Summary on Natural Circulation Phenomena Observed in ROSA/AP600 Tests

presented by Y. Sibamoto

prepared by T. Yonomoto

Japan Atomic Energy Agency

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Outline

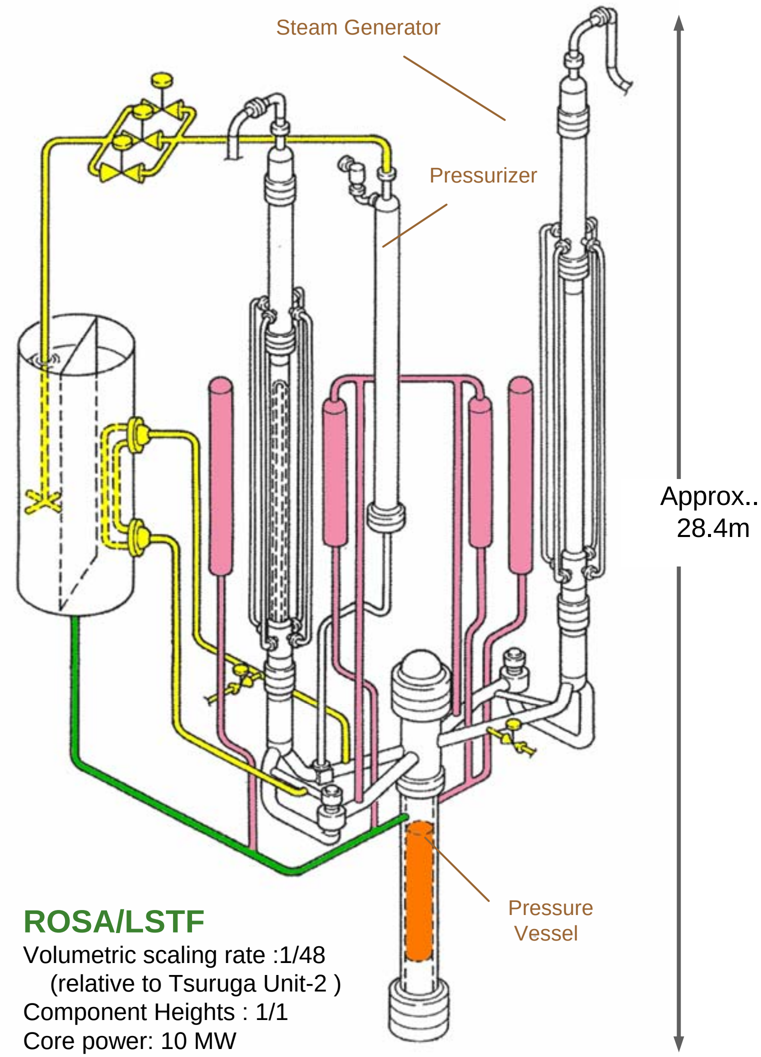
- ROSA/AP600 Project
- Test Facility
- Typical System Responses to SBLOCA
- PRHR
- CMT
- Primary Loop
- Conclusions

ROSA/AP600 Project

- Cooperative research program between JAERI and USNRC.
- Perform a series of confirmatory testing on response of the Westinghouse AP600 design by using ROSA/LSTF of JAERI.
- Objectives
  - Characterize and quantify the important phenomena.
  - Assess and verify the RELAP5/MOD3 code.
- 24 Tests had been conducted for various test conditions in the period between 1993 to 1997.

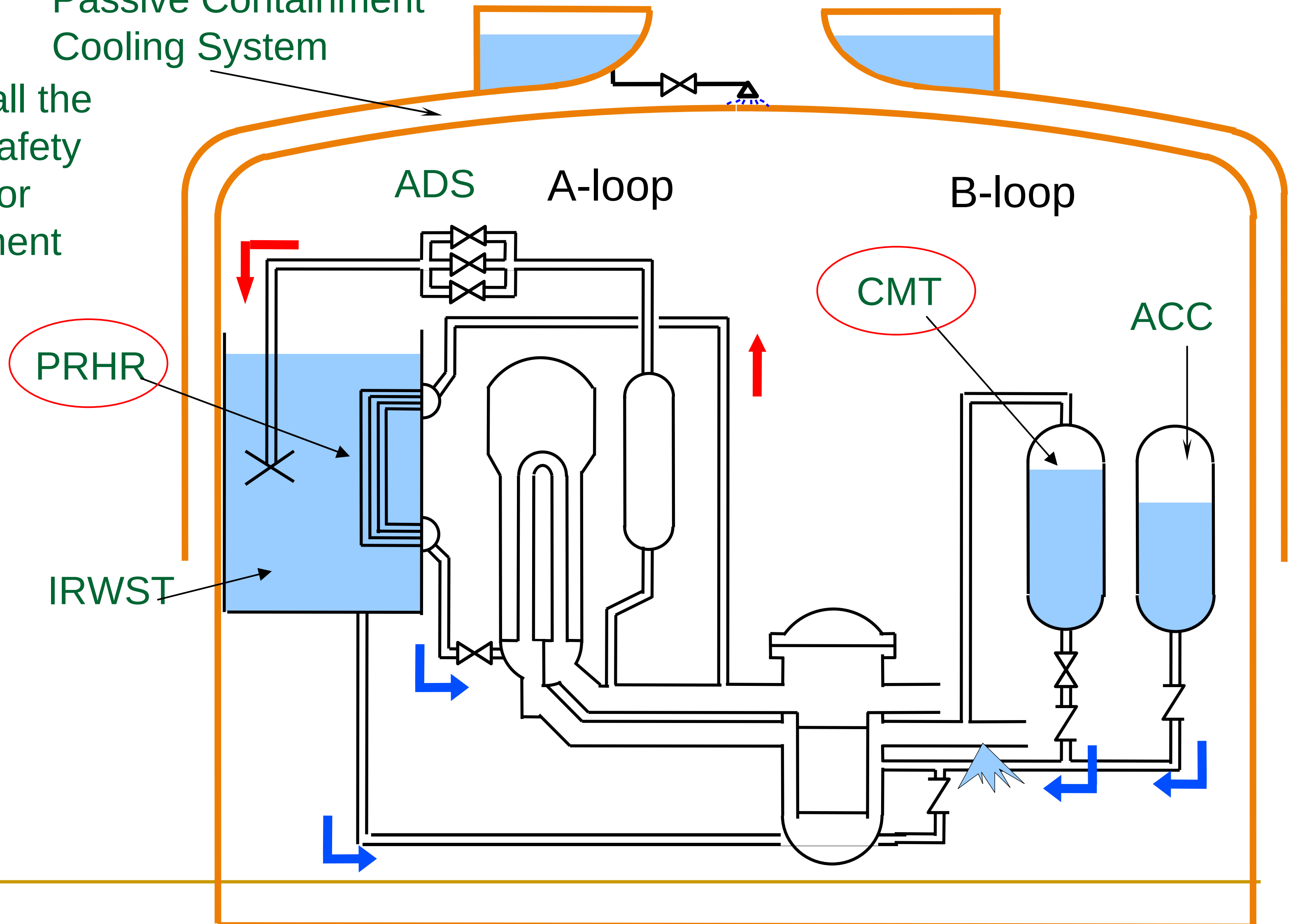
Test Facility

- Reference reactor: Tsuruga-2, 1100MWe Westinghouse-type four-loop PWR
- 1/48 volumetric scaling
- Full height (~30 m)
- Full pressure (16 MPa)
- Core: 10 MW electrical heater composed of 1008 heater rods
- ~2500 instruments
- AP600 passive safety systems (1/30 volumetric scaling)



Passive Safety Systems of AP600

LSTF simulates all the AP600 passive safety systems except for passive containment cooling system



Typical System Responses

- 1 inch cold leg break without any failure of safety systems (AP-CL-03: base case test)

PRHR and CMT are actuated at an early stage after break.

N2 discharge from ACC affects PRHR and CMT behavior.

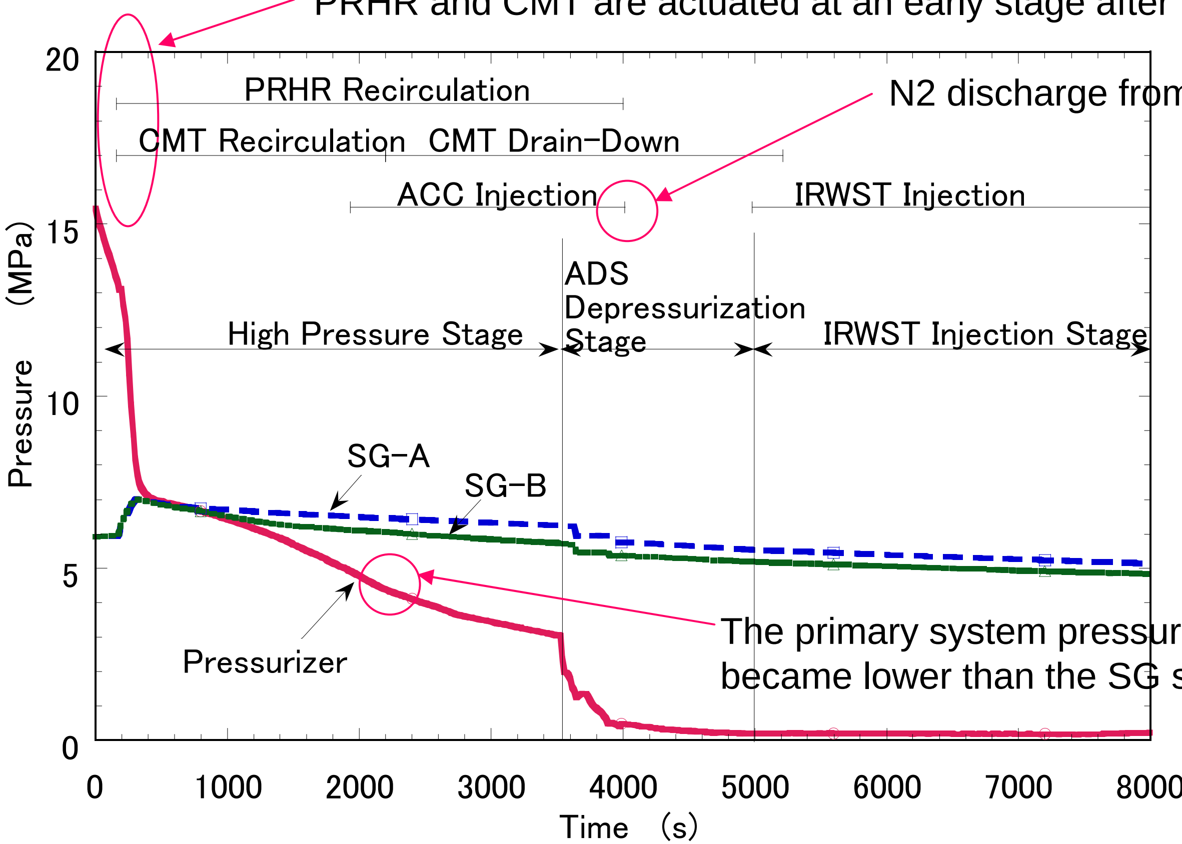


Figure 5.1.1 Typical primary depressurization during 1-inch SBLOCA AP-CL-03

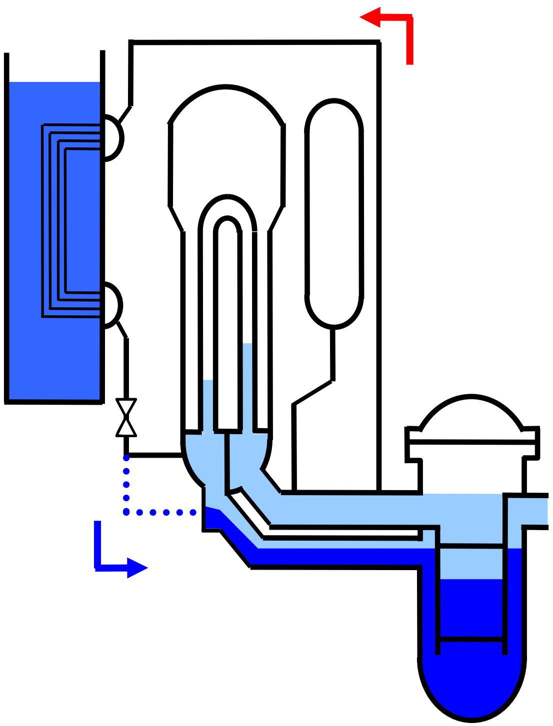
The primary system pressure decreased continuously even after it became lower than the SG secondary-side pressure.

- **Break at Cold leg B**
- **PZR & PRHR in loop A**

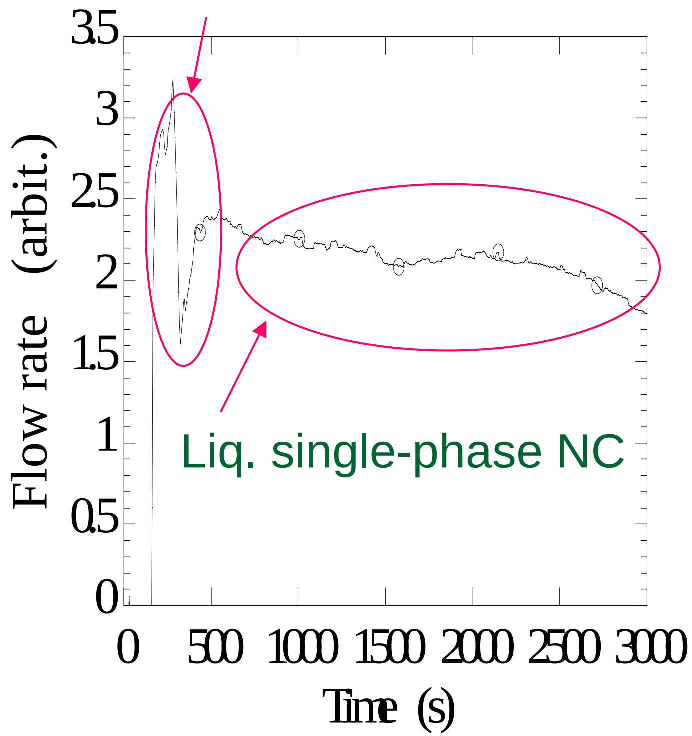
Steam condensation on the steam/water interface in PV and CL

PRHR NC

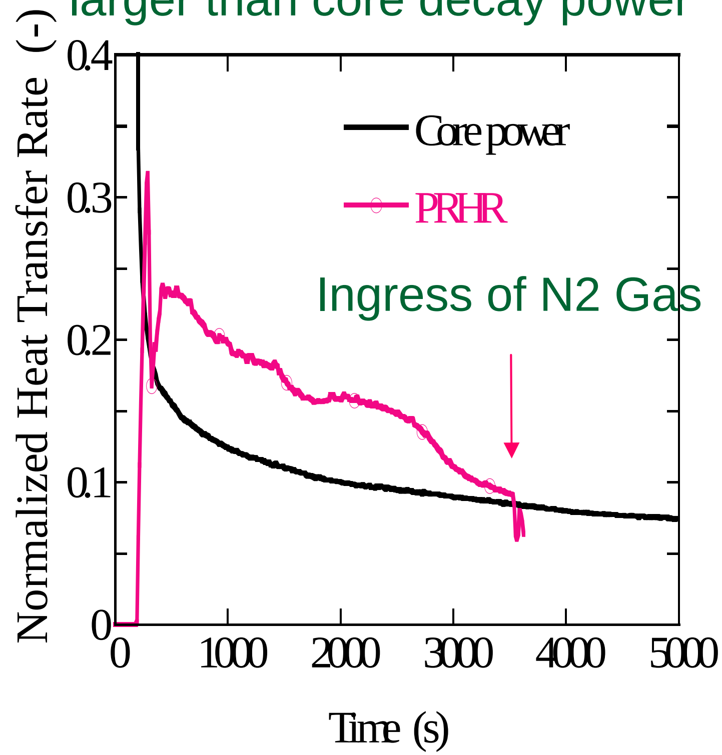
- **PRHR NC starts when the isolation valve opens and terminates when N2 gas accumulates**



Two-phase flow ingress and condensation from PZR

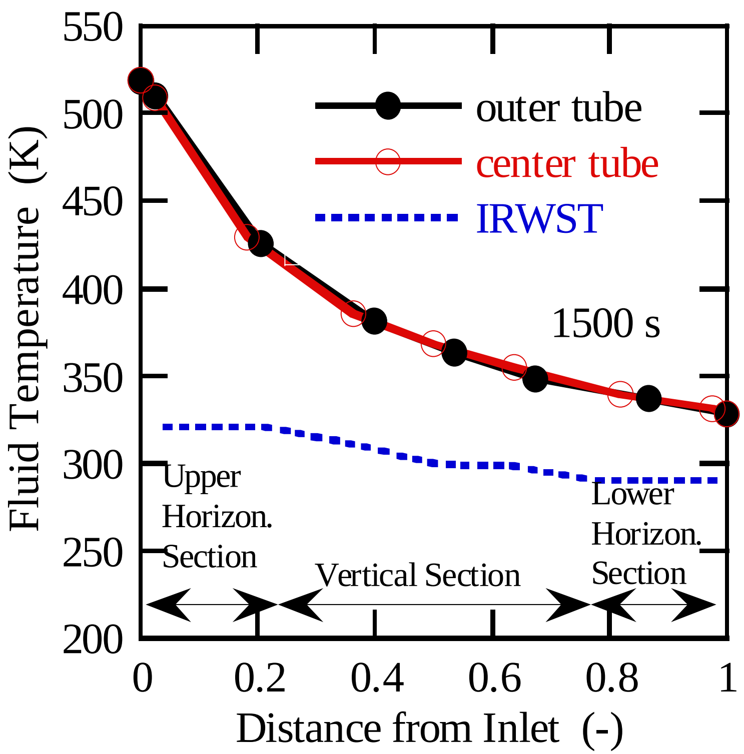


Heat removal rate become larger than core decay power

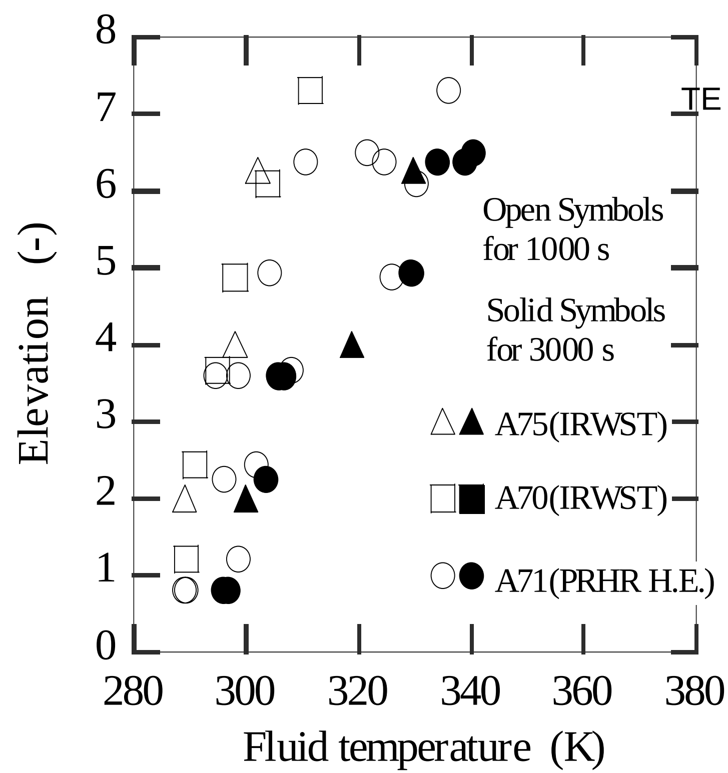


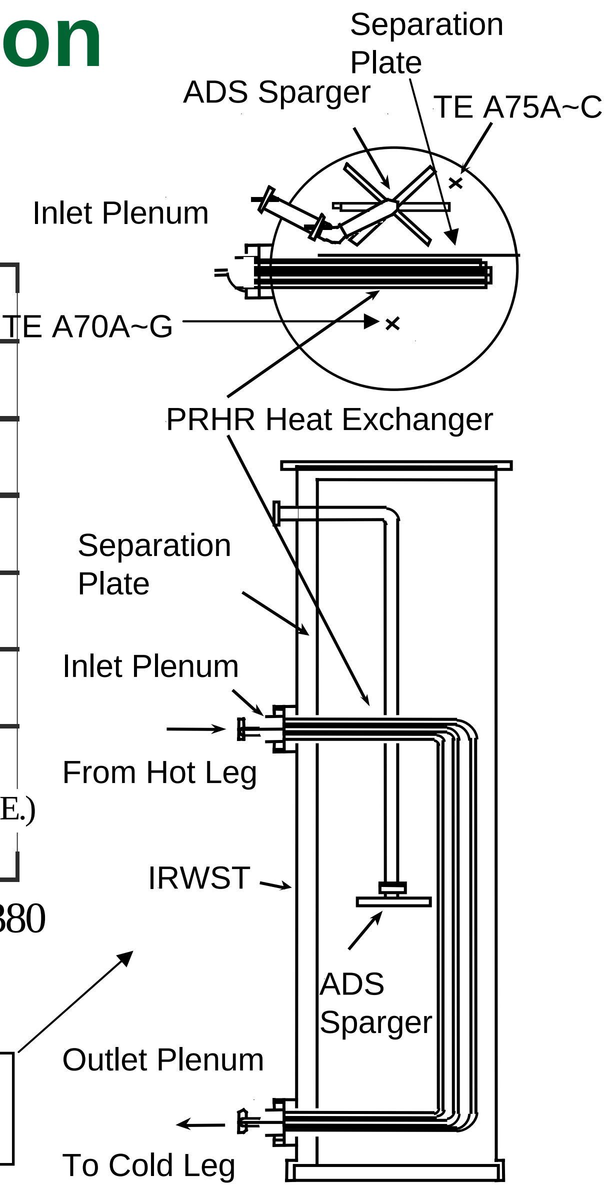
PRHR and IRWST temp. distribution

One-dimensional temperature distribution of HEX tubes



Temp distribution of vertical cross-section

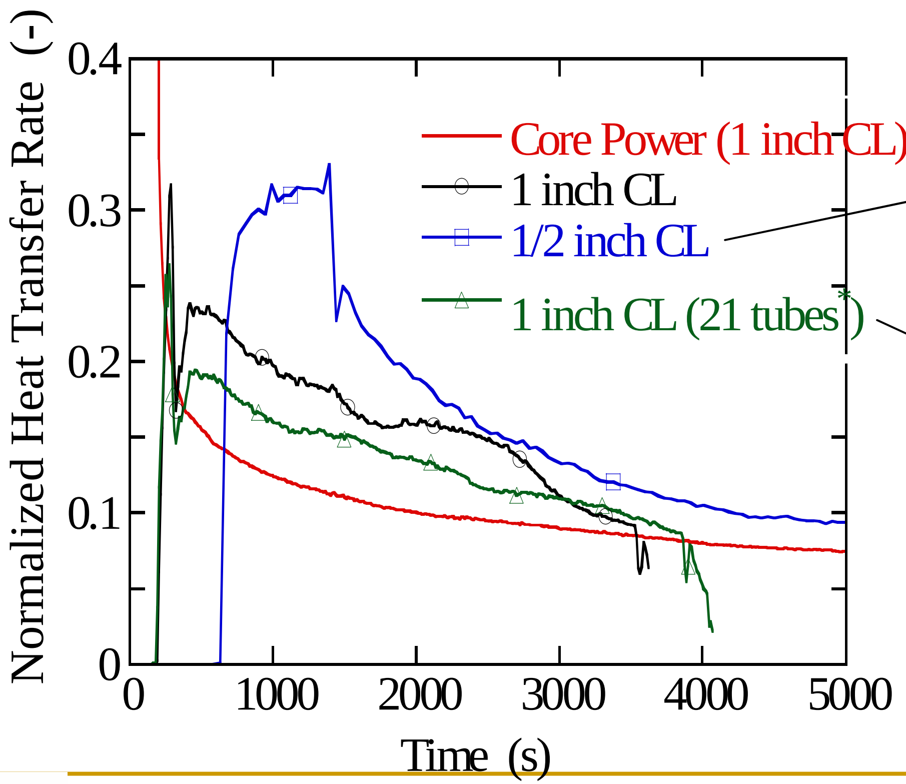




The IRWST internal space is divided into two regions by separation plate.
The effect of this atypical geometry on the heat transfer behavior is discussed later.

Behavior Observed in Other Tests

- PRHR significantly affects the system behavior during high pressure stage for SBLOCA tests with break dia. < 1”
  - Heat transfer rate is higher than core power assuming decay heat.
  - Liquid single-phase NC continues for more than 3000 sec.



The PRHR inlet temperature was higher for test of half-inch break due mainly to the delayed core power trip.

The flow resistance of the HX tubes was only a minor contributor to the total resistance of the PRHR NC loop.

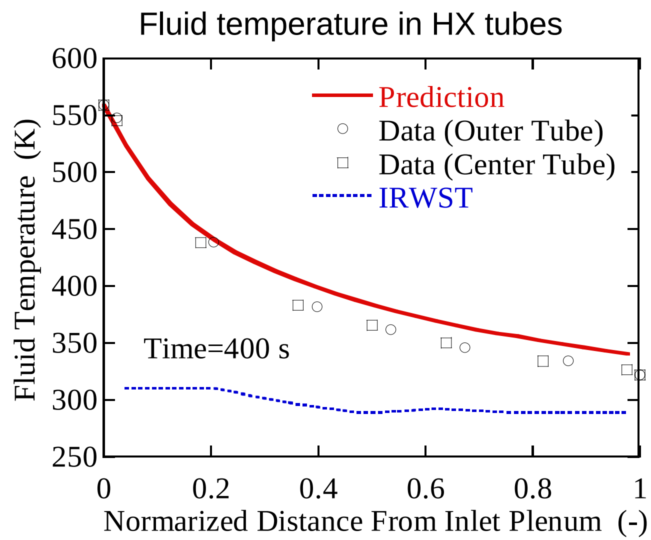
*45 tubes for the other tests

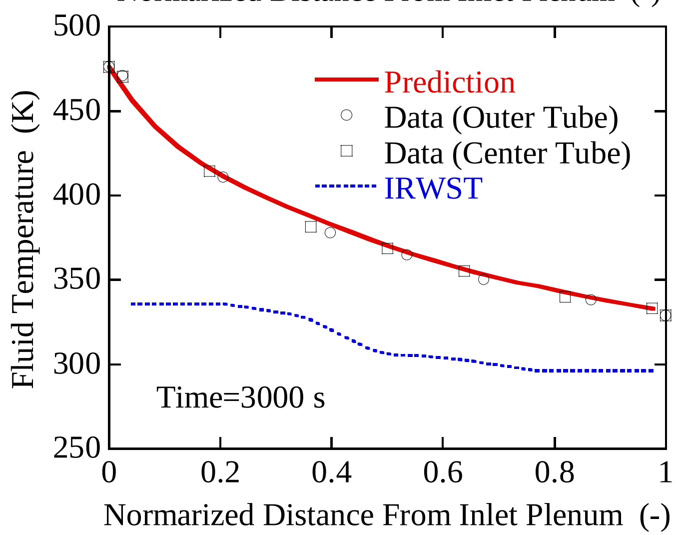
PRHR Heat Transfer Rate simulation

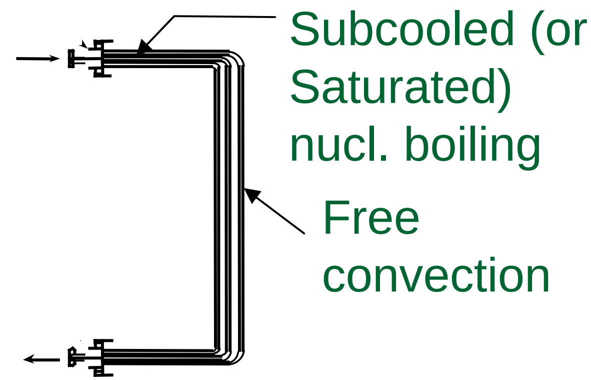
- HTR were well predicted generally by correlations available in literature

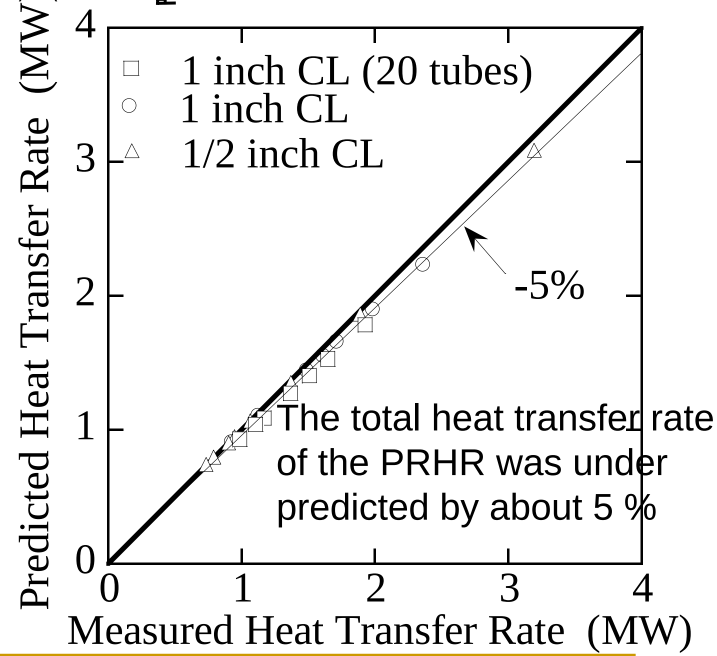
HTC package

- Colburn for inner tube turbulent forced convection
- Bergles-Rohsenow for onset of nucleation
- Jens-Lottes for nucl.boiling
- Langmuir for horizontal free convection in IRWST
- Churchill & Chu for vertical free convection in IRWST



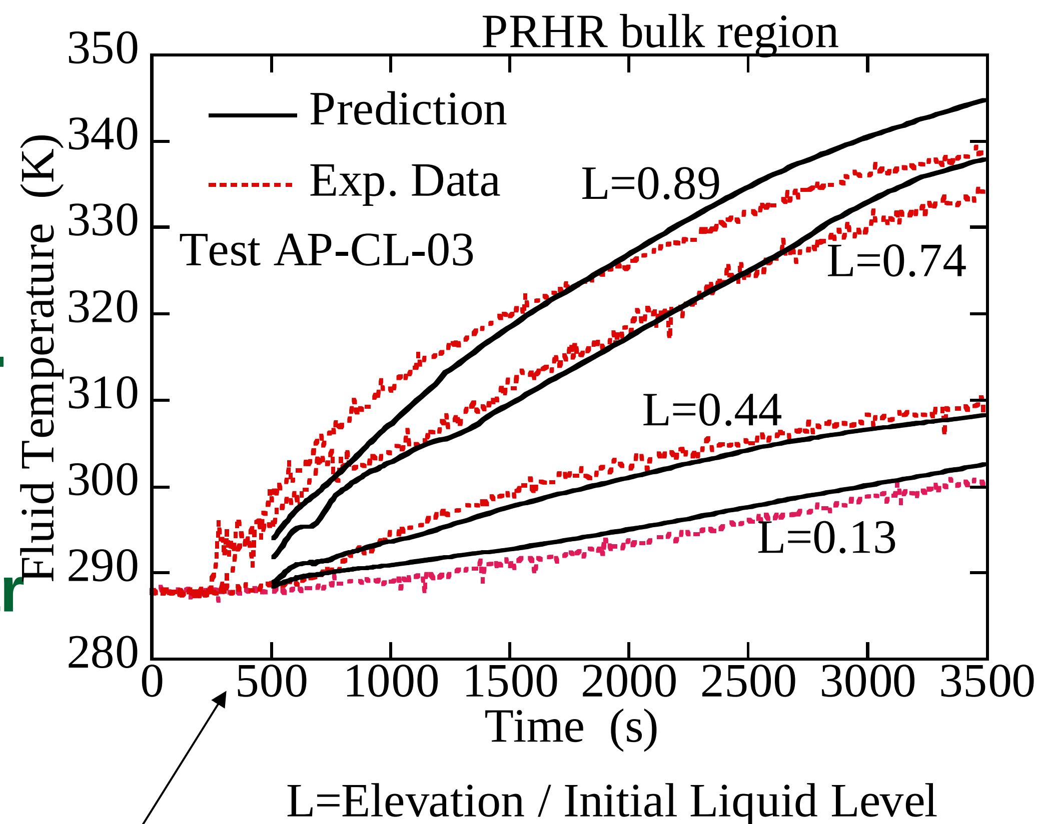






IRWST NC analysis using FLUENT(1/2)

- **Subcooled free convection was analyzed by neglecting subcooled boiling in IRWST side.**
- **23x20x34=15640 meshes.**
- **To gain the insight the effects of atypical IRWST configuration in particular the presence of the separation plate.**



The calculation agree with the experimental data within 5K.

IRWST NC analysis using FLUENT(2/2)

- Effects of atypical separation plate is not large
  - Cross flow velocities are less than ~0.1m/s for upper horizontal section.
  - Not high enough to cause effects on the boiling HT.
  - Along the vertical section, the horizontal components were generally much smaller than the vertical upward components.
  - One-D flow along vertical section is established as the NC.

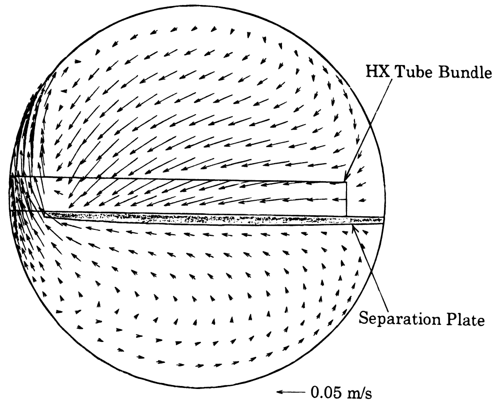


Figure B.22 Calculated IRWST Velocity Distribution in Horizontal Cross-Section of Upper Horizontal Tube Bundle at 1500 s for Test AP-CL-03

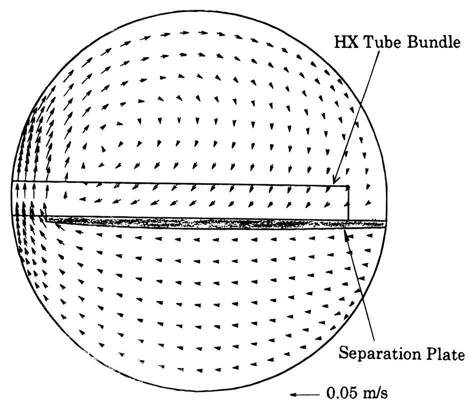


Figure B.23 Calculated IRWST Velocity Distribution in Horizontal Cross-Section of Lower Horizontal Tube Bundle at 1500 s for Test AP-CL-03

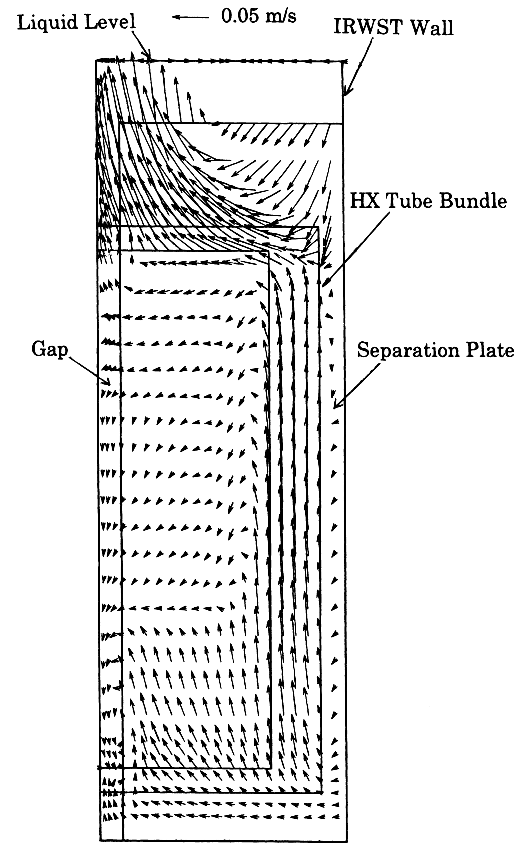
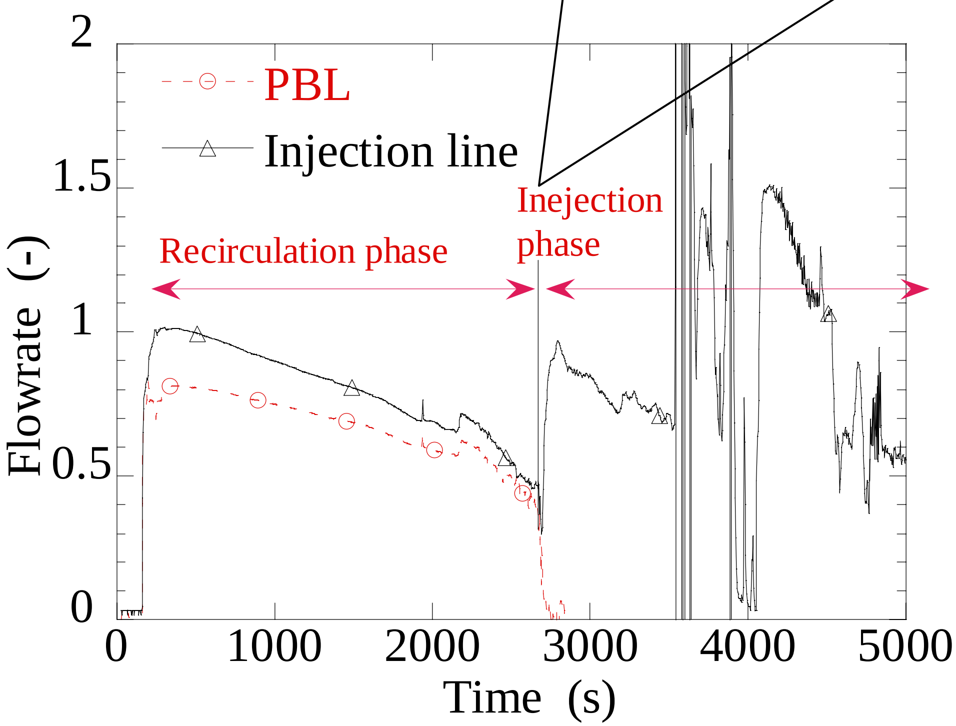


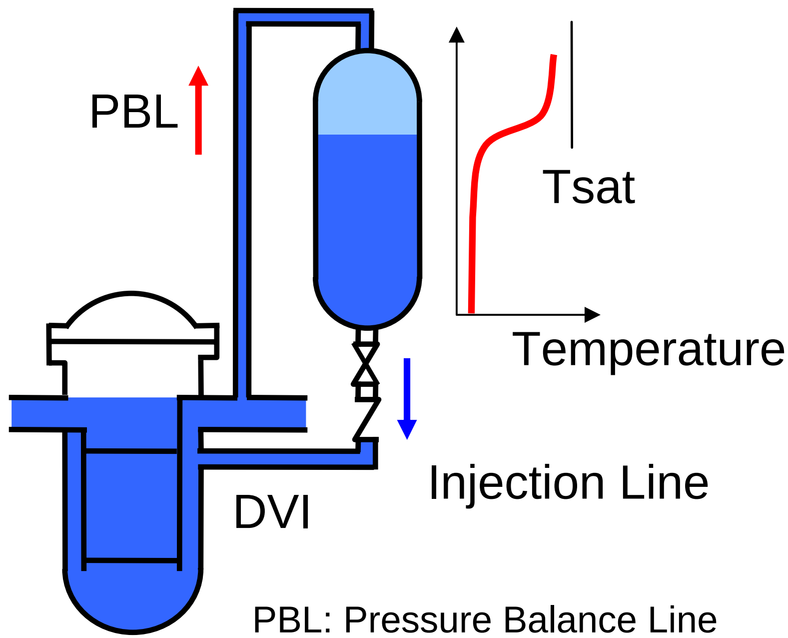
Figure B.21 Calculated IRWST Velocity Distribution in Vertica Cross-Section of Tube Bundle at 1500 s for Test AP-CL-03

CMT NC

- CMT NC starts immediately after opening of isolation valve in the injection line
- Thermal stratification is formed after NC starts

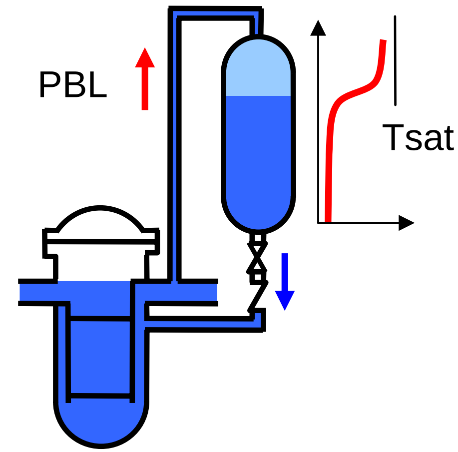
The circulation mode is terminate by non-condensable gas injection from PBL line, the injection mode continues after that.





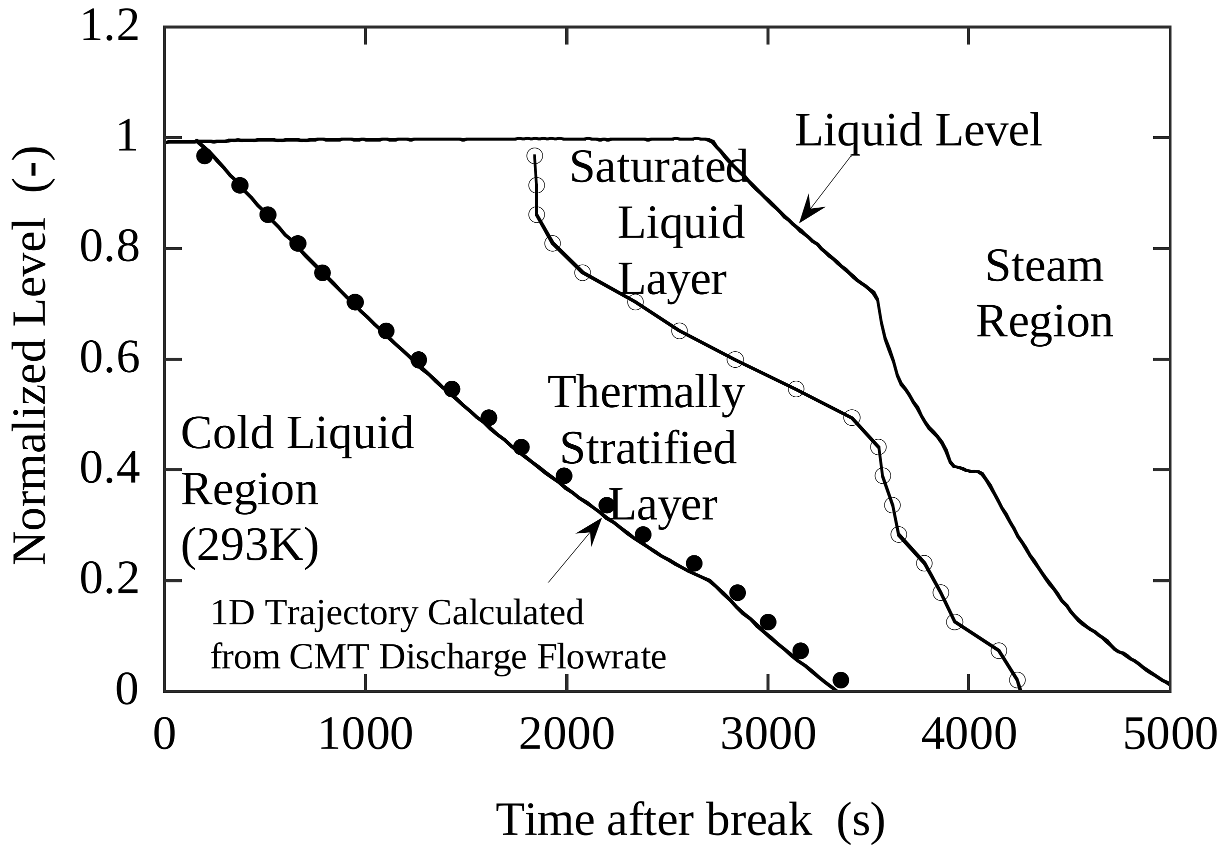
PBL: Pressure Balance Line
DVI: Direct Vessel Injection

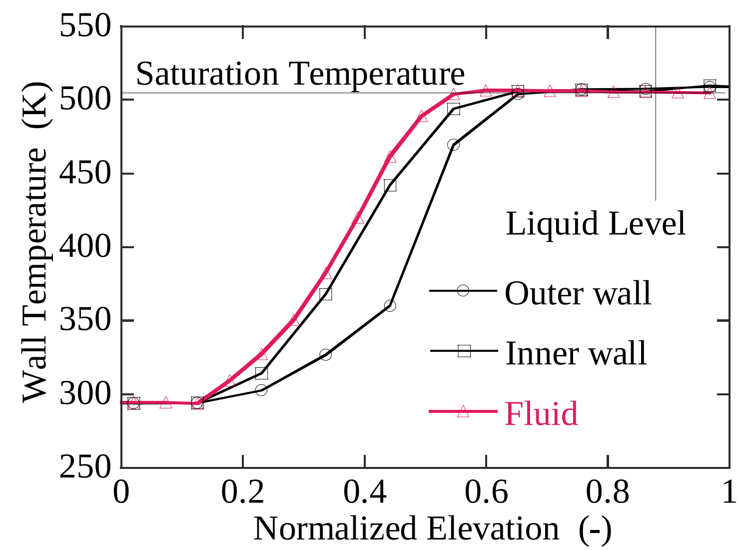
Thermal Stratification



During single phase NC, the hot water from the CL accumulated in the upper part of the CMT by replacing the initial cold water inventory.

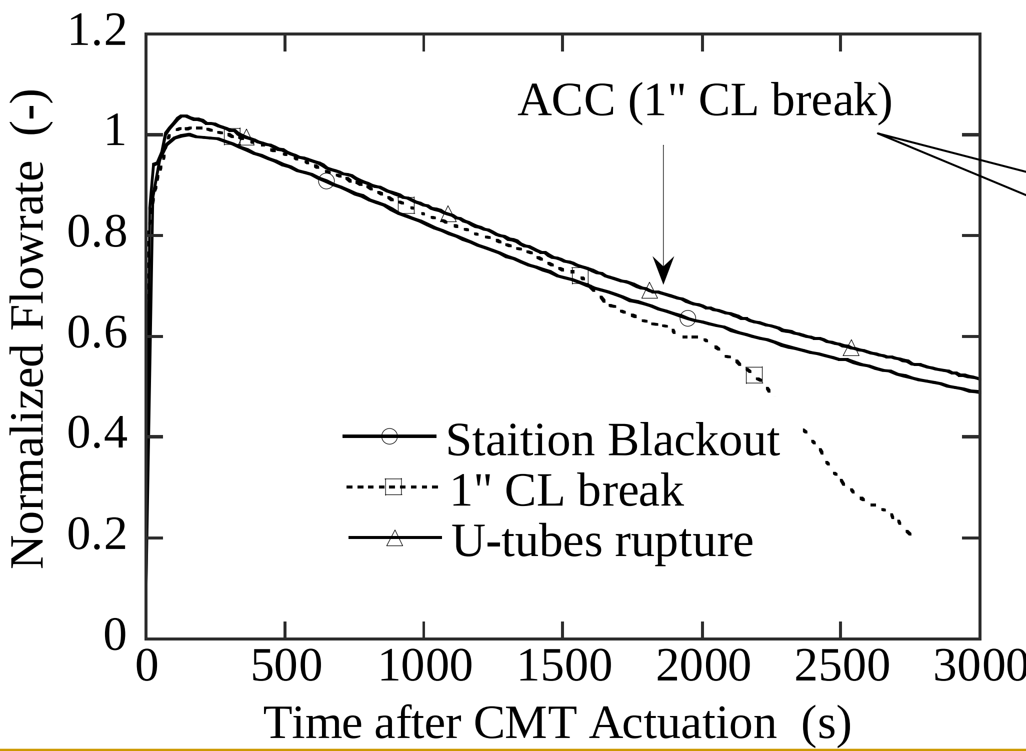
Thermal stratification in CMT-A





CMT NC in the other tests

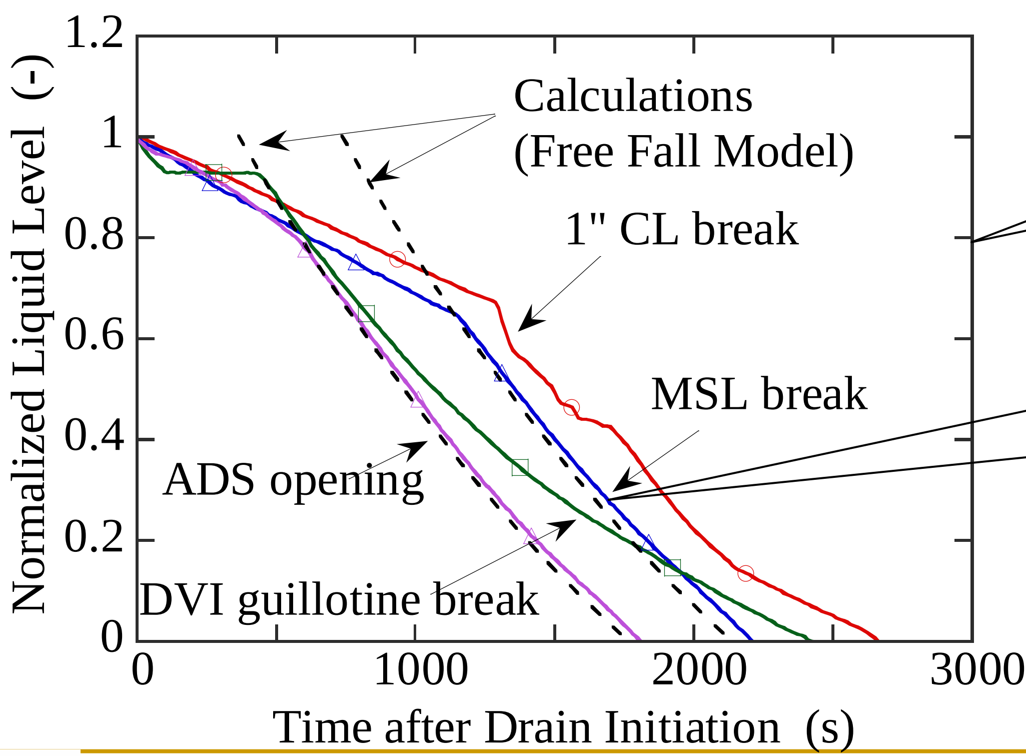
- Natural circulation flow rates were almost the same among the tests due to similar temppature distribution
- Accumulator injection affects the flow rate



The ACC flow into the DVI line increased the frictional pressure drop in the CMT loop, causing the CMT flow rate to decrease.

CMT drain

- Two different mechanism: flashing in CMT and PBL or gaseous flow from CL.
- No adverse effects on injection flow by condensation in CMT.
- The pre-heating by thermal stratification during NC phase had the effect of preventing the occurrence of steam condensation on the wall.

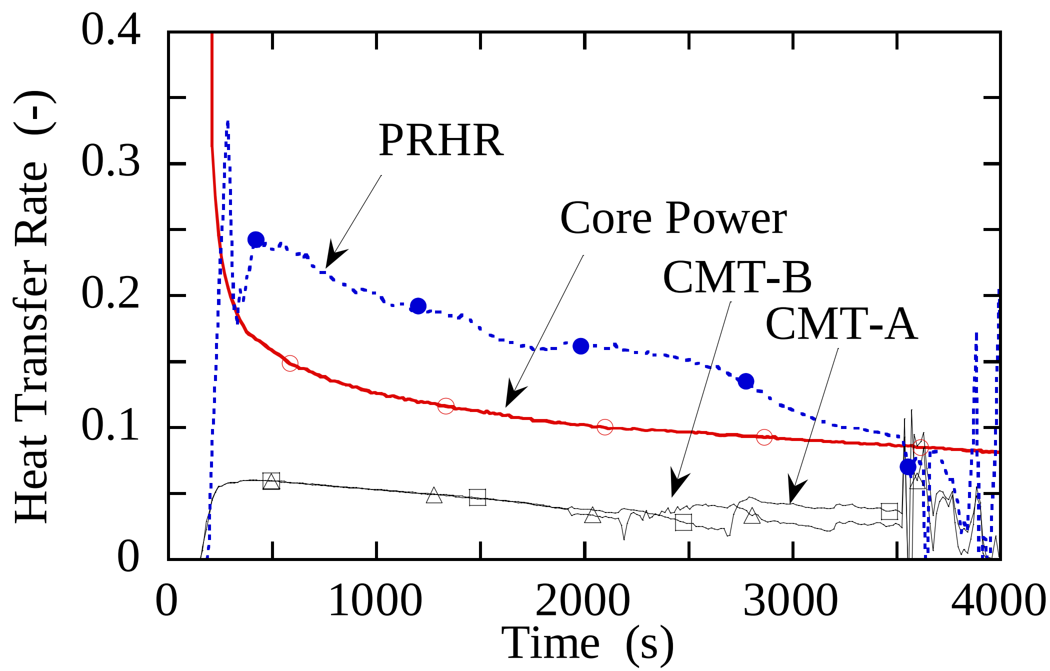


The measured level decrease rates were roughly the same irrespective of various differences in flow conditions.

The CMT level drop is simply represented by a free gravitational drain of a tank.

Heat absorption effects by CMT

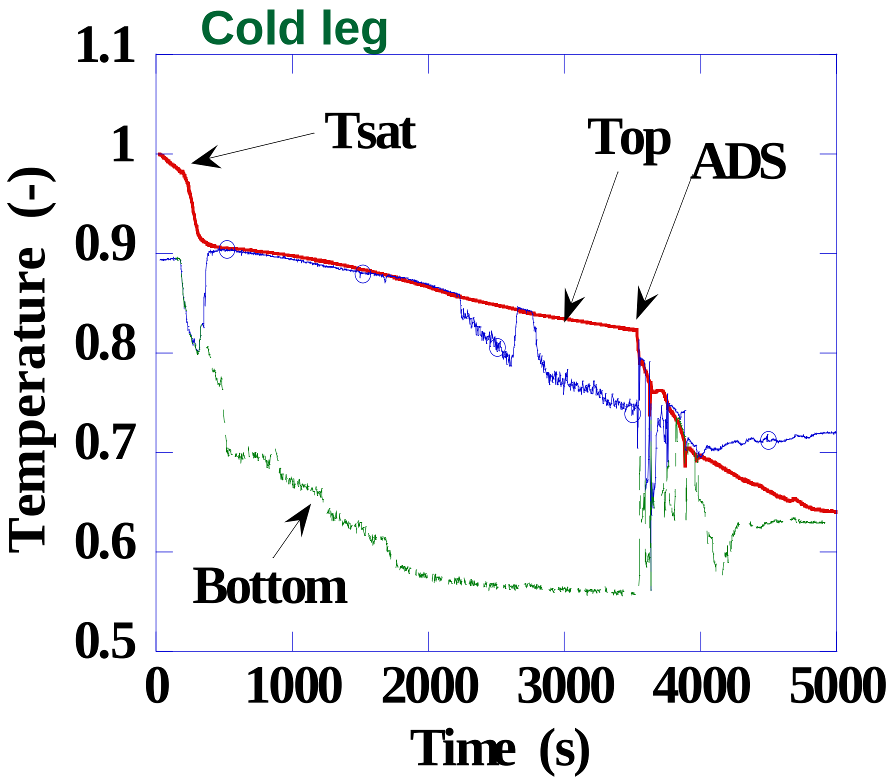
- **Total of heat removal by PRHR and absorption by CMT were much larger than the core power**

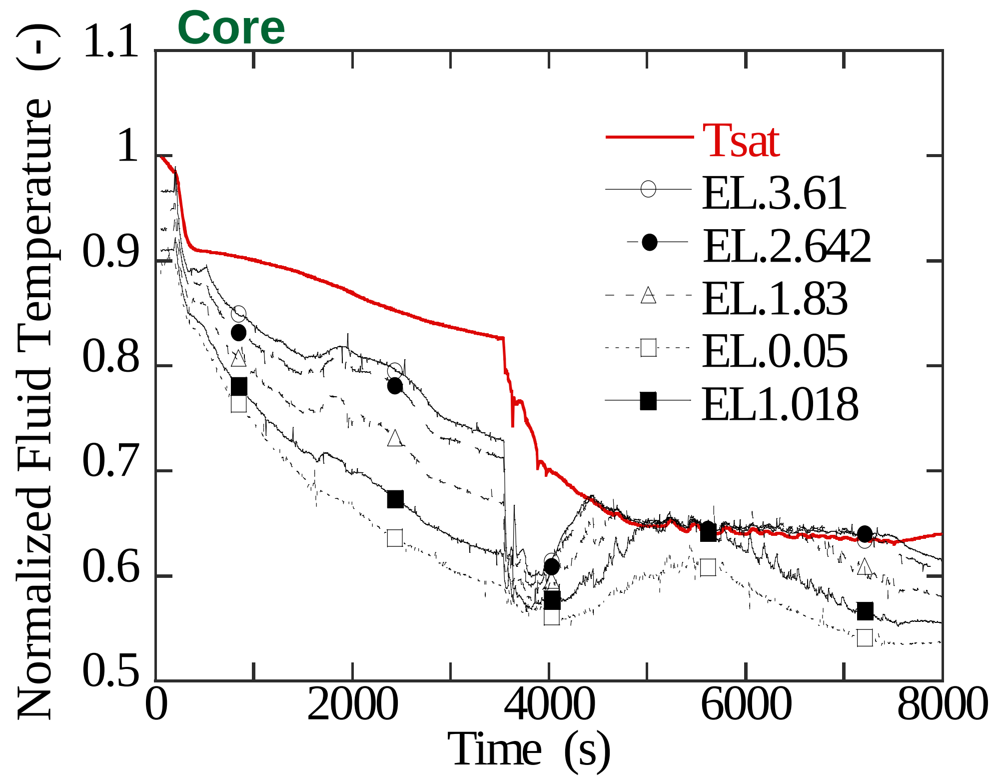


Heat transfer and absorption rates

Effects of PRHR and CMT actuation

- The cooling by the PRHR and the CMT caused a thermal stratification to occur in the cold leg and the core after NC.
- Because of these cold liquid flows into vessel, the fluid in the core region was kept subcooled until the ADS actuation.

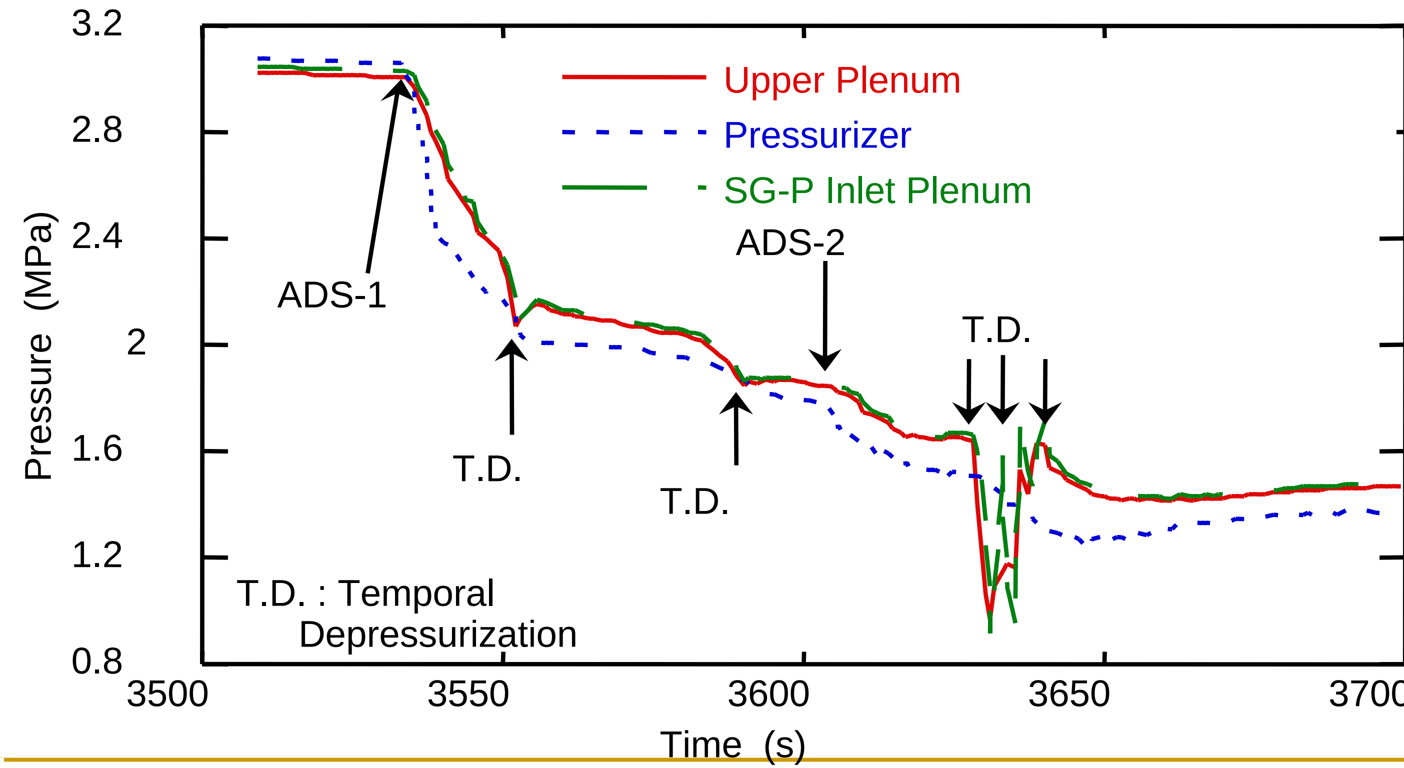




Temperature is normalized by the initial saturation temp.

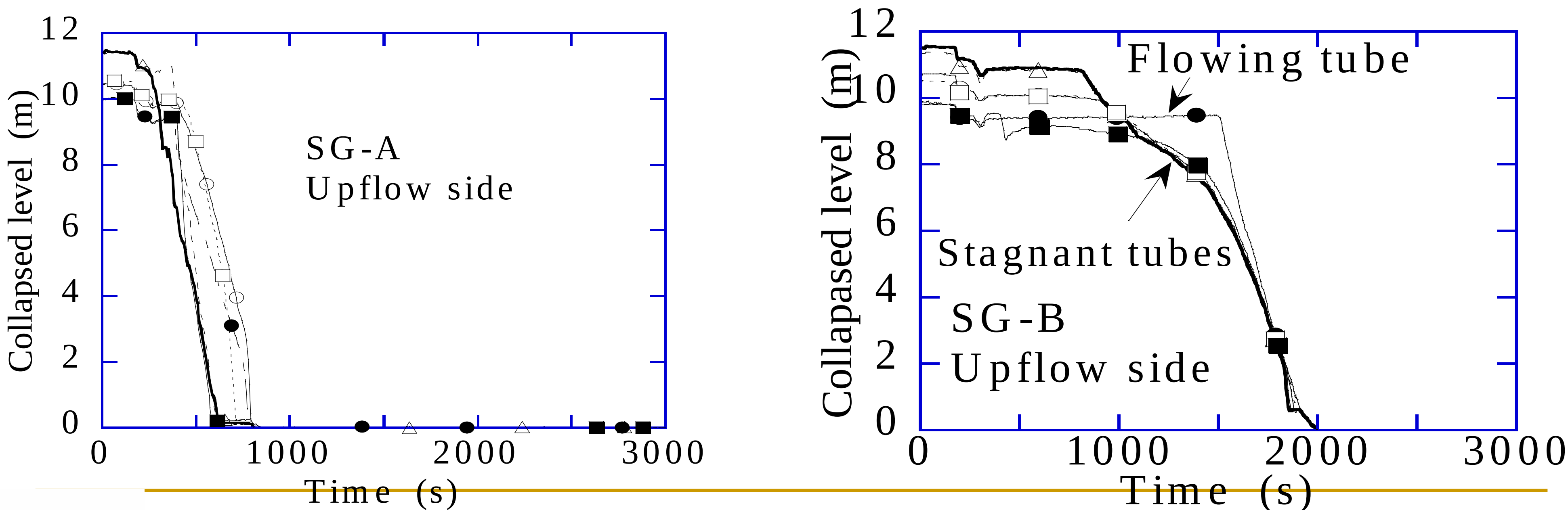
Direct Contact Condensation

- Thermally stratified layer was stable before ADS action
- After the ADS actuation, the Thermal stratification was disturbed and the cold liquid layer was exposed to the free surface.
- A temporal depressurization was observed caused by direct contact condensation



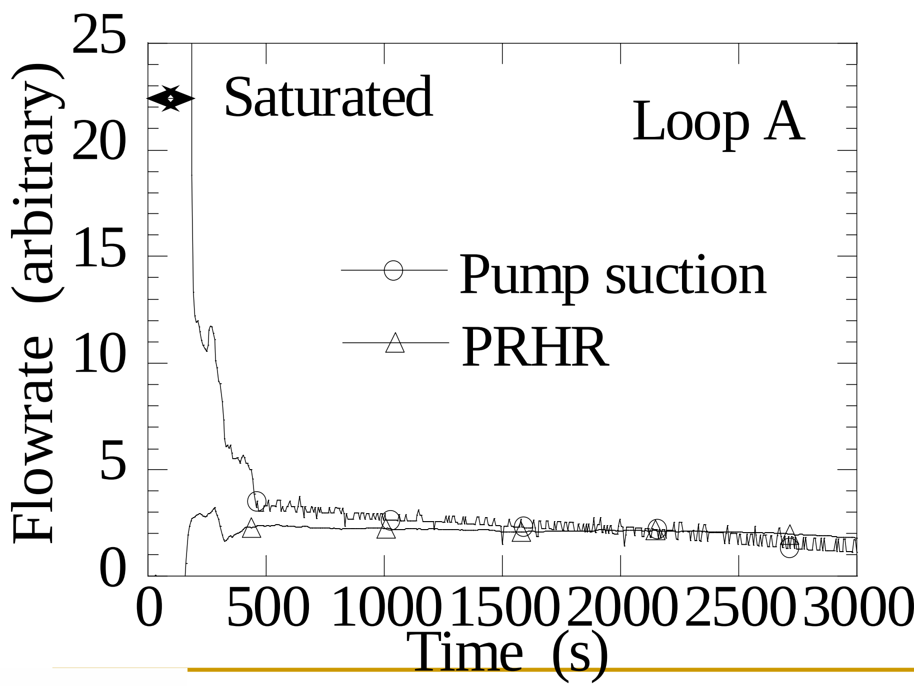
Primary Loop NC through SGs (1/2)

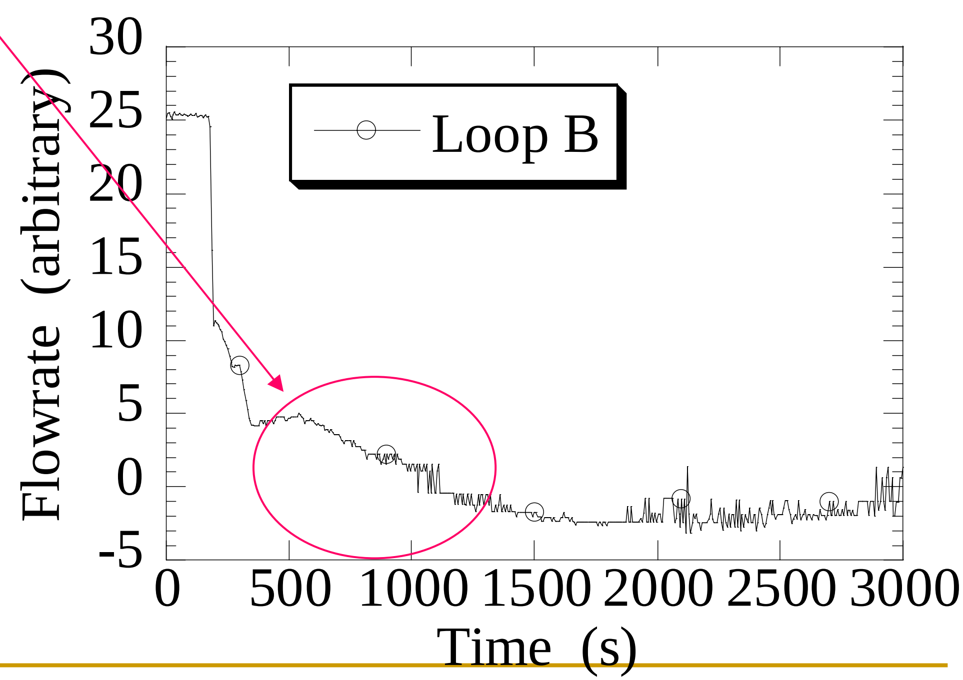
- **Not important on core cooling mechanism**
- **Asymmetric SG U-tubes drain**
  - **Sat. liquid discharge from Pressurizer in Loop A**
  - **SG U-tubes are soon drained for Loop A**
  - **PRHR exist as SG bypass for Loop A**



Primary Loop NC (2/2)

- **Asymmetric drain of SG U-tubes**
  - **Prolonged NC for Loop B is observed.**
  - **It continues for not so long time as the PRHR NC.**





Conclusions(1/3)

- NC observed in the ROSA/AP600 tests in
  - PRHR loop
  - CMT loop
  - Primary loop
- The energy removal by the PRHR exceeded the core decay power soon after the PRHR actuation, causing
  - pressures and temperatures to decrease continuously.
  - significant thermal stratification in cold legs and PV
  - the core outlet subcooling continues until the ADS actuation for the tests with a break dia. < 1 in.

Conclusions(2/3)

- CMT indicated circulation and subsequent drain-down
- Liquid single-phase NC observed in CMT loop, causing
  - one-dimensional, thermal stratification in the fluid
  - heatup of the tank wall
- Drain-down behavior after the PBL emptied agreed with the free fall model, indicating no adverse effects of condensation on draining

Conclusions(3/3)

- The actuation of PRHR and CMT prevented voiding in the legs before the ADS actuation for one or smaller break LOCA and no-LOCA transient, causing
  - Liquid single-phase NC both in CMT and PRHR loops
  - Simplify the behavior of the system response
- The absence of either of the PRHR and two CMTs actuation caused voiding in the legs and thus the two-phase NC to occur.