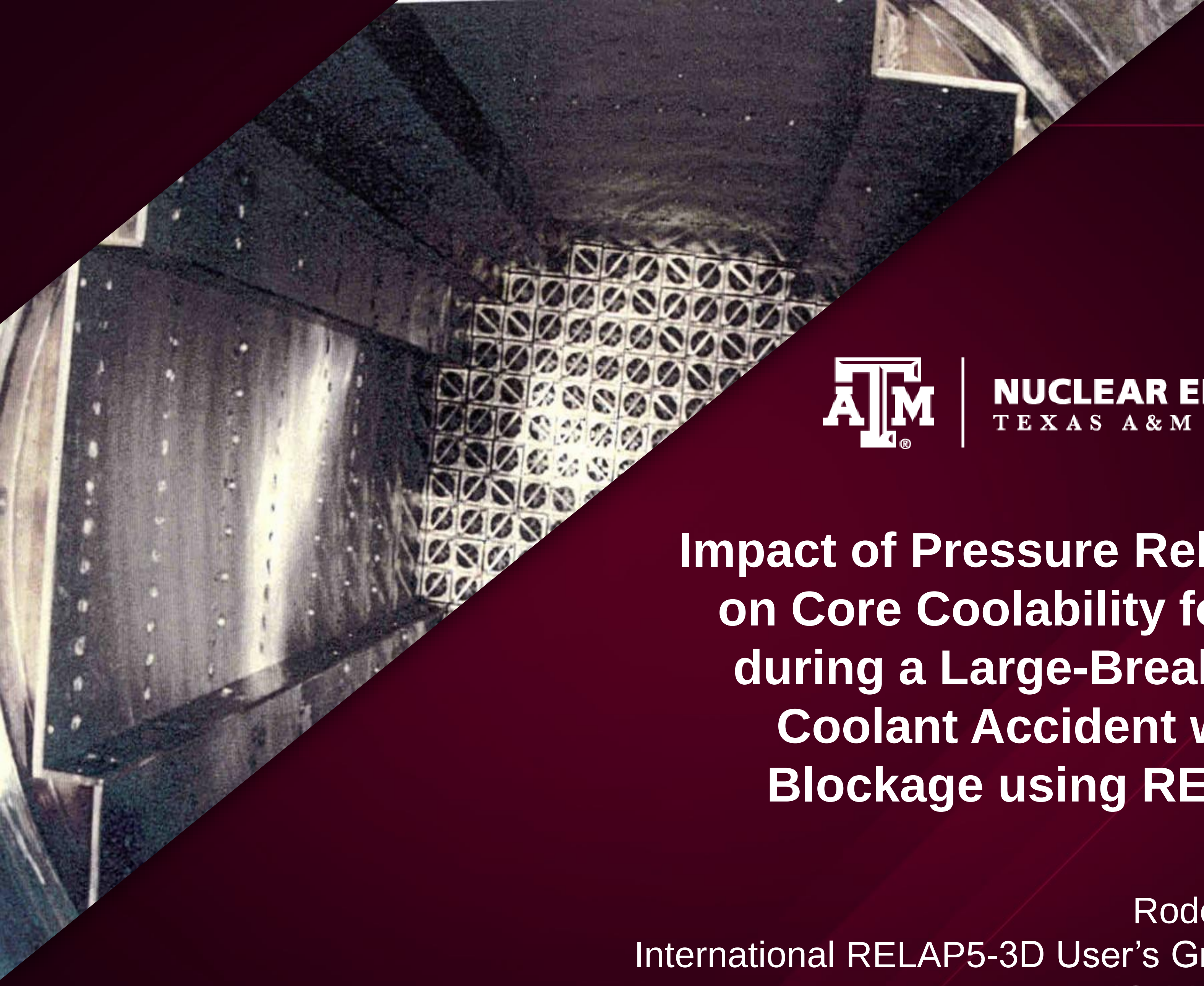

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Impact of Pressure Relief Holes on Core Coolability for a PWR during a Large-Break Loss of Coolant Accident with Core Blockage using RELAP5-3D

Rodolfo Vaghetto

International RELAP5-3D User's Group Meeting
13-14 August 2015

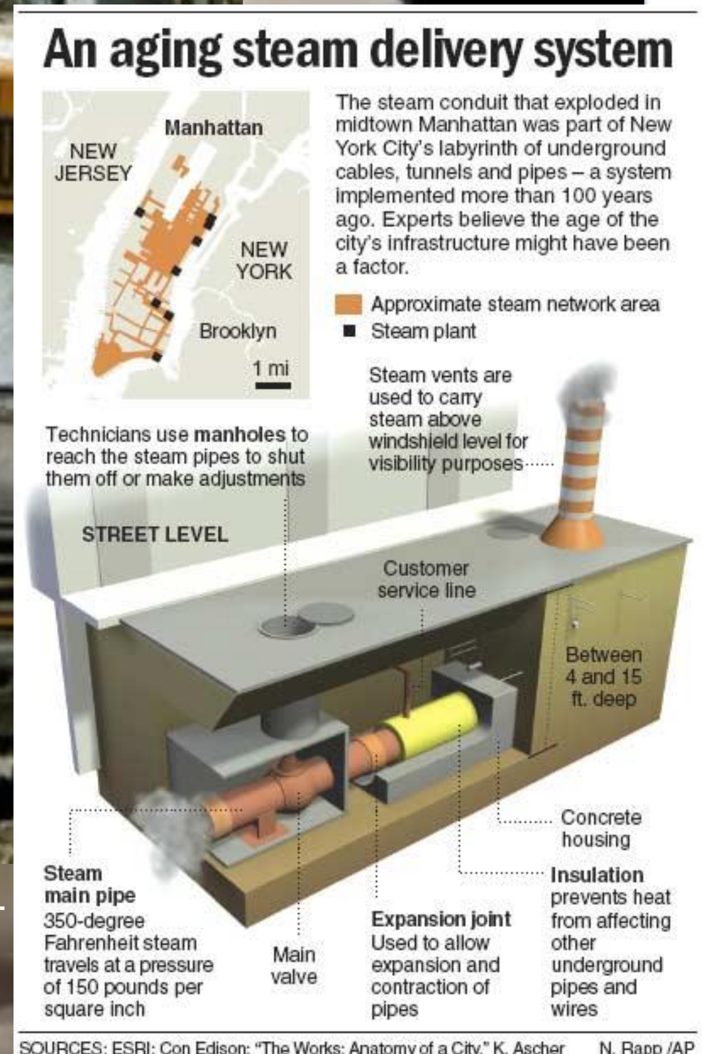
Introduction

GSI-191 Background

Accident Scenario

Study Motivation

Introduction



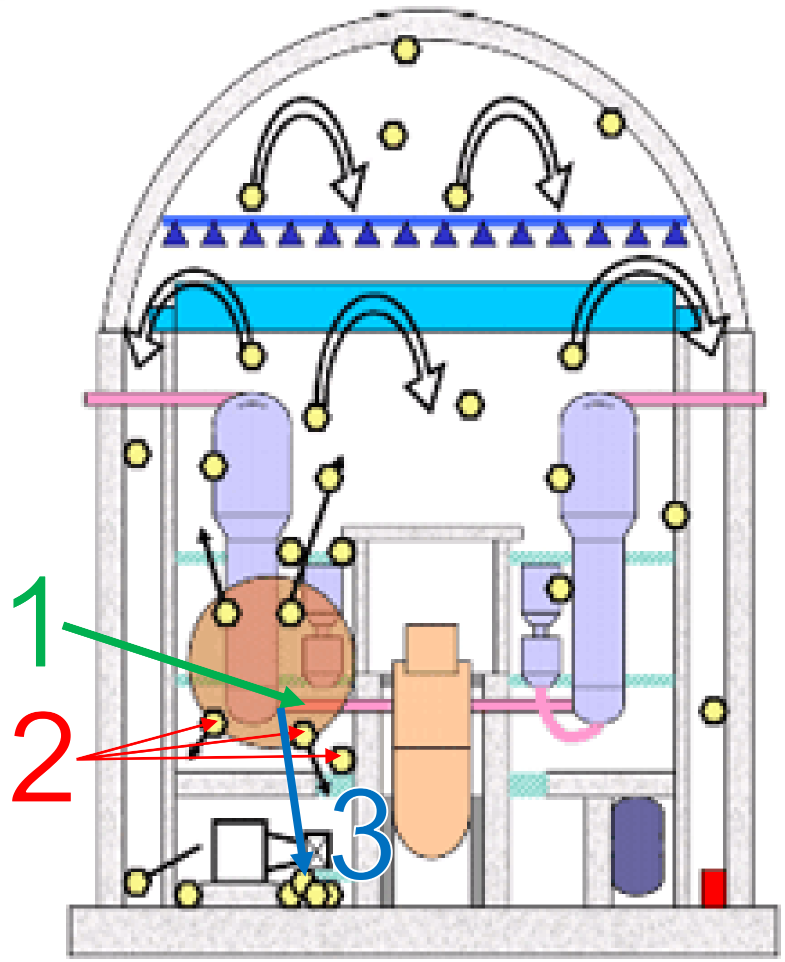
http://www.nbcnews.com/id/19844481/ns/us_news-life/t/aging-ny-pipes-raise-concerns-more-blasts/#.VDX10mddWSo

Introduction (Accident Scenario)

- When the break occurs, high energy jet from the break impinges into surrounding materials other components such that reactor/pipe insulation , producing debris
  - Debris generated could accumulate on strainers and impair pump performance
  - Debris could also bypass sump strainers and enter the primary system
- ECCS Process during a break
  - Coolant is drawn from the RWST (Refueling Water Storage Tank) and pumped into the primary system until the RWST is empty
  - Then pumps recycle water by drawing from the containment sump, cooling it via RHR (Residual Heat Removal) system, and pumping back into primary

Introduction (Accident Scenario)

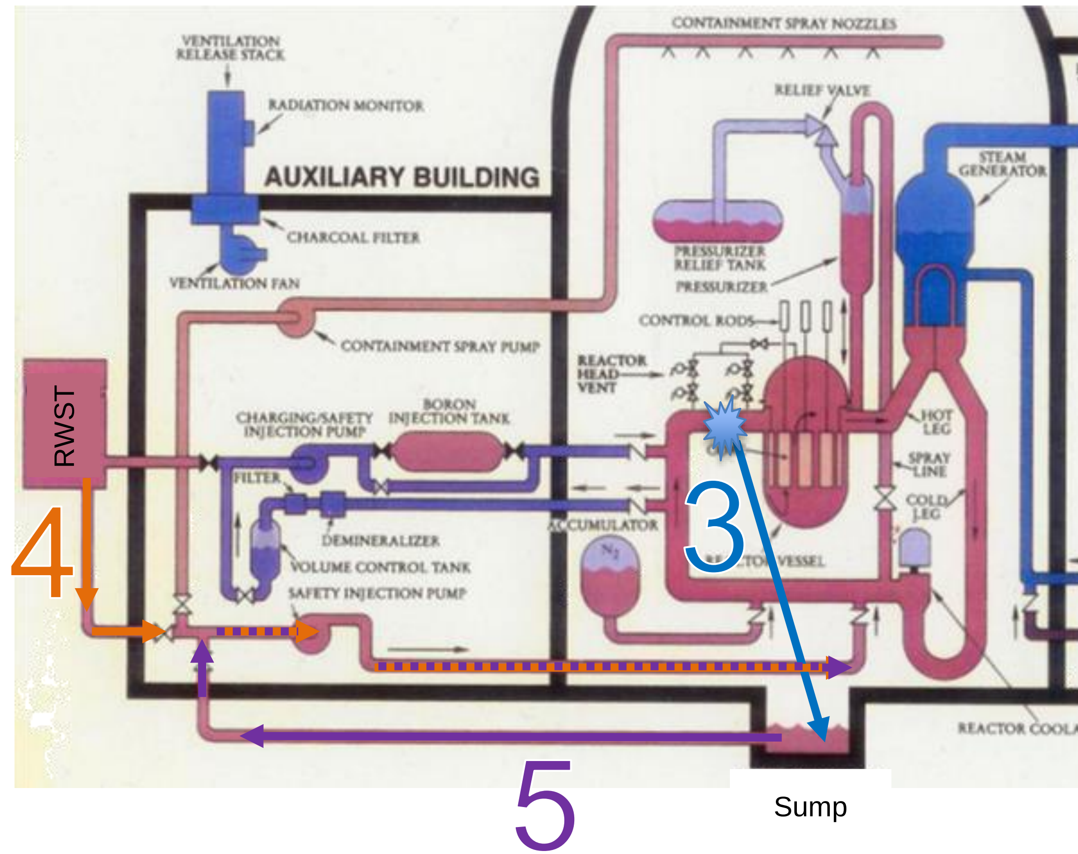
1. Break occurs
2. Hot water jet from break creates debris
3. Water & debris drain from break to sump compartment



http://www.nrc.gov/reactors/operating/ops-experience/pwr-sump-performance/safety-concern.html

Introduction (Accident Scenario)

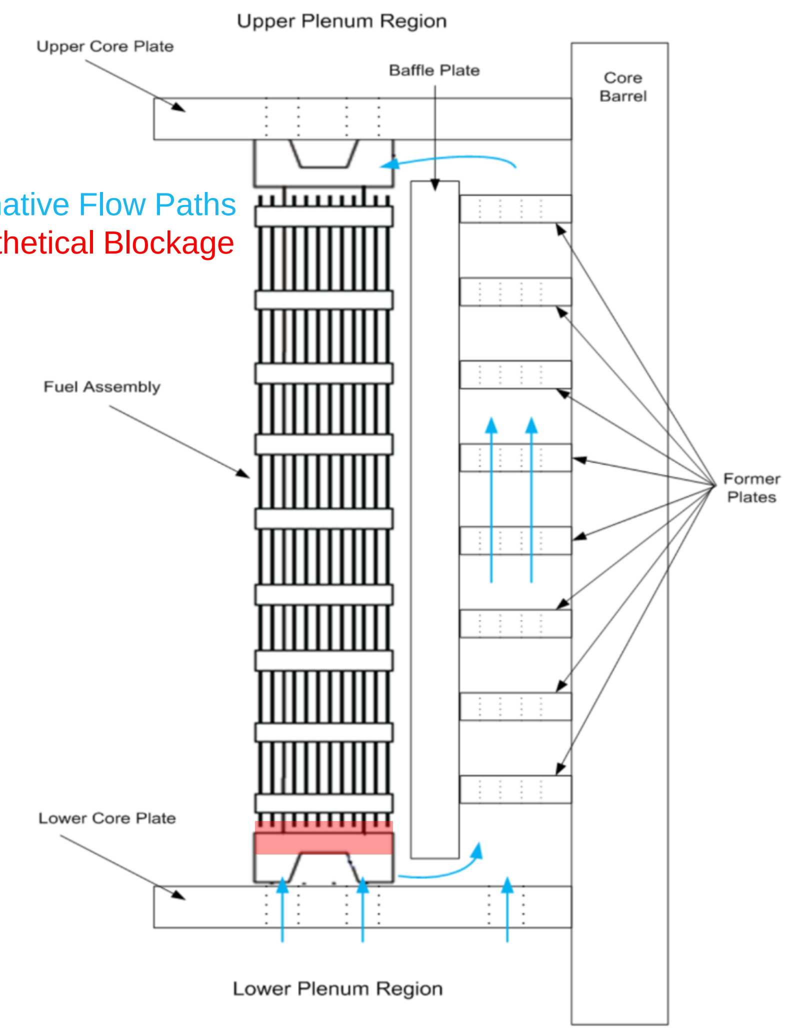
3. Water & debris drain from break to sump compartment
4. ECCS draws water from RWST (Safety Injection Phase), pumping into primary and containment sprays
5. RWST reaches low level, water is now drawn from sump pump (Sump Switchover)



http://www.ucsusa.org/sites/default/files/legacy/assets/documents/nuclear_power/pwr-intro.pdf

Introduction (Study Motivation)

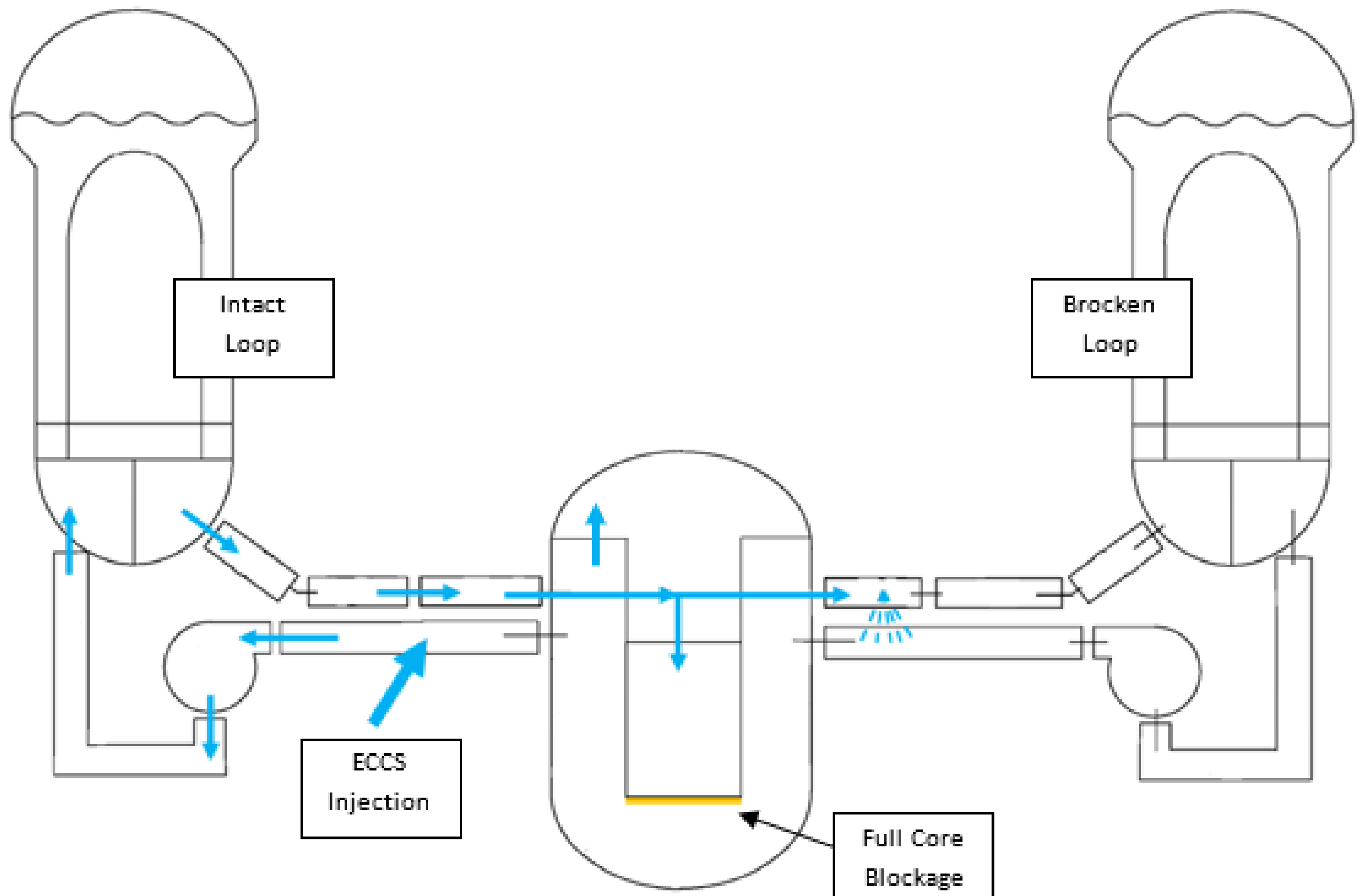
- When sump switchover occurs, debris could be drawn into the primary and accumulate at the core inlet
- For this hypothetical scenario, it was assumed full and instantaneous blockage of the core occurred at sump switchover
- In this scenario, coolant can only reach the core through alternative flow paths such as the core bypass or upper head sprays
  - This is realistic due to flow path sizes; the lower core plate/fuel assembly base has much smaller openings than the core bypass



Pressurized Water Reactor Owners Group, GSI-191 Comprehensive Analysis and Test Program Update: Findings from Thermal Hydraulic Analyses with Simulated Core Inlet Blockage, NRC Public Meeting, April 1, 2014

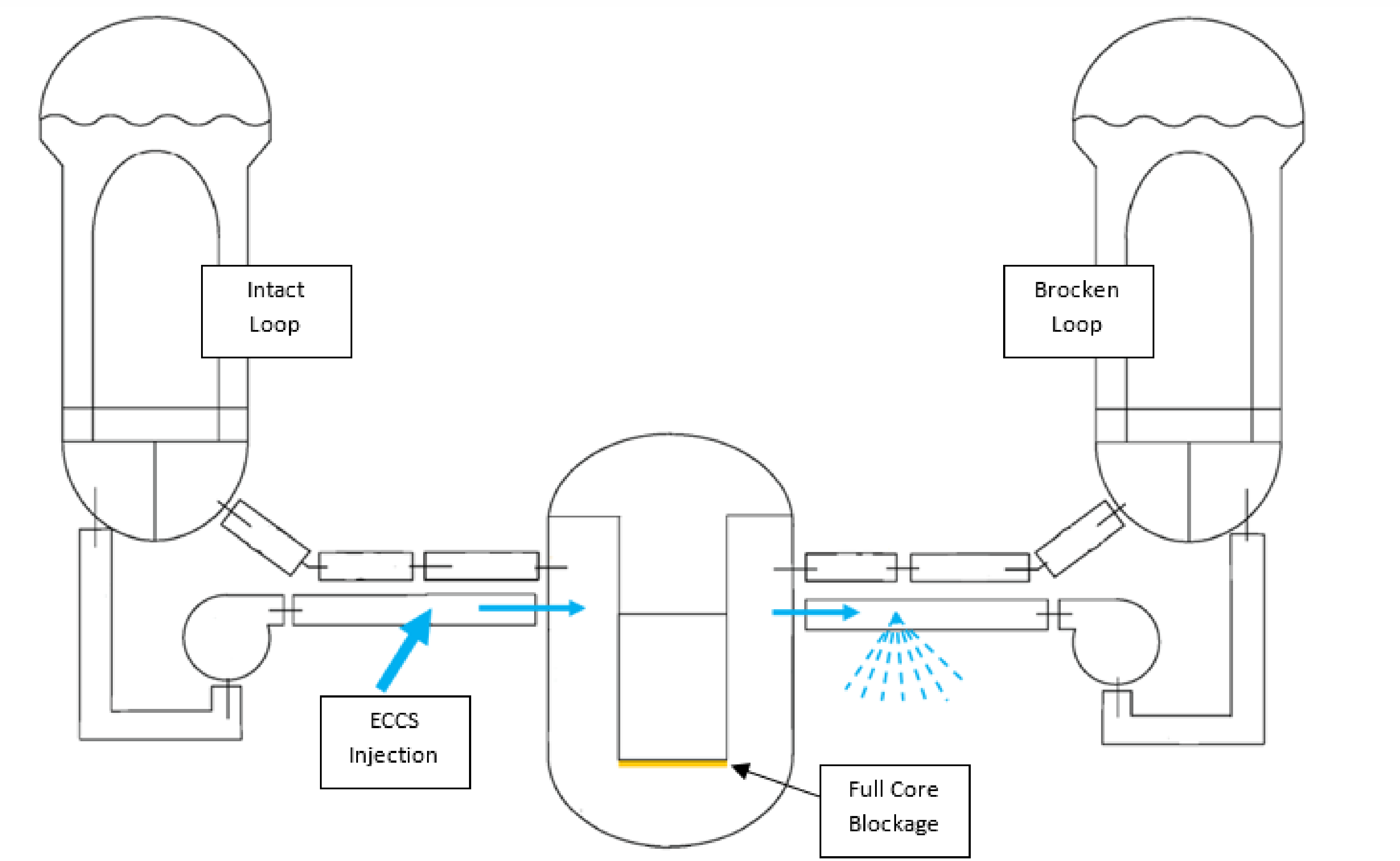
Previous Study

Hot Leg Break – Any Size



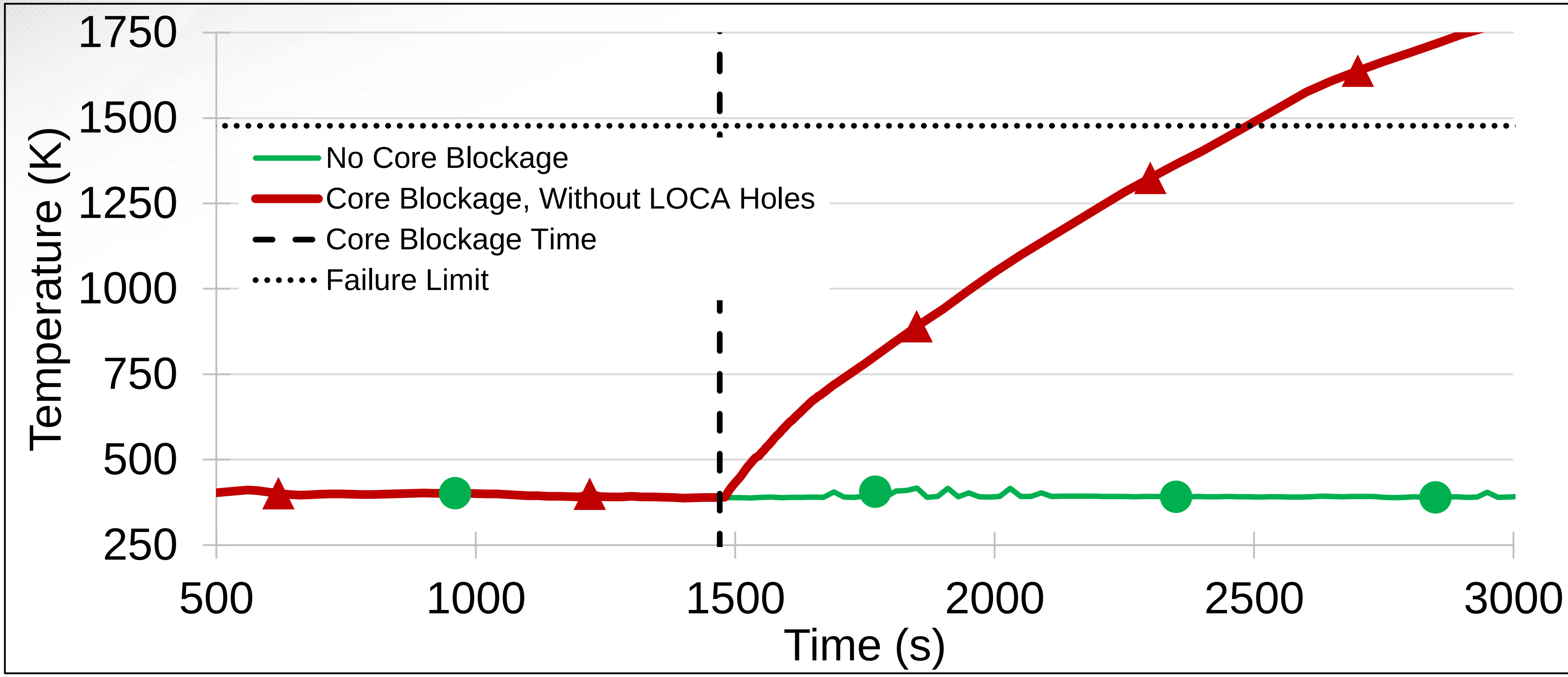
Previous Study

Cold Leg Break – Large Size



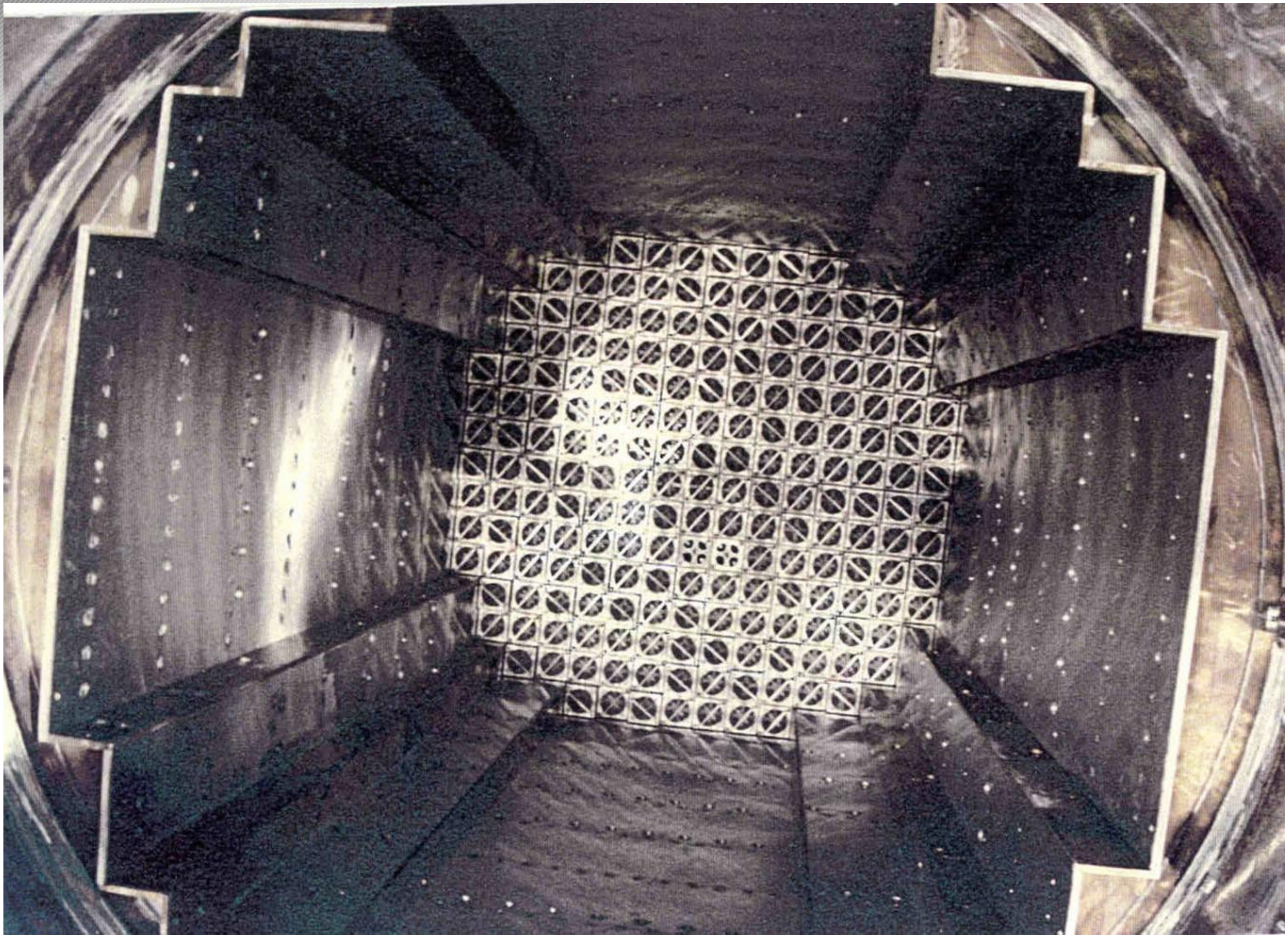
Introduction (Study Motivation)

DEG – Cold Leg



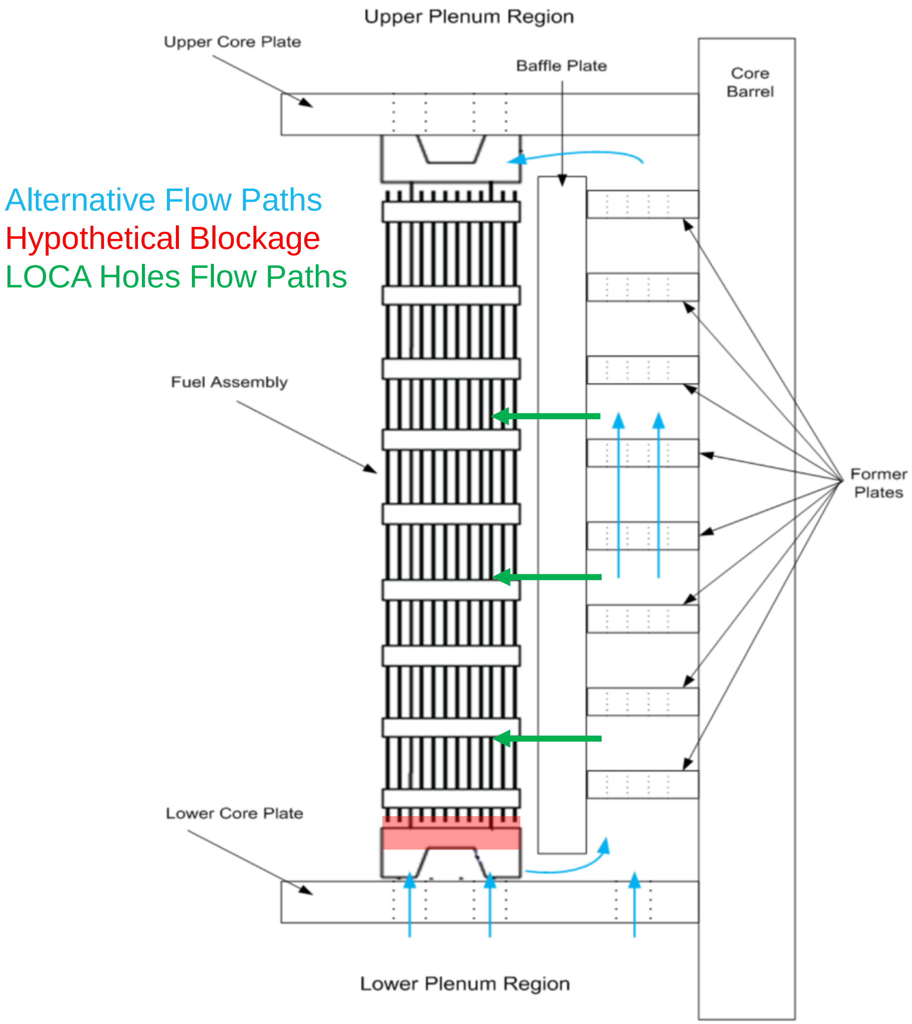
- Alternative Flow Paths to be investigated

Introduction (Study Motivation)



Introduction (Study Motivation)

- Alternative flow path of interest: Pressure Relief (LOCA) Holes
- LOCA holes consist of a series of holes through Baffle Plate connecting the Core and Core Bypass



Pressurized Water Reactor Owners Group, GSI-191 Comprehensive Analysis and Test Program Update: Findings from Thermal Hydraulic Analyses with Simulated Core Inlet Blockage, NRC Public Meeting, April 1, 2014

Input Model Description

Model Without LOCA Holes

ECCS System

Break Simulation

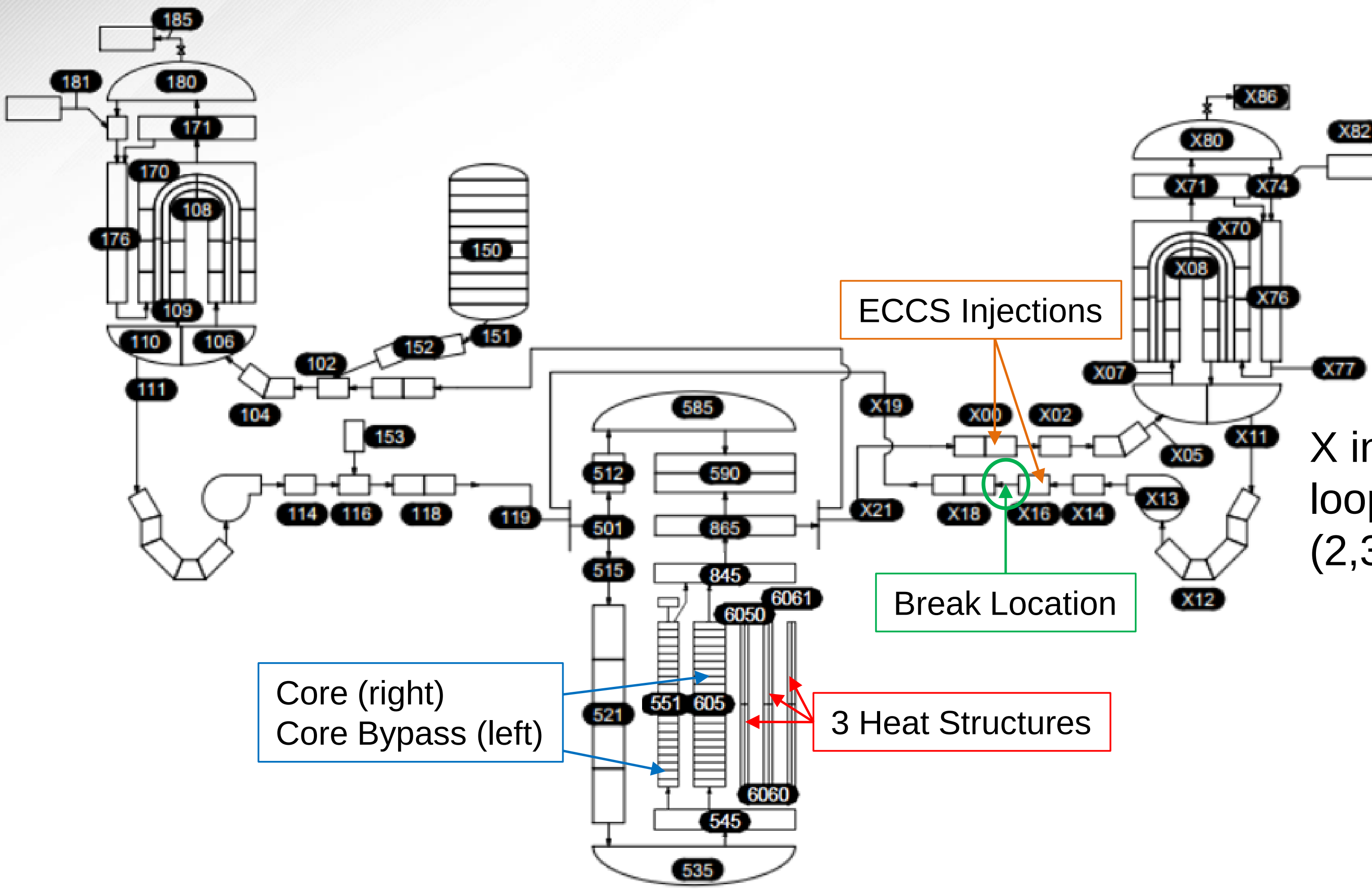
Model With LOCA Holes

Blockage Simulation

Input Model Description (Model w/o LOCA Holes)

- RELAP5-3D was used for the primary system model
- The model included:
  - 1D Components, 1D Core
  - Four Independent Loops
  - Three Core Heat Structures
    - Average Channel (192 Assemblies)
    - Hot Channel (1 Assembly, minus 1 fuel rod)
    - Hottest Rod (1 fuel rod)
  - Full ECCS (3 trains connected to loops 2, 3, & 4)

Input Model Description (Model w/o LOCA Holes)

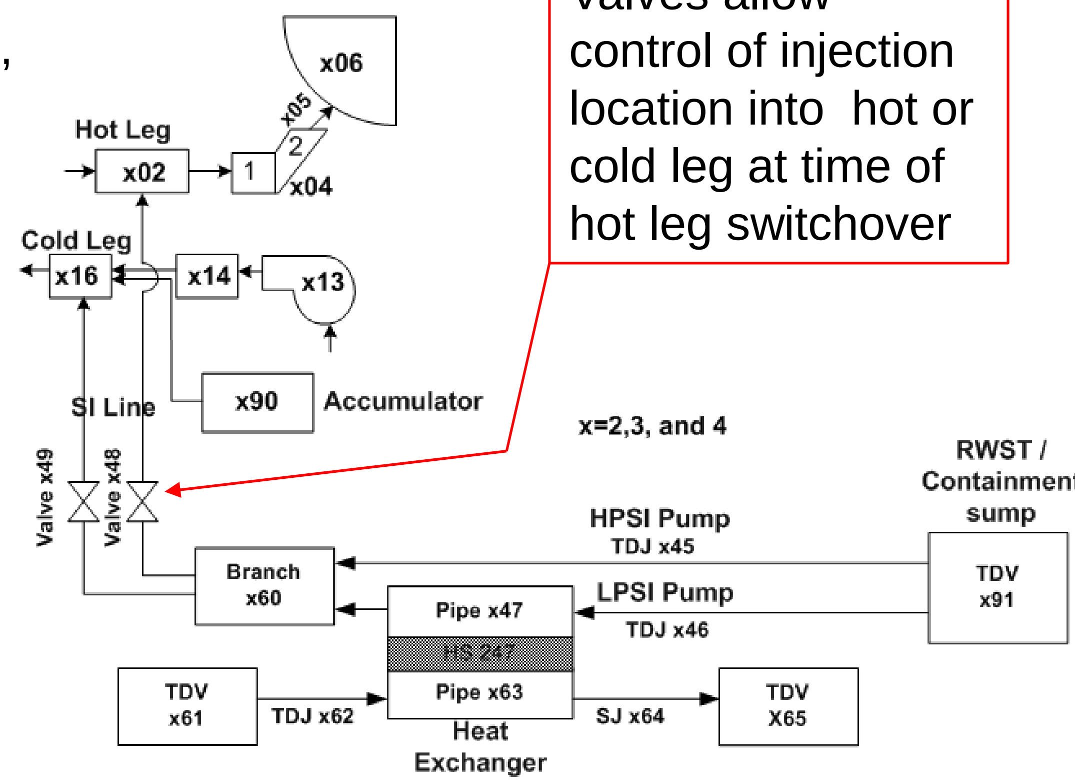


X indicates loop # (2,3,4)

Input Model Description (ECCS System)

- The model includes the ECCS with three independent safety injection trains connected to loop 2, 3, and 4. Each train includes:
  - One Low Pressure Safety Injection (SI) pump
  - One High Pressure SI pump
  - One Residual Heat Removal (RHR) heat exchanger
  - One Accumulator
- During the long term cooling phase, the heat is removed from the system through the RHR heat exchangers

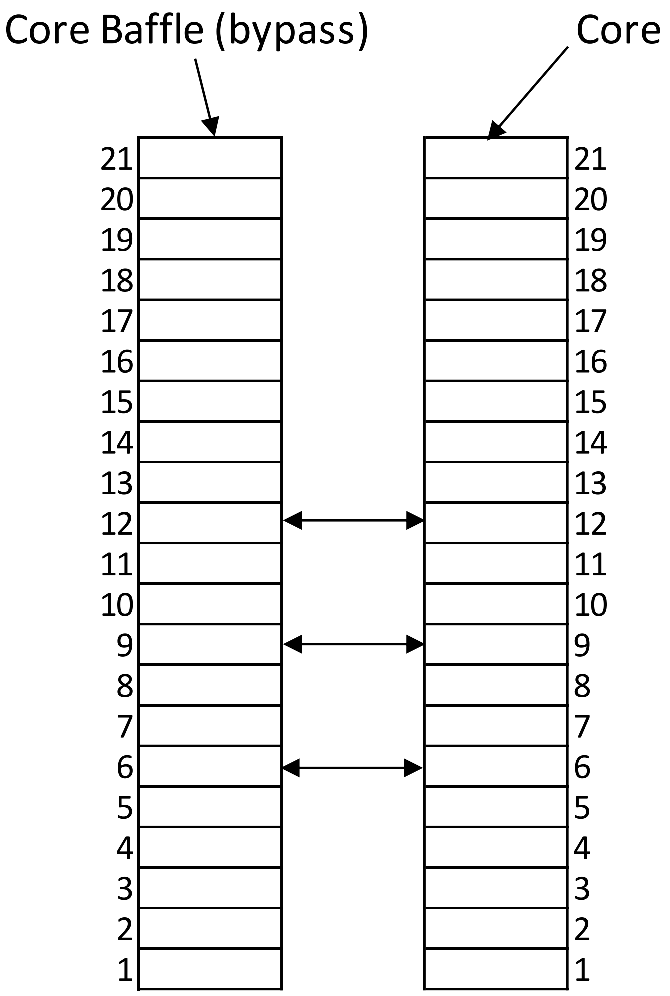
Valves allow control of injection location into hot or cold leg at time of hot leg switchover



Input Model Description (Model with LOCA Holes)

- Pressure Relief (LOCA) Holes: A ring of holes through Baffle Plate connecting the Core and Core Bypass
- Simulated 1, 2, and 3 levels
- 1D Model means we take a “lumping” approach
  - All holes at each level combined are into 1 hole (so 1-3 holes)
  - Hydraulic Diameter is that of 1 hole
  - Flow Area is the sum of ALL holes (at each level)
- Friction losses (k-losses) modeled as flow through an orifice:

$$k = \frac{\Delta p}{\rho w_0^2/2} = \left(1 + 0.707\sqrt{1 - \frac{F_0}{F_1}} - \frac{F_0}{F_1}\right)^2 = 2.914$$



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Input Model Description (Model with LOCA Holes)

- Friction losses (k-losses) modeled as flow through an orifice
  - This model considers k-loss as a function solely of geometry, following this formula:

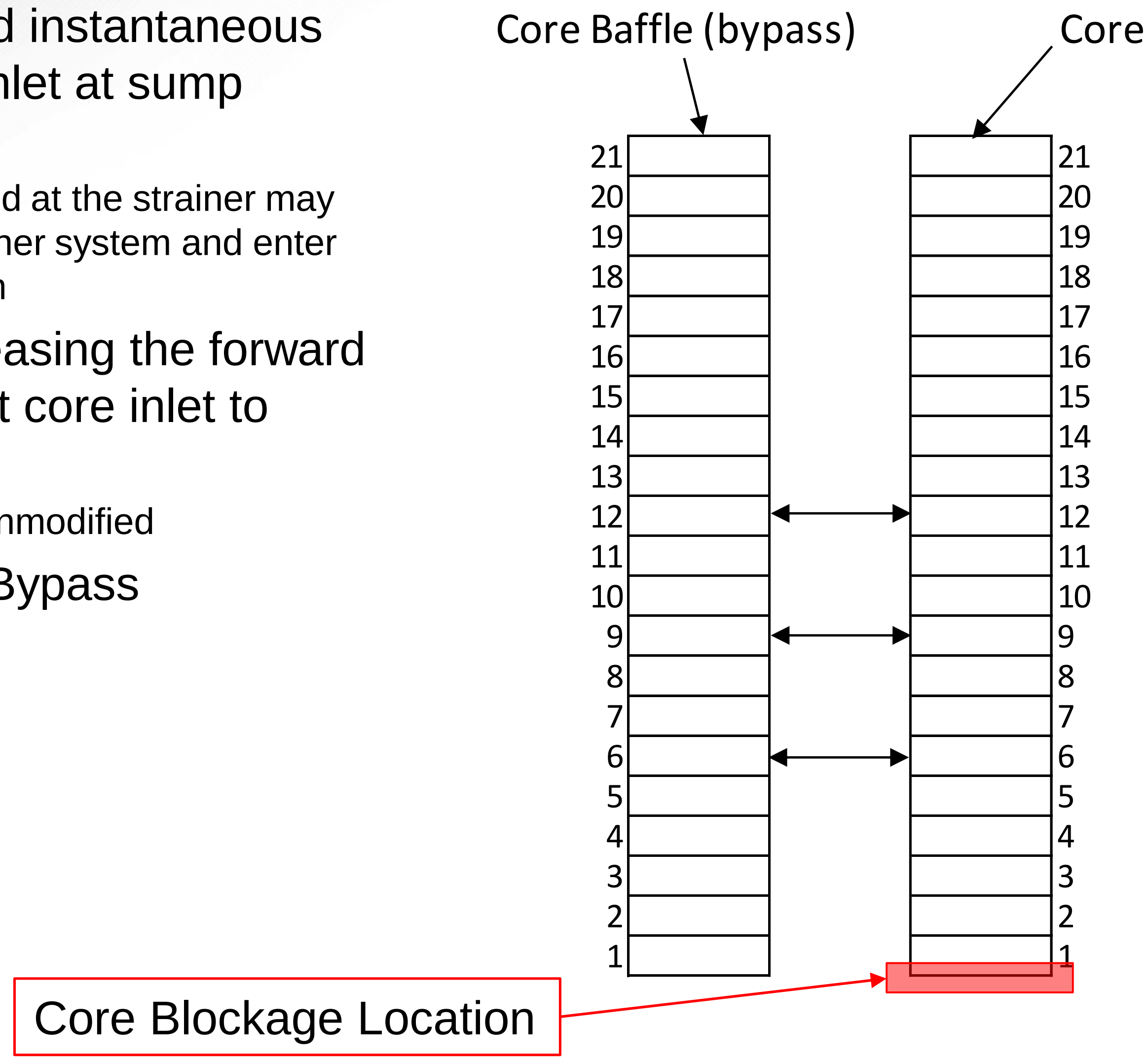
$$k = \frac{\Delta p}{\rho w_0^2/2} = \left(1 + 0.707\sqrt{1 - \frac{F_0}{F_1}} - \frac{F_0}{F_1}\right)^2 = 2.914$$

  - F_0 is the flow area of the LOCA Hole, F_1 is the area of injection ambient
  - The flow area of the core or bypass channel is significantly larger than individual LOCA Holes, such that: $F_0/F_1 = 0$

- Other models were considered for flow past an orifice
  - Functions of stream and hole flow velocities
  - Not able to be implemented in RELAP5-3D as there is no control function to adjust k-loss at a junction during the simulation

Input Model Description (Blockage Simulation)

- Assumed a full and instantaneous blockage of core inlet at sump switchover
  - Debris accumulated at the strainer may penetrate the strainer system and enter the primary system
- Simulated by increasing the forward k-loss (to 1.0E6) at core inlet to prevent flow
  - Backward k-loss unmodified
- Free (unblocked) Bypass



Simulation Results

Simulation Approach

Results without LOCA Holes

Impact of LOCA Holes

Simulation Results (Simulation Approach)

- 8 total simulations
  - No LOCA Holes
    - With Core Blockage
    - Without Core Blockage
  - With 1 LOCA Hole
    - With Core Blockage
    - Without Core Blockage
  - With 2 LOCA Holes
    - With Core Blockage
    - Without Core Blockage
  - With 3 LOCA Holes
    - With Core Blockage
    - Without Core Blockage

- Parameters of Interest:
  - Peak Cladding Temperature (1478/700 K early/late limits)
  - Core Collapsed Liquid Level
  - Bypass Flow

Simulation Results (Simulation Approach)

- 4 "base" models were simulated
  - First, the simulation was run at steady-state for 300 seconds (from "-300 to 0 seconds")
  - Then, the break opened (at "0 seconds")
  - Sump switchover occurs 1470 seconds later
    - At this time, each simulation was allowed to run normally, to simulate long term cooling without blockage
    - Also, a restart file was created at 1470 seconds and blockage simulations were run for each

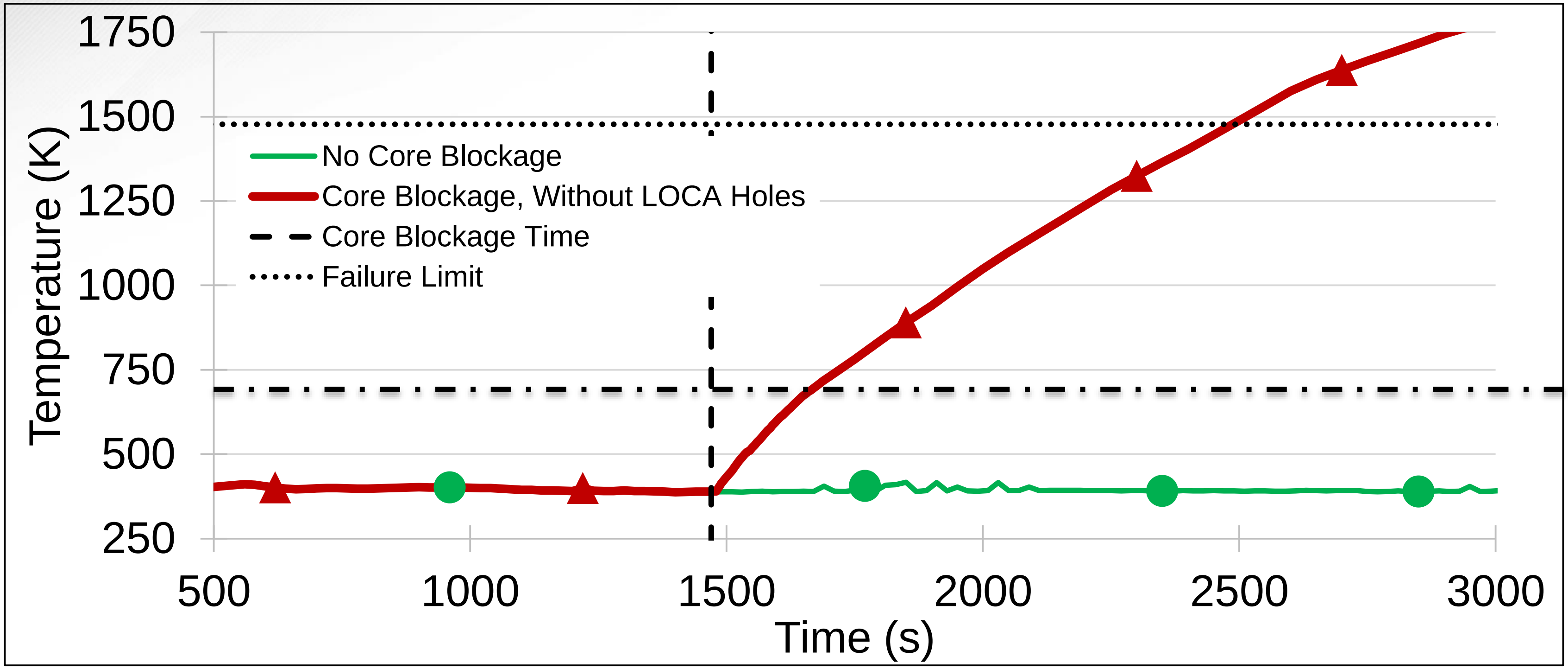
(-300 to 0 seconds) → (0 to 1470 seconds) → (1470 to 5000+ seconds)

	Simulation Phase			
	Steady-State	Safety Injection	(symb)	Long-Term Cooling
Without LOCA Holes	Null Transient	DEG CL Transient	▲	Core Blockage
			●	No Core Blockage
With 1 LOCA Hole			●	Core Blockage
			●	No Core Blockage
With 2 LOCA Holes			◆	Core Blockage
			●	No Core Blockage
With 3 LOCA Holes			■	Core Blockage
			●	No Core Blockage

● NOTE: there is negligible difference in results for all unblocked cores, so they are lumped as green results

Simulation Results (Results w/o LOCA Holes)

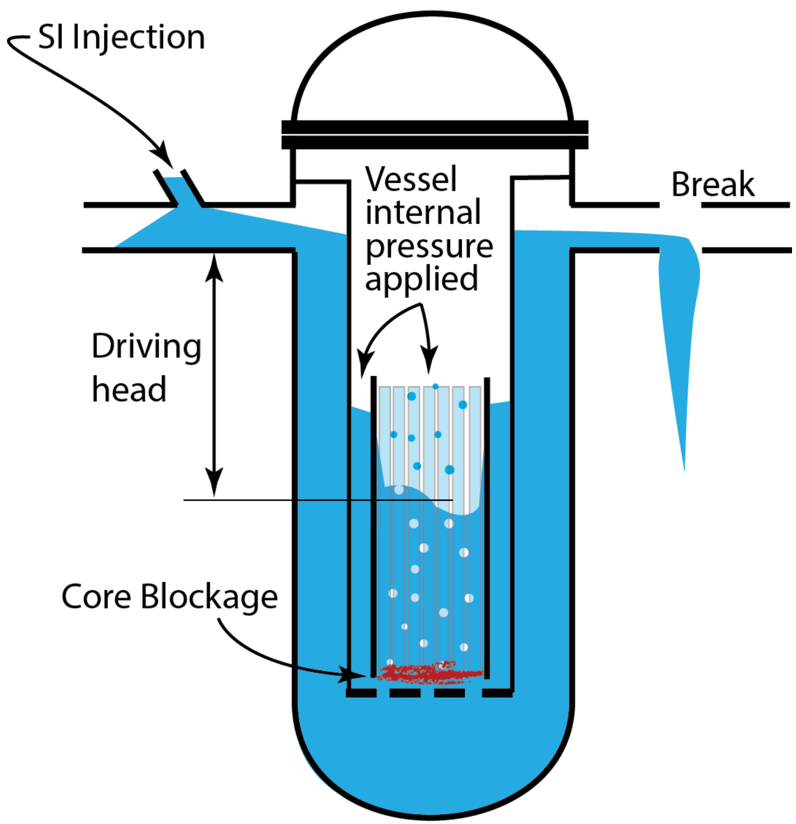
- Initial simulations indicated failure



- Why?

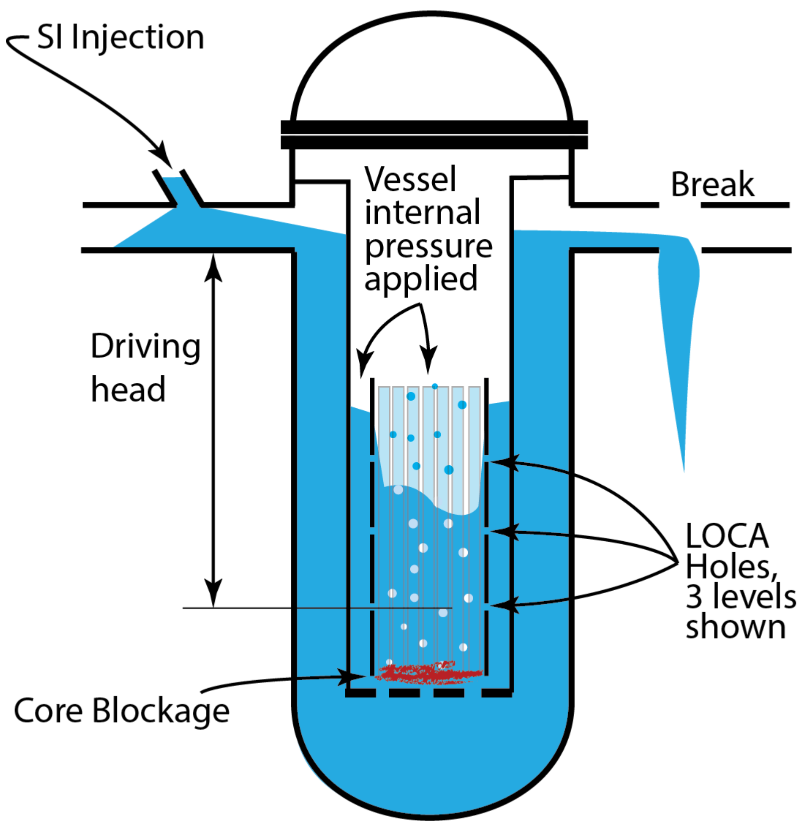
Simulation Results (Results w/o LOCA Holes)

- Supply of coolant to the core is primarily determined by the hydrostatic head between the cold leg (injection location) and the top of the core
- Due to the lower pressure drop between the injection point and the break, the injected water is preferentially directed toward the break and a small fraction goes through the core bypass



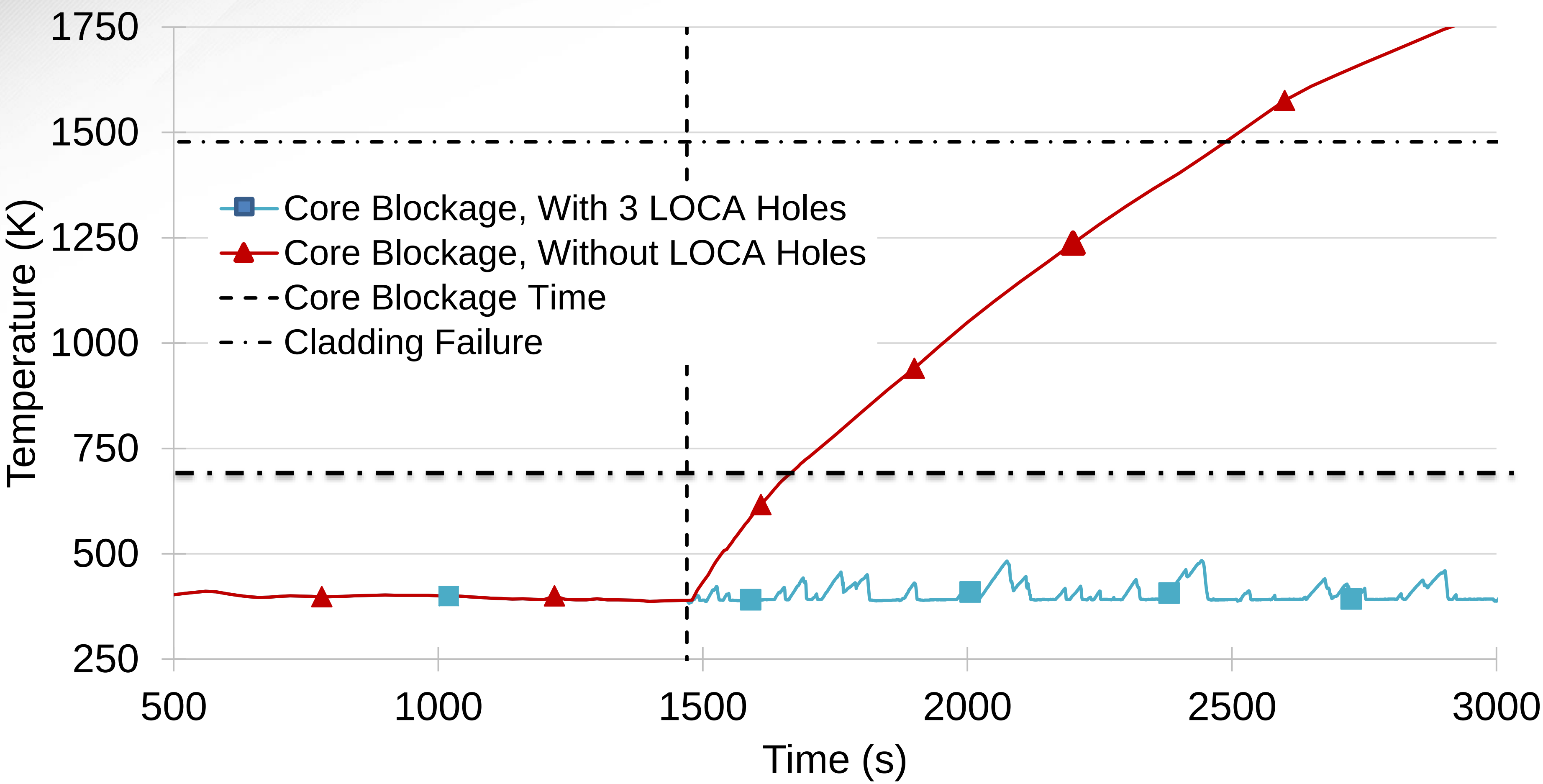
Simulation Results (Results with LOCA Holes)

- Preliminary thoughts on the possible effects of the LOCA holes on the core coolability:
  - Higher hydrostatic head between the cold leg injection and the levels of holes (coolant doesn't have to make it all the way to the top of the core)
  - Additional coolant should be directed into the core



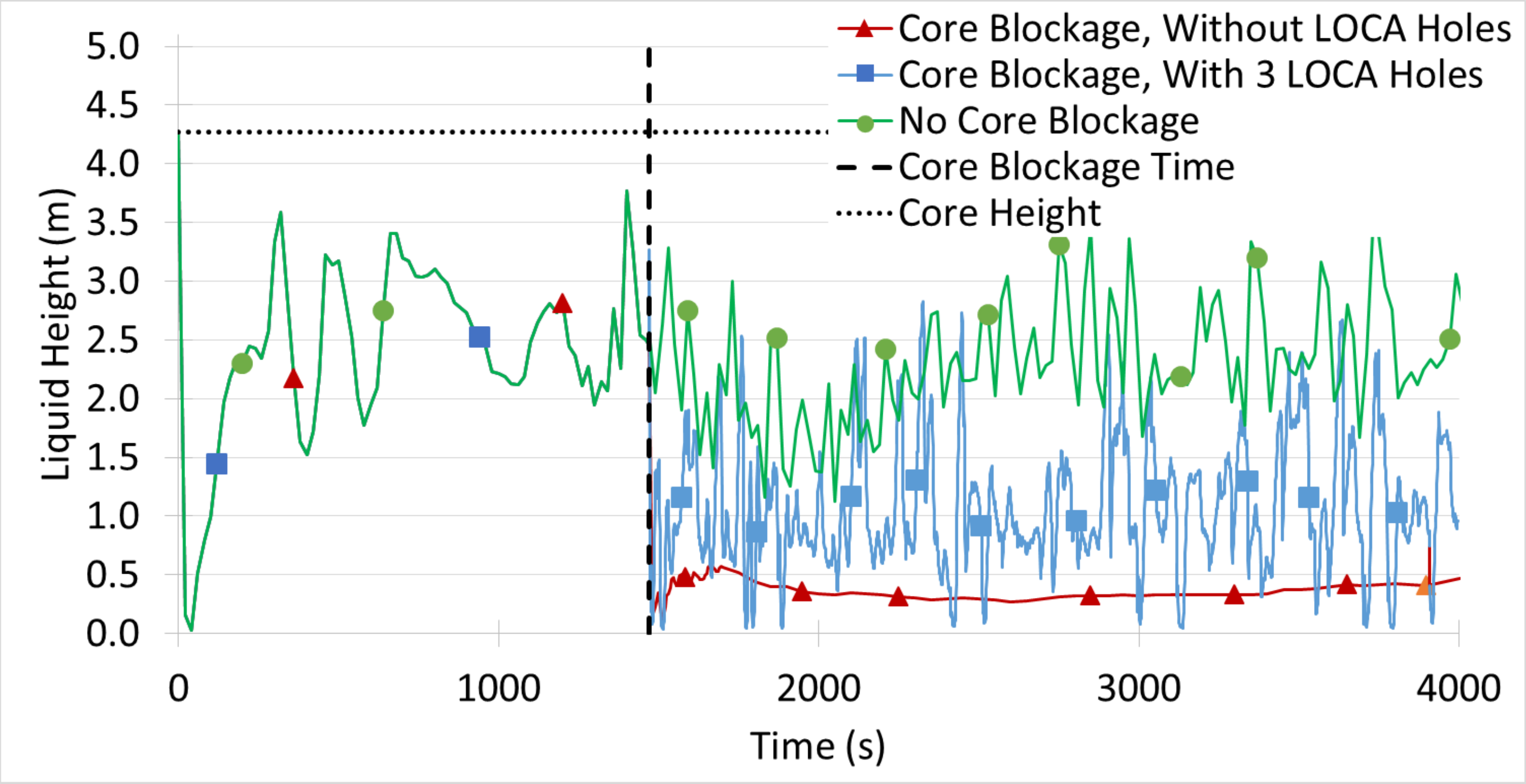
Simulation Results (Results with LOCA Holes)

- The addition of LOCA holes improved core coolability substantially based on examination of peak cladding temperature



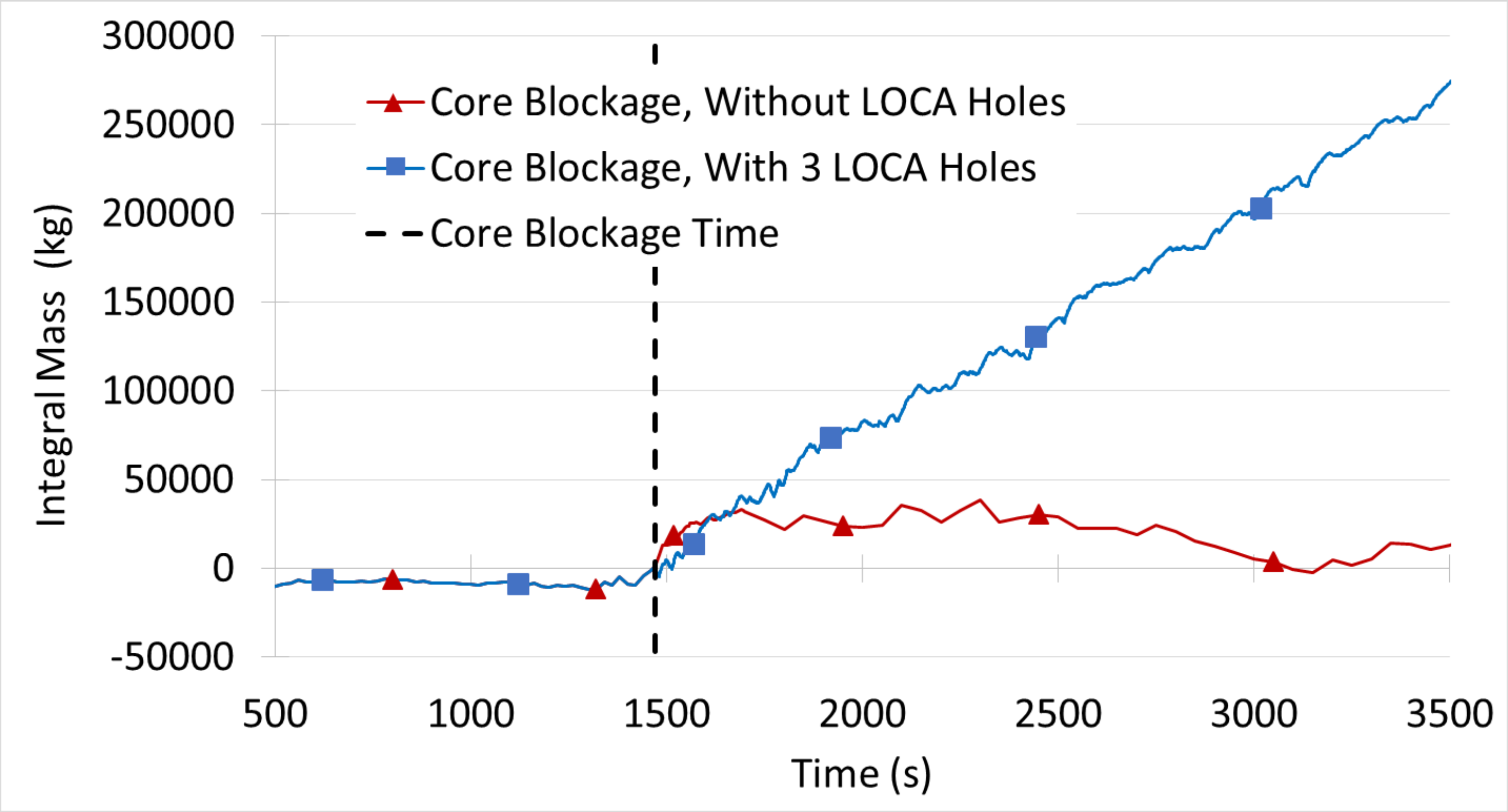
Simulation Results (Impact of LOCA Holes)

- Effect of the LOCA holes is shown as a higher core liquid level than the simulation without LOCA holes
- Blockage simulations with LOCA holes have a lower total liquid volume than a simulation without blockage, but the amount of liquid is sufficient to maintain an adequate heat removal rate



Simulation Results (Impact of LOCA Holes)

- Bypass integral flow mass represents the total mass of the flow through bypass region over time
- After the core blockage time, bypass inlet mass flow has a net increase as an effect of the presence of the LOCA holes, whilst in the model without the LOCA holes, the net flow was substantially lower



Discussion

Summary

Conclusions

Discussion (Summary)

- Performed RELAP5-3D simulations
  - Cold-leg DEG LOCA with full core blockage
  - Three simulation sets included LOCA holes, one did not
- Determined LOCA hole effect on core flow and coolability by examining:
  - Peak Cladding Temperature
  - Core Collapsed Liquid Level
  - Core Bypass Integral Flow

Discussion (Conclusions)

- No LOCA Holes
  - Substantially less coolant supplied to core
  - Cladding temperature increased above specified limit

- With LOCA Holes
  - More coolant flowed into the bypass
  - More coolant reached the core itself
  - Core Coolability was improved (Peak Cladding Temperature always below the specified limit)

Nomenclature and References

Nomenclature

ABBREVIATIONS

- CL: Cold Leg
- DEG: Double-End Guillotine
- ECCS: Emergency Core Cooling System
- GSI-191: Generic Safety Issue 191
- LOCA: Loss of Coolant Accident
- LWR: Light Water Reactor
- N/A: Not available
- NRC: (United States) Nuclear Regulatory Commission
- PCT: Peak Cladding Temperature
- PWR: Pressurized Water Reactor
- RCP: Reactor Coolant Pump(s)
- RHR: Residual Heat Removal
- RPV: Reactor Pressure Vessel
- SC: Subcooled
- SH: Superheated
- SI: Safety Injection
- TP: Two-Phase

SYMBOLS

- k: Frictional energy loss factor (k-loss factor) [unitless]
- Δp: Pressure change [Pa]
- ρ: Density [kg/m^3]
- w_0: LOCA hole flow velocity [m/s]
- F_0: LOCA hole flow area [m^2]
- F_1: Ambient (bypass/core) flow area [m^2]

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8. R. VAGHETTO, B.A. BEENY, Y.A. HASSAN, K.VIEROW, “Sensitivity Analysis of a Typical Large, Dry Containment Response during a Loss of Coolant Accident using RELAP5-3D and MELCOR,” ANS Annual Meeting, Atlanta, GA, June 16-20 (2013).
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11. R. VAGHETTO, A. FRANKLIN, Y.A. HASSAN, “Sensitivity Study of Hypothetical Debris-Generated Core Blockage Scenarios,” ANS Annual Meeting, Washington, DC, November 10-14 (2013).

Simulation Results (Impact of LOCA Holes)

- The impact of the addition of LOCA holes is so substantial, that even a single hole at the lowest elevation was predicted to be sufficient to prevent cladding temperatures from exceeding failure limits