	7350	7205	6917	7181	6773	6534	7009
L	7063	6703	6768	7485	7594	7293	7610	7429	6969	7408	7578	7192	7604	7370	7521	7085	6347	6977
M	6534	6332	6959	7093	7512	7437	7761	7224	7280	7060	7692	7574	7267	7561	7015	6768	6473	6538
N	6549	6374	6749	7428	7228	7037	7164	7526	7517	7338	7322	7434	7039	7317	7353	6882	6233	6557
O	6300	6652	6632	7070	7438	7262	7382	7605	7045	7062	7596	7704	7142	7263	7332	6740	6576	6145
P		6377	6498	7166	6719	7374	7563	7289	6910	7170	7259	7129	7353	7258	7053	6330	6492	
Q		6073	6288	6931	6702	7208	7118	6638	6675	6591	6646	7258	7391	6689	6876	6402	6058	
R			5973	6181	6643	7094	6598	6794	6464	6576	6936	6690	7209	6609	6447	6040		
S					5834	6672	7032	7265	7001	6819	7253	7190	6584	6092				

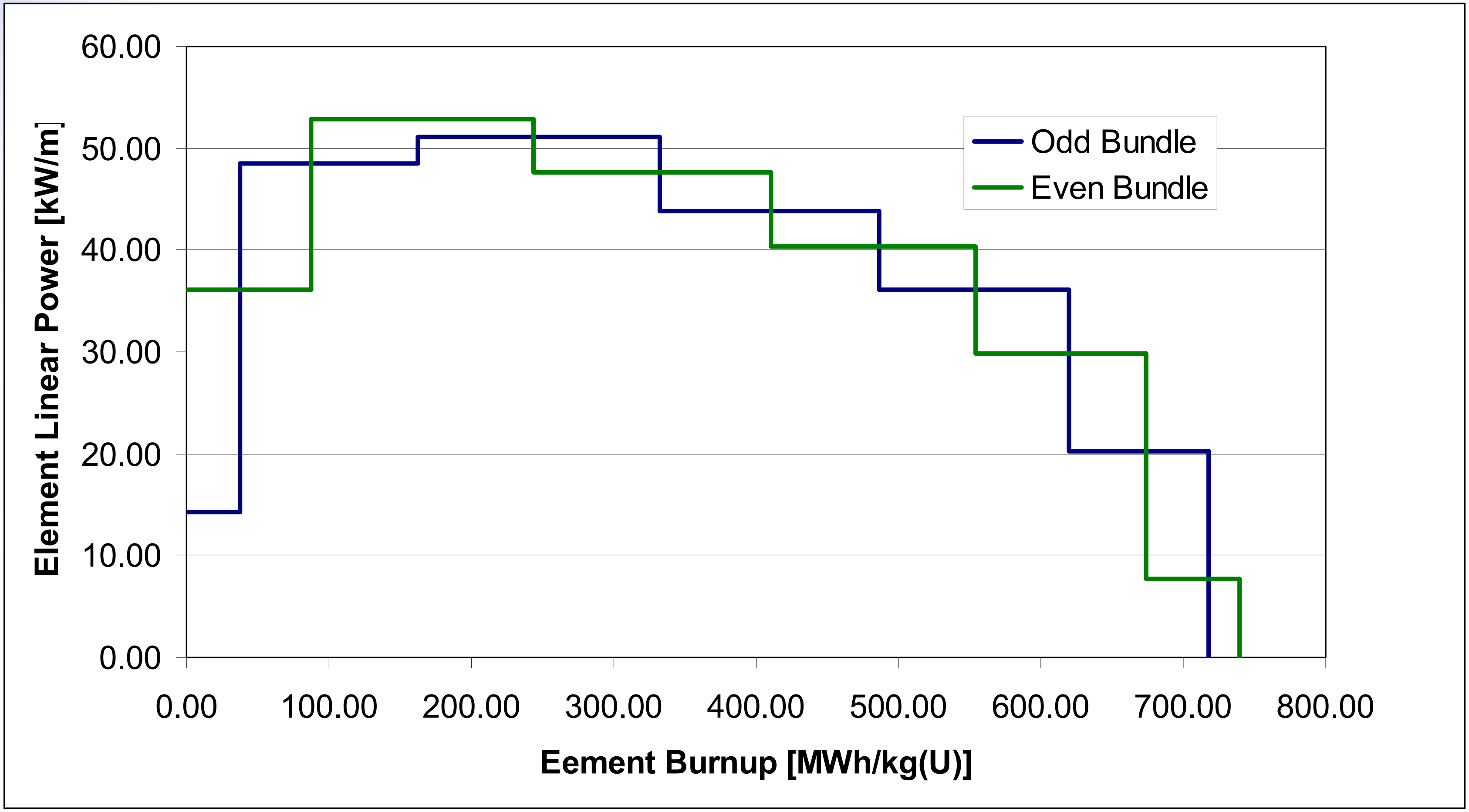
Axial Channel Power Profile



Channel Groups

Group	Power [MW]	Number of Channels
1	7.76	11
2	7.61	28
3	7.45	35
4	7.30	44
5	7.14	43
6	7.00	69
7	6.60	62
Total	2080	292

Element Power/Burnup History



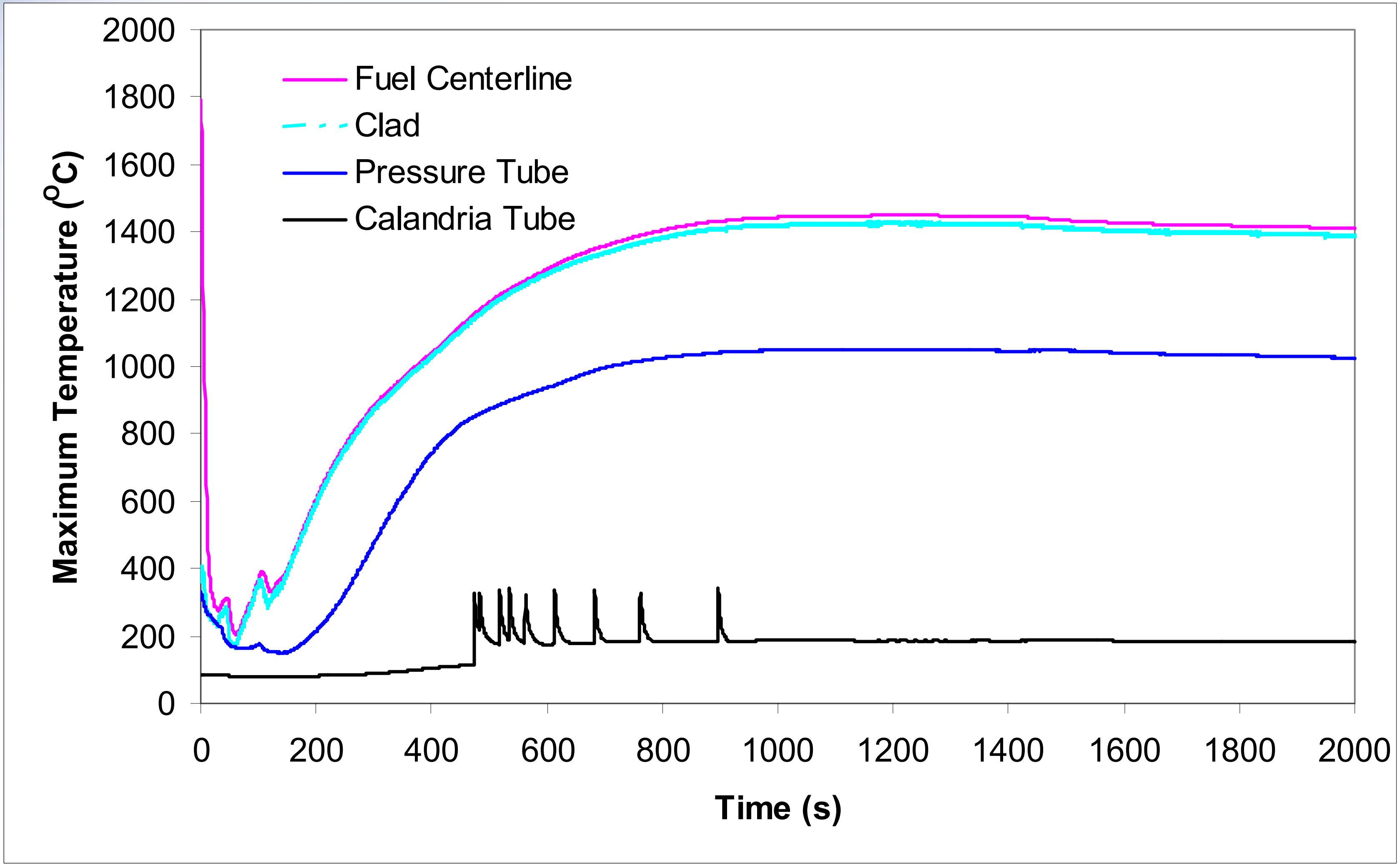
Core Inventory

	Total Inventory [Ci]	Gap Inventory [Ci]	Fraction
Noble Gases	639 MCi	2.95 MCi	0.0046
Halogens	623 MCi	7.12 MCi	0.0115
Alkali Metals	224 MCi	1.76 MCi	0.0079

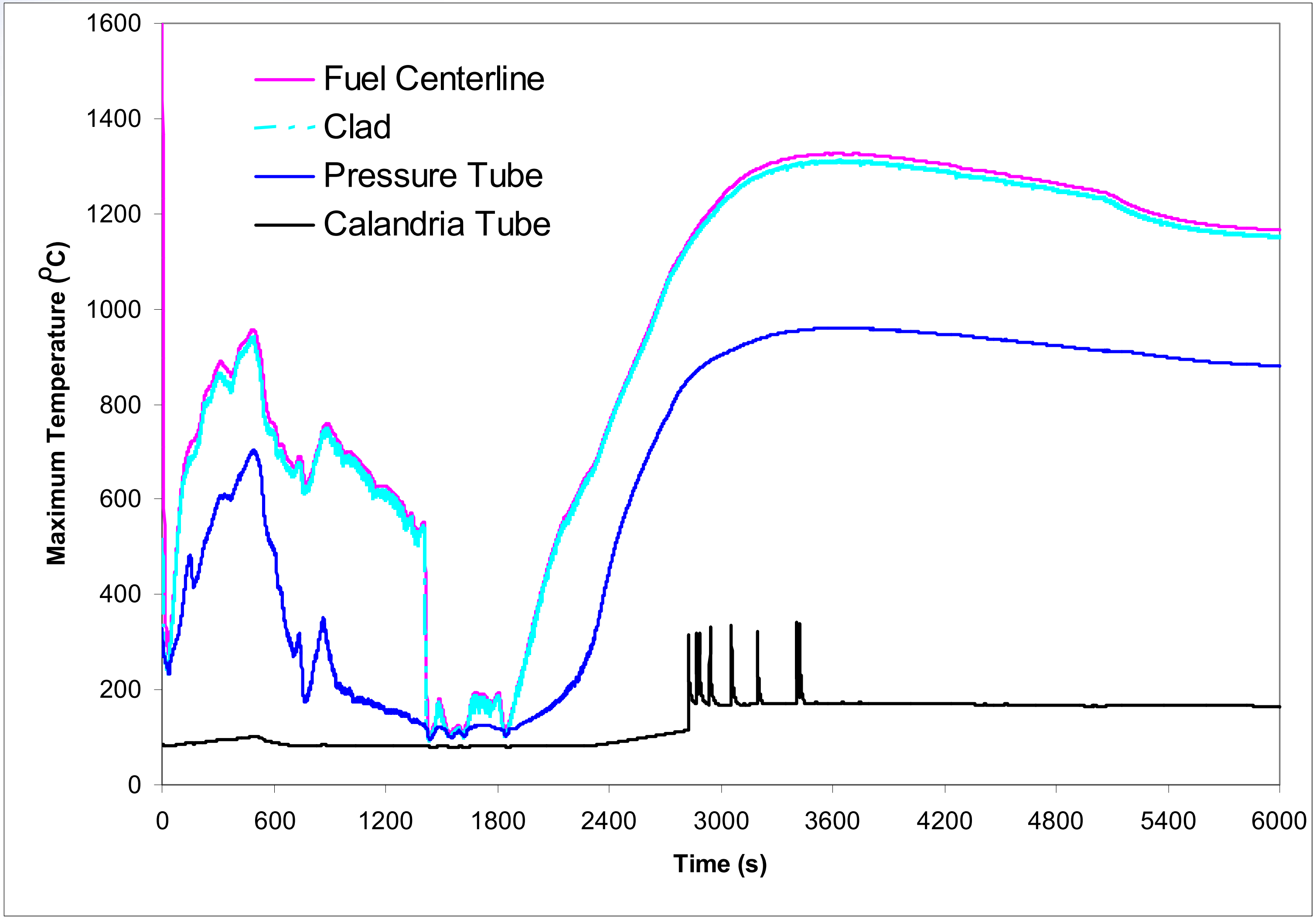
Thermal Hydraulic Analysis

- Uses mechanistic models in the calculations.
- First reactor trip is credited.
- Only RIH breaks considered (effectively removes one ECI and RWT injection point).
- RWT head accounts for only the piping to the tank, and not the tank water level.
- Maximum bundle power in the maximum power channel calculations are shown.

100% RIH Break with loss of RWT



100% RIH Break with loss of ECI



Source Term Calculation

- ELOCA calculations (from CATHENA boundary conditions) to get number and timing of fuel failures.
- SOURCE calculations (from ELOCA temperature conditions) to get the fission product release fractions.
- SOPHAEROS calculations (from CATHENA conditions and SOURCE fission product release transient) to get fission product release into containment.

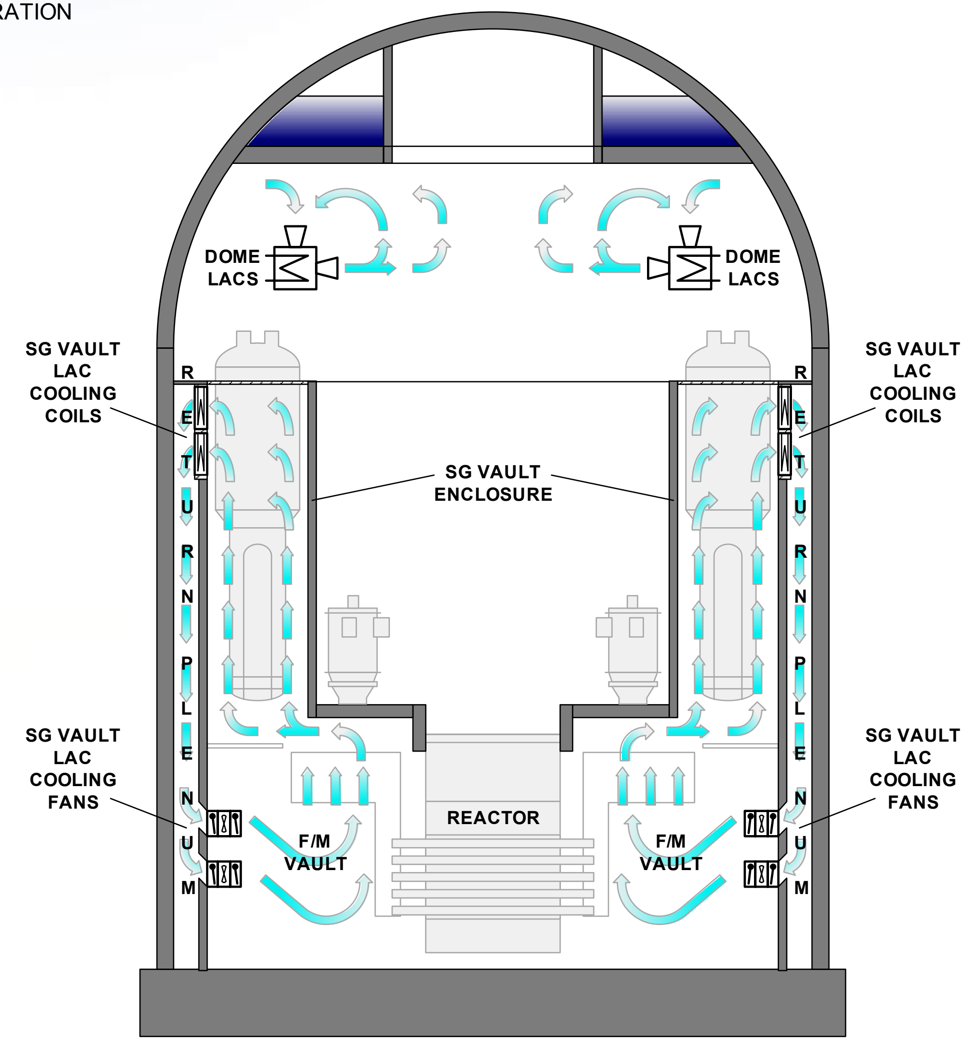
Fission Product Release

- Very conservative simplified assumption that a constant temperature is kept from the initiation of the event for 10,000 seconds. The resulting inventory releases are:

Temperature [°C]	Release Fraction [%]
1000	0.07
1200	1.4
1300	4.6
1400	15.4

Containment Cooling Systems

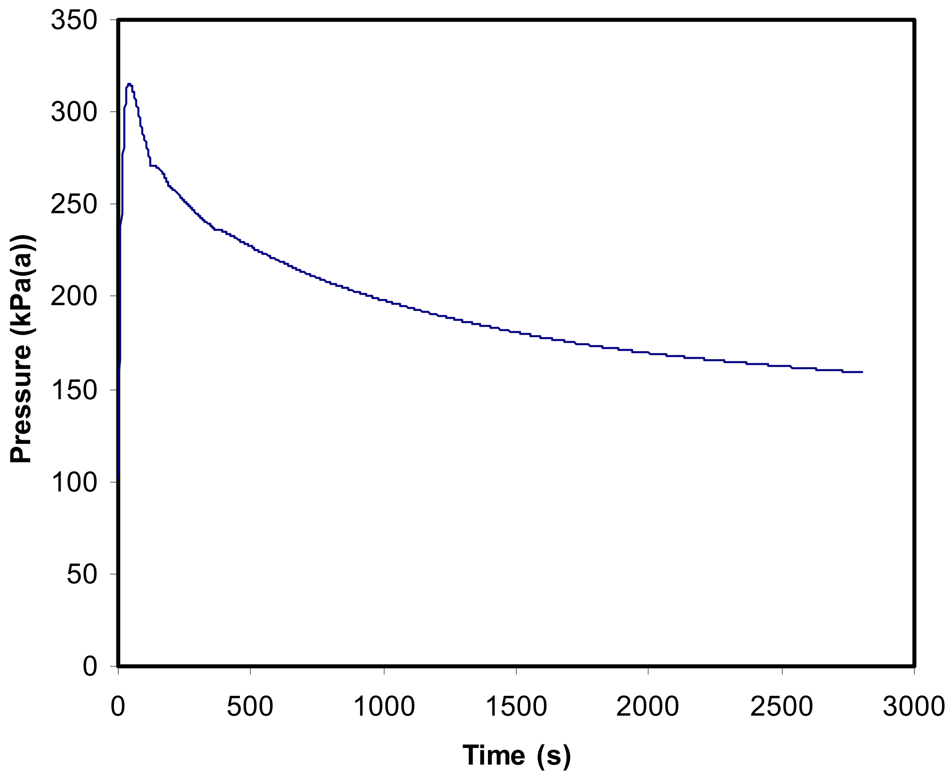
NORMAL OPERATION



Containment Analysis Assumptions

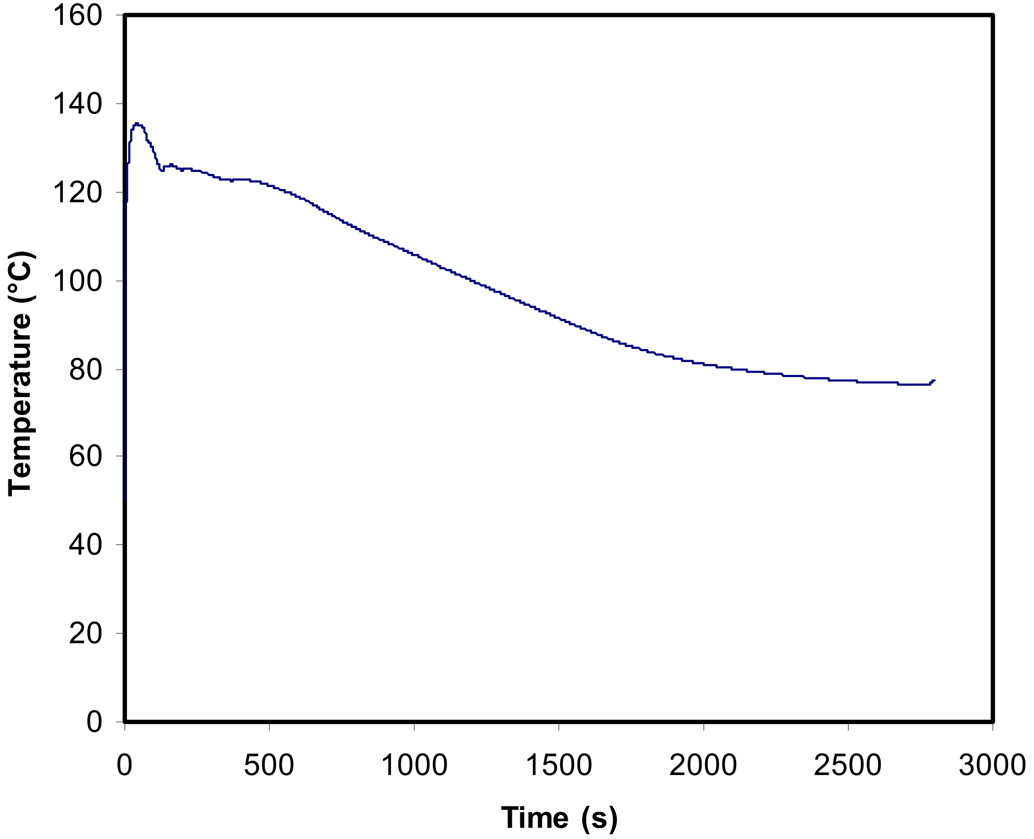
- For peak pressure calculations, credit half of the local air coolers (LAC's);
- Credit 100% of wall surface area, 80% of steel surface area, and no credit for cold water surface areas;
- Containment isolation is 3 seconds;
- Containment leakage is 0.5% of free volume per day at design pressure.

Containment Analysis Results



Pressure in Fueling Machine Vault

Containment Analysis Results



Temperature in Fueling Machine Vault

Fission Products in Containment

- SMART calculates fission product inventories and species in containment based upon GOTHIC (containment atmospheric conditions) and SOPHAEROS fission product source term.
- The quantities and species of fission products escaping containment are then used for dose calculations.

Summary and Conclusions

- Very conservative assumptions used to show that peak fuel temperatures are less than ~1400°C.
- Long term fuel temperatures are relatively low, and there are large margins to fuel melting.
- Fission product inventories are over-estimated.
- Fission product releases to containment will be less than ~10% of the total inventory (not accounting for deposition).

Summary and Conclusions

- **These results are due to the engineered features of the ACR:**
  - **Redundant and passive heat sinks (ECI, RWT, and the moderator),**
  - **Low fuel element powers and fuel temperatures (leading to low fission product inventories and releases),**
  - **The large RCS piping surface areas for the deposition of fission products,**
  - **Expect significant fission product deposition in containment, and**
  - **Very low leakage rates from containment.**

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