IMPACT OF INSTRUMENTION TUBE FAILURE ON NATURAL CIRCULATION DURING SEVERE ACCIDENTS

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February 2009

Outline

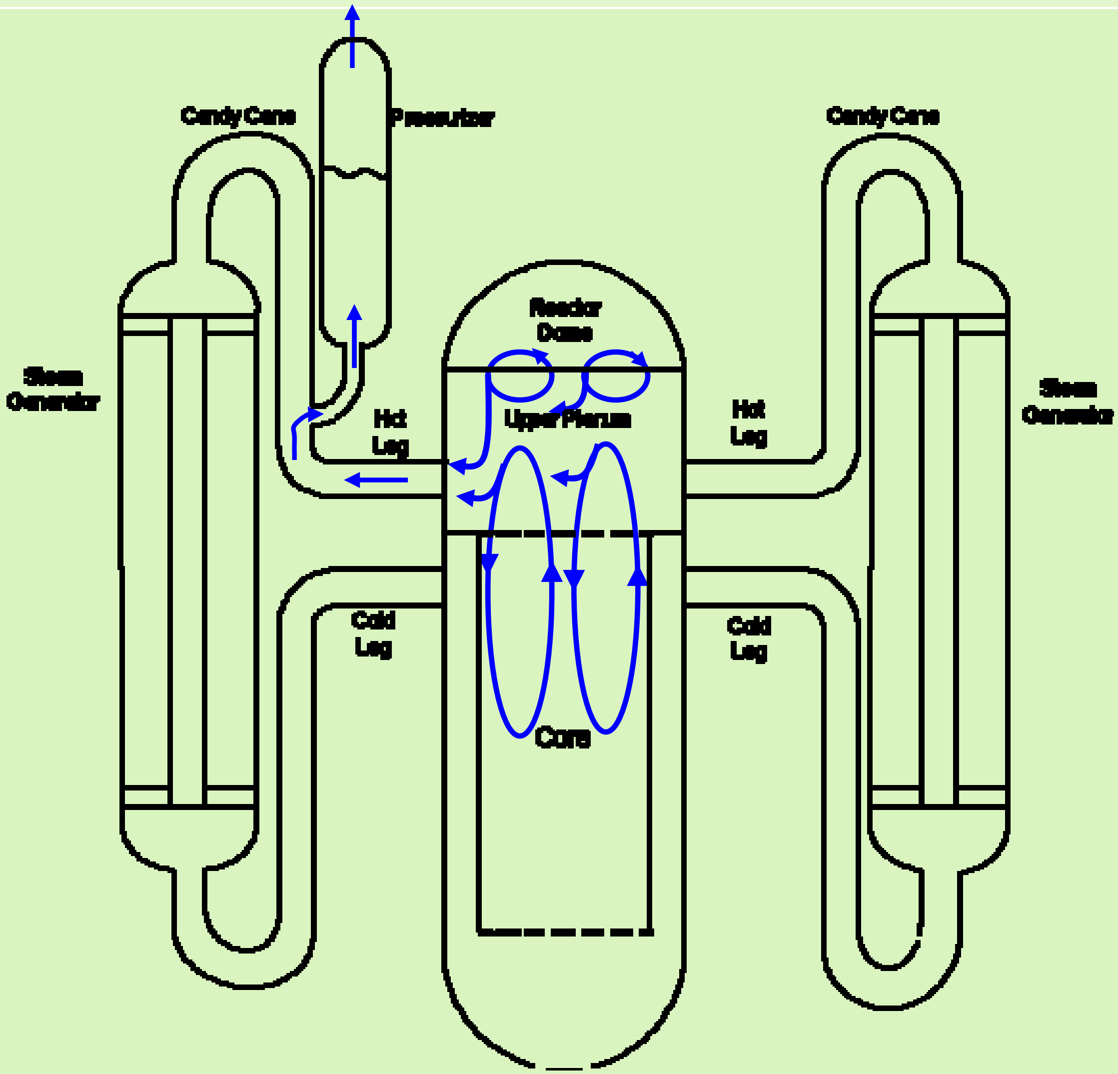
- Background
- TMI-2 Observations
- Modeling & Analysis of Instrumentation Tube Failure
  - TMI-2
  - PWR with Inverted U-Tube Steam Generator
- Summary & Conclusions

Background

- During a severe accident in a PWR where system pressure remains elevated, there is a great propensity for large recirculation of steam & hydrogen between the damaging reactor core & the upper plenum.

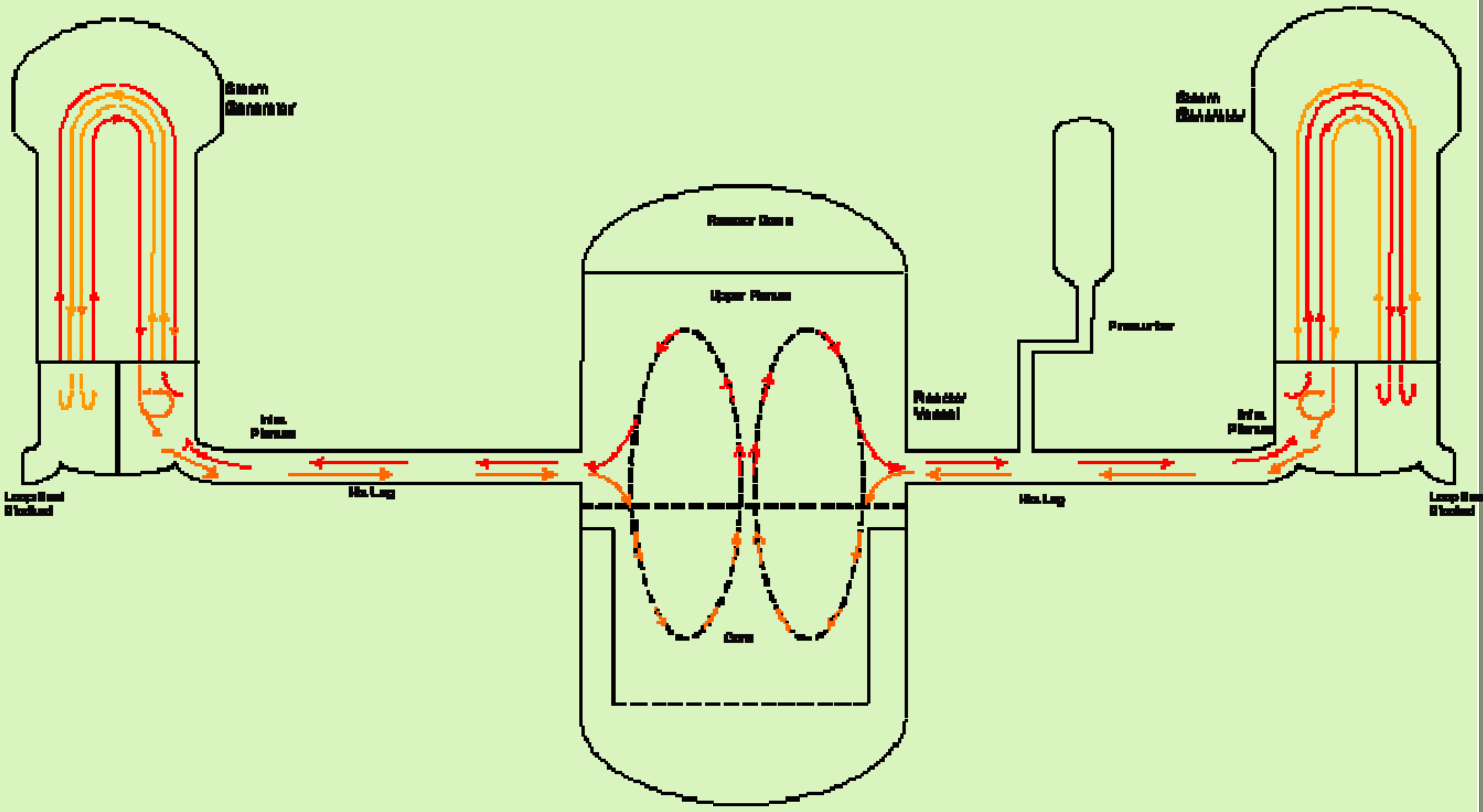
- In case of PWRs with inverted U-tube steam generators (i.e., most of operating and new plants), also between upper plenum, hot leg, and steam generator tubes.

Background (Cont.)



PWRs with Once-Through Steam Generators (TMI-2)

Background (Cont.)



PWRs with Inverted U-Tube Steam Generators

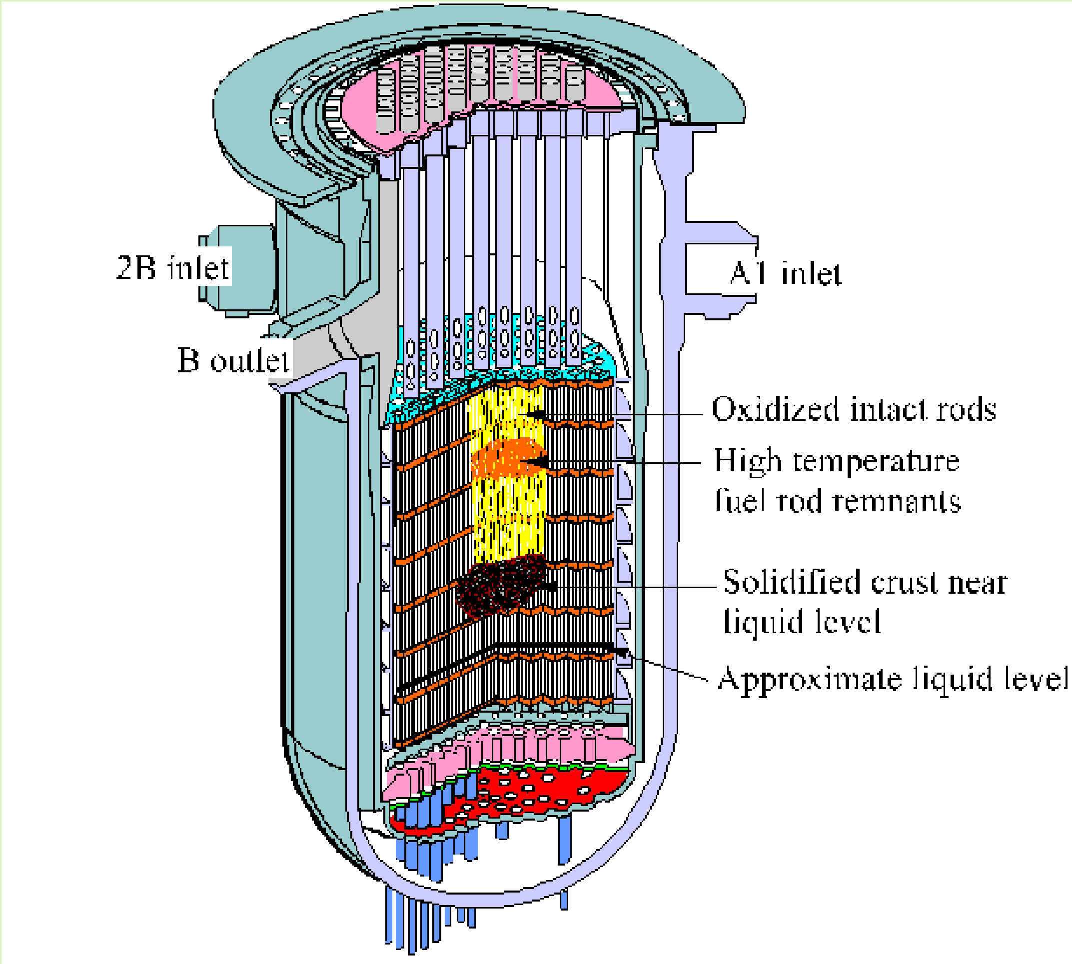
TMI-2 Observations

- Closure of ERV (PORV) occurred at 6:22:37 am (i.e., 142 minutes into the accident) - Stopping any flow from reactor to containment

- Radiation monitors inside containment started to show increased levels starting at 6:39 am (16 minutes and 23 seconds later)

∴ Other Leakage Paths (i.e., Instrumentation Tubes)

TMI-2 Observations

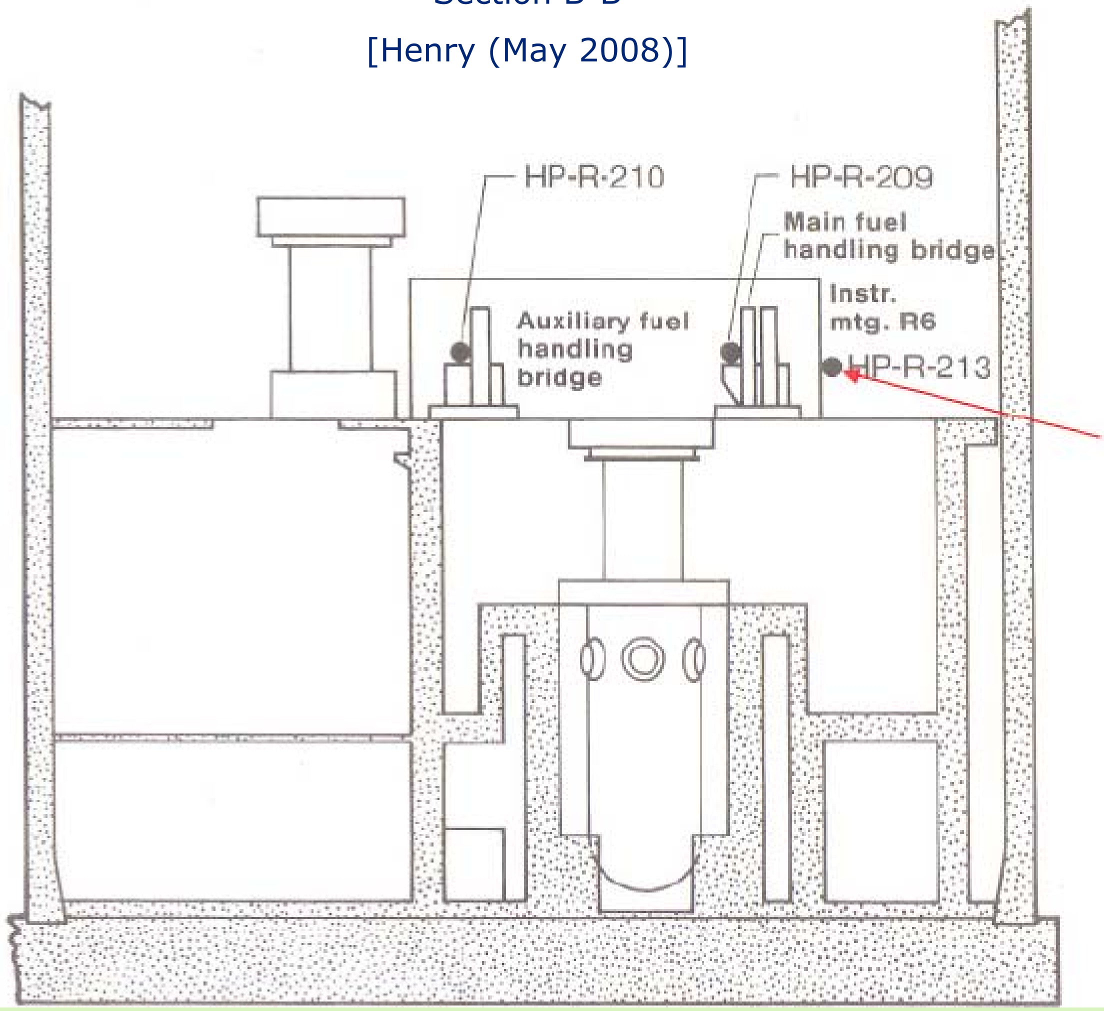


~150 – 160 minutes

Location of Radiation Monitors

Section B-B

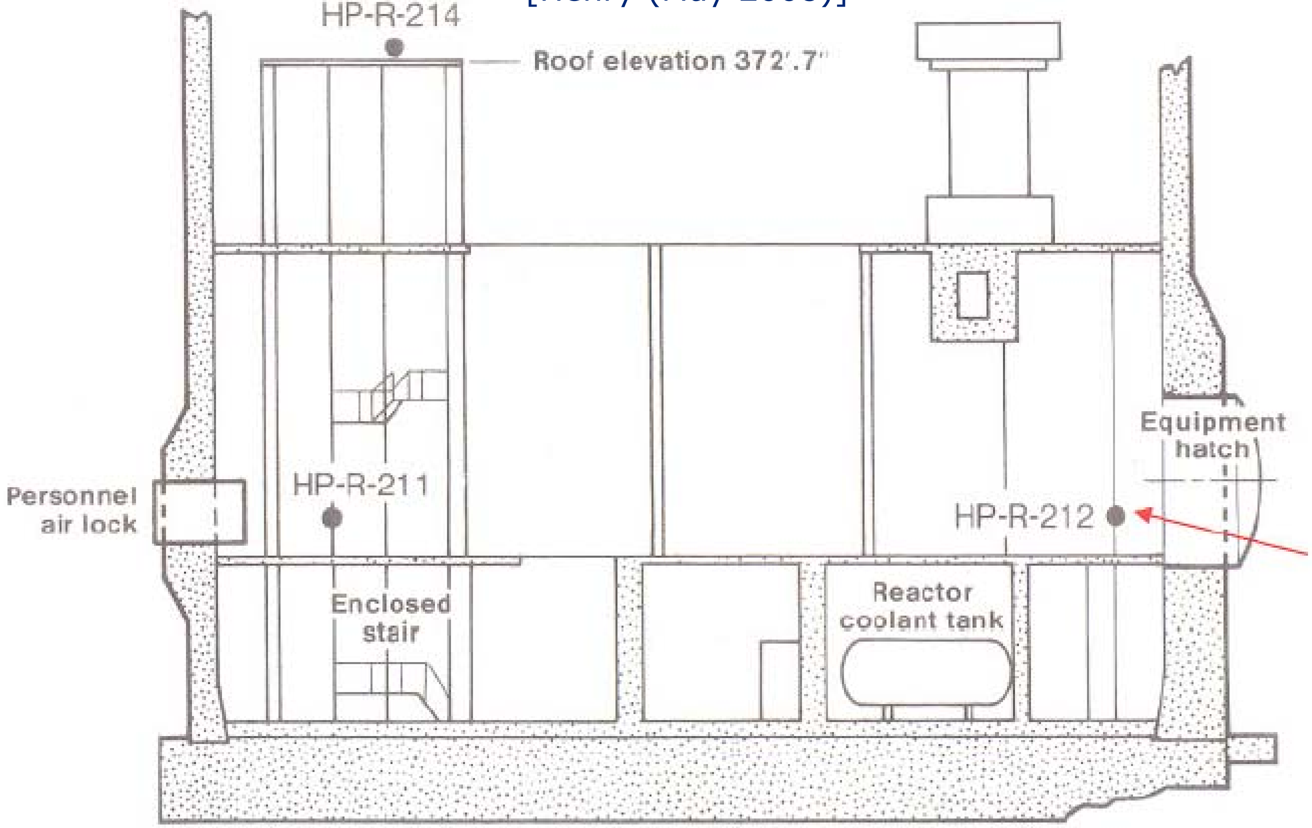
[Henry (May 2008)]



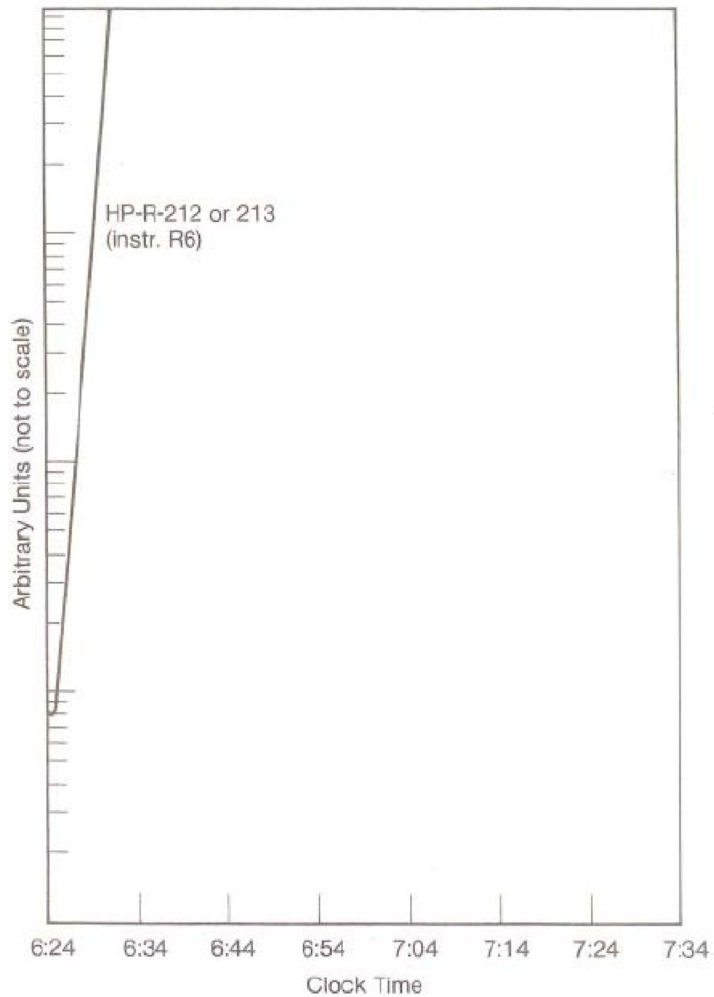
Location of Radiation Monitors

Section C-C

[Henry (May 2008)]

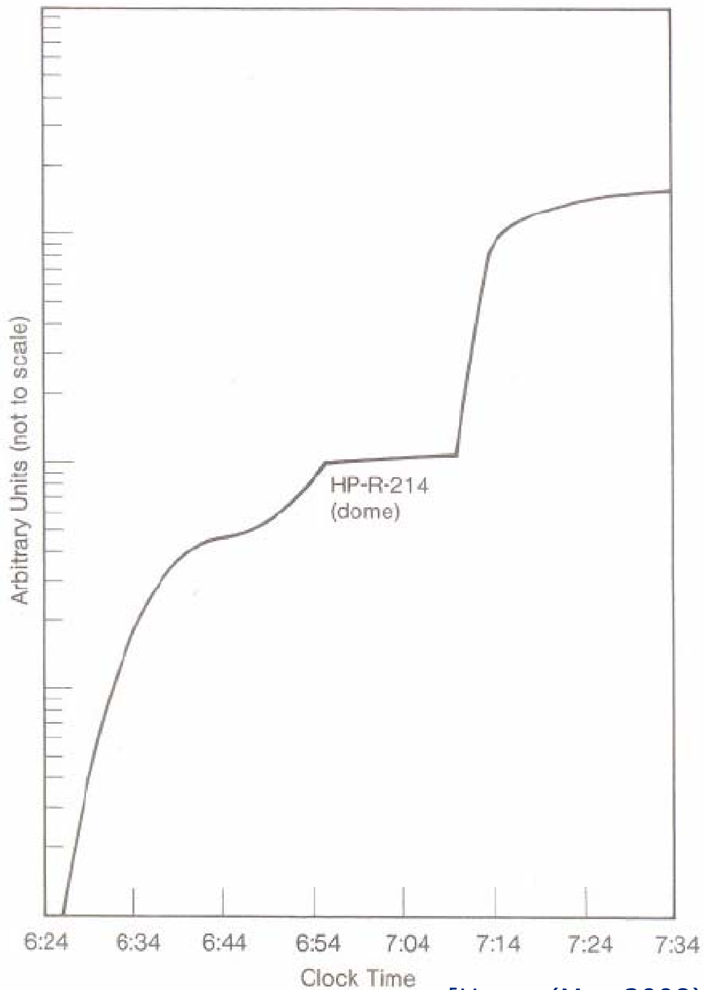


Measured Radiation Near In-Core Instrumentation Panel



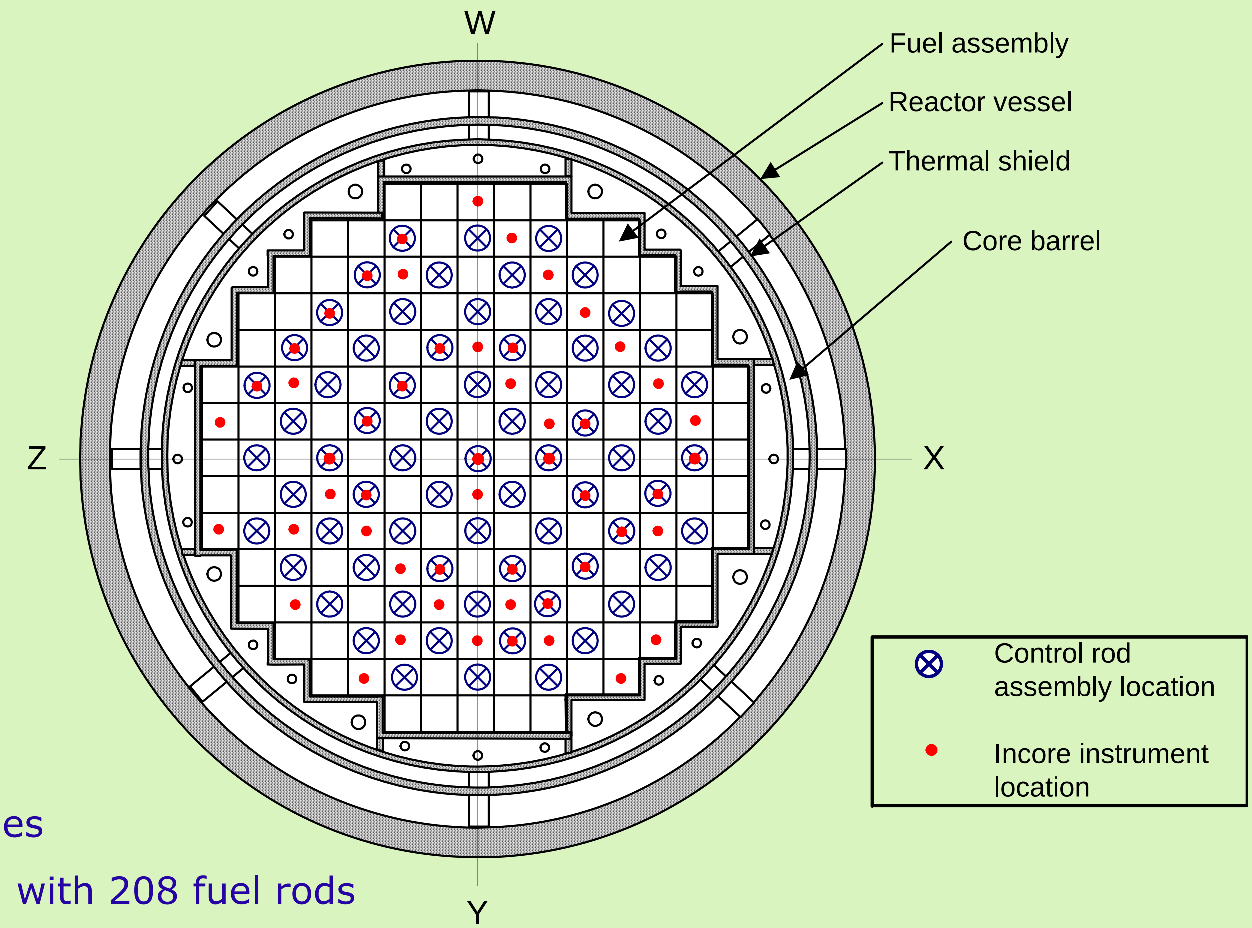
[Henry (May 2008)]

Measured Radiation
In vicinity of the Containment Dome



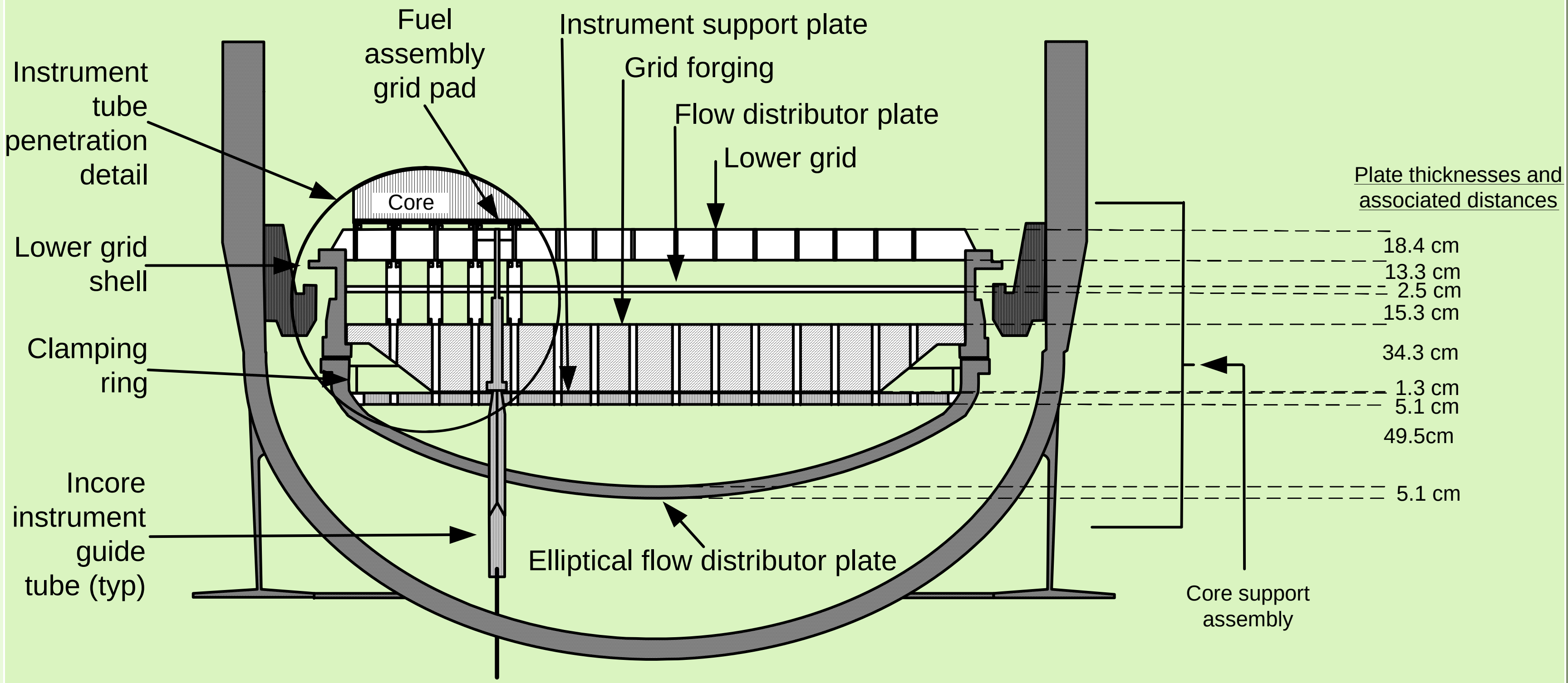
[Henry (May 2008)]

TMI-2 In-Core Instrumentation Design

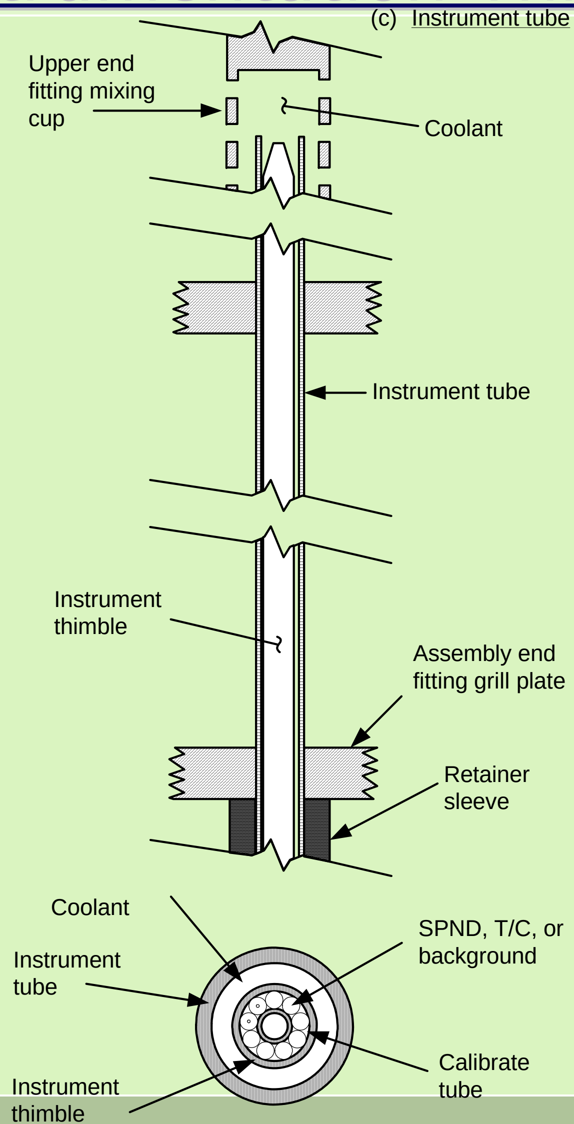


- 177 fuel assemblies
  - 15x15 (225) with 208 fuel rods
  - 16 control rod guide tubes
  - An instrumentation guide tube (in the center of the each assembly)

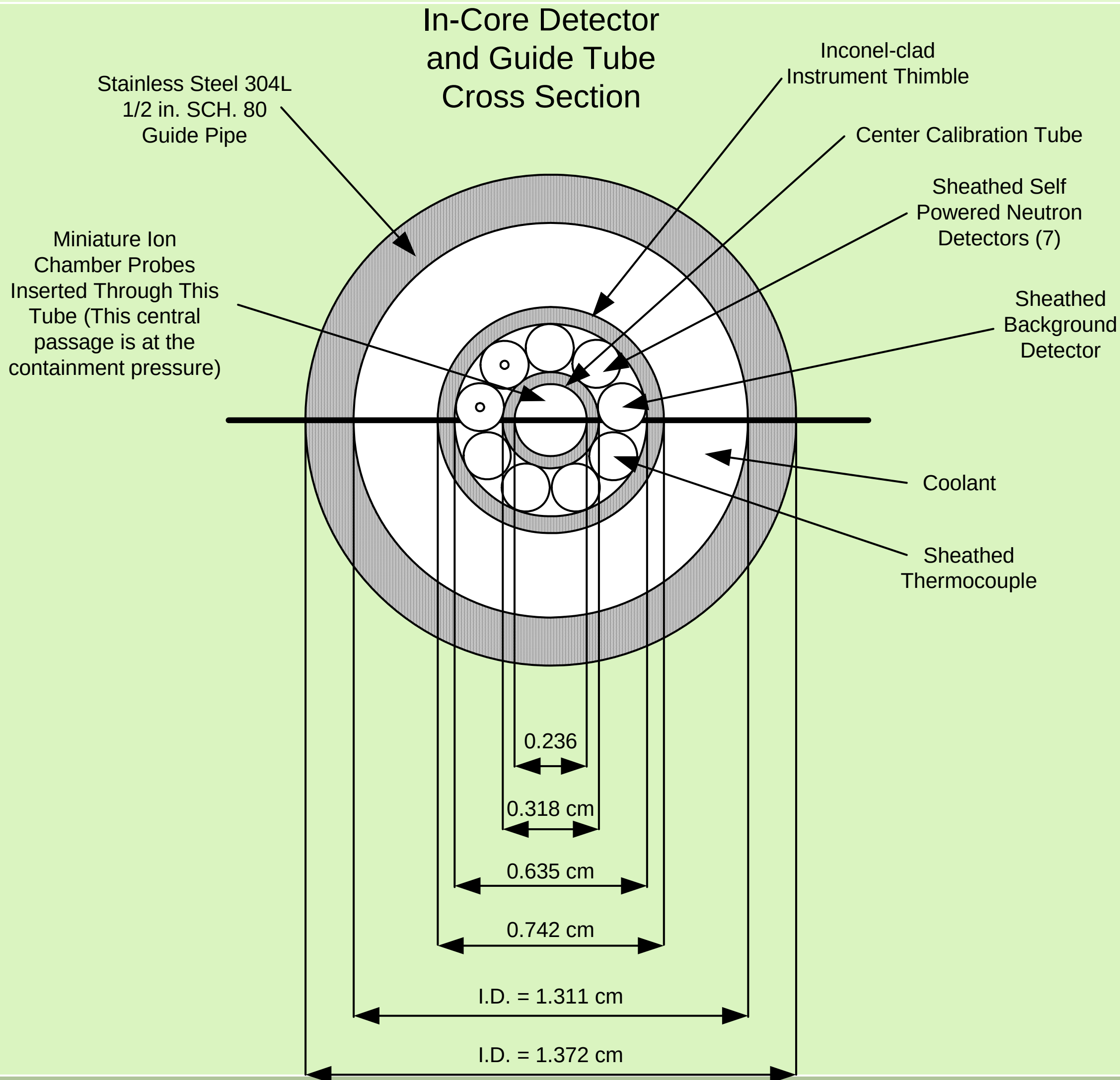
TMI-2 Lower Head Core Support Structure



TMI-2 Instrumentation Guide Tube & Instrumentation Thimble



TMI-2 In-Core Detector & Guide Tube



Modeling Approach

- Use MELCOR 1.8.6
- Parametric in order to enable understanding of the impact of uncertainties
- Characteristic time of instrumentation tube and associated structure:

$$\tau = \frac{\rho C\left[D^2 - d^2\right]}{4Dh}$$

D = outside diameter of the thimble tube

d = inside diameter of the calibration tube

C = effective specific heat

ρ= effective density of the entire instrumentation tube structure, including the sensors, and

h = heat transfer coefficient to thimble tube.

Modeling Approach (Cont.)

$D = 0.742$ cm (7.42×10^{-3} m)

$d = 0.236$ cm (2.36×10^{-3} m)

$C \sim 540$ J/kg-K (Inconel)

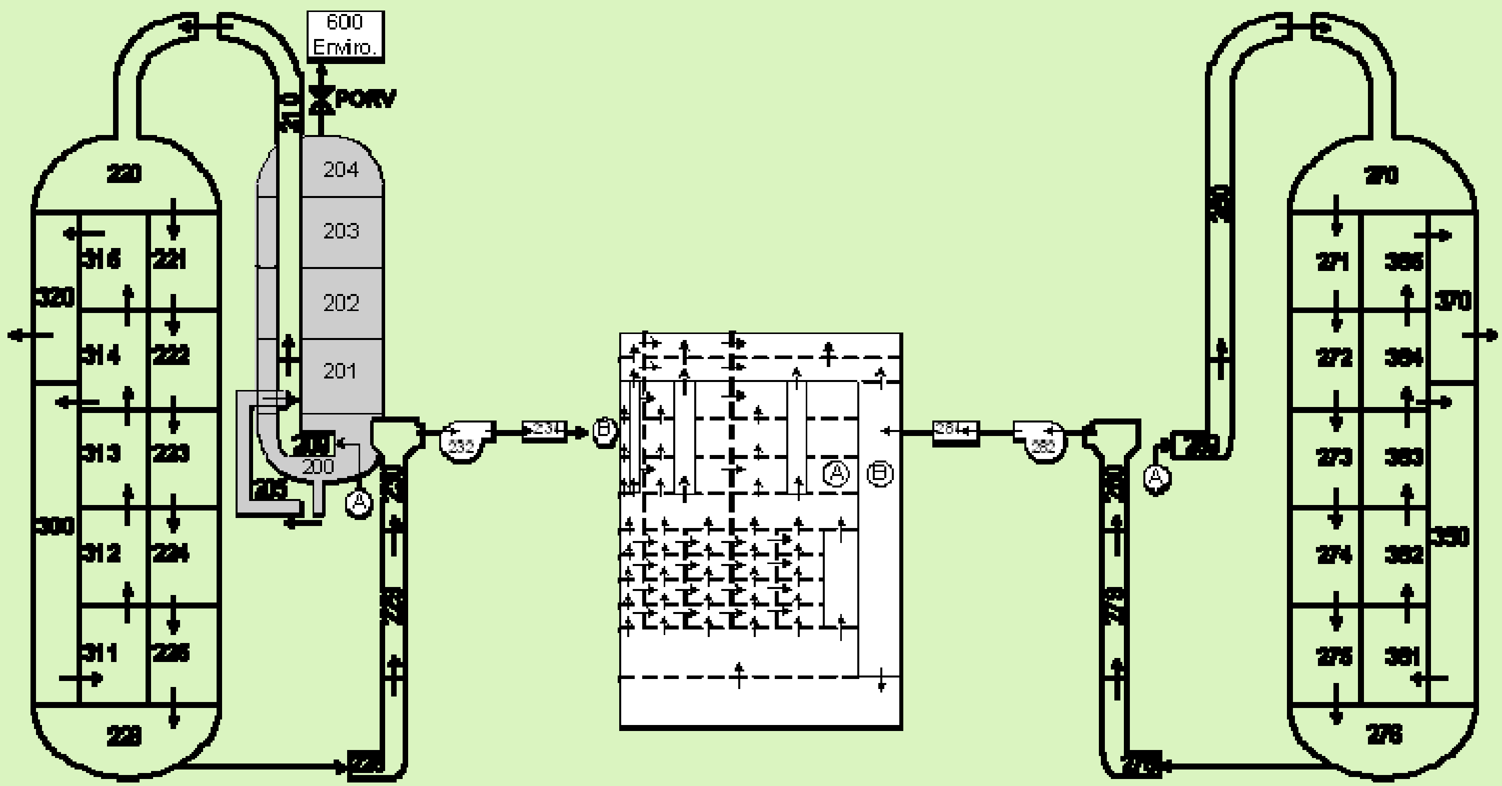
$\rho \sim 8200$ kg/m^3

$50\ W/m^2\text{-}K \leq h \leq 80\ W/m^2\text{-}K$

τ ranges from $\leq$ 1.5 minute to ~ 2.5 minutes

Therefore, adequate to assume thermal response of tubes is on the same time scale as steam inside fuel assemblies. (More detailed models can represent the instrumentation tubes as a separate core structure)

Modeling Approach (Cont.)

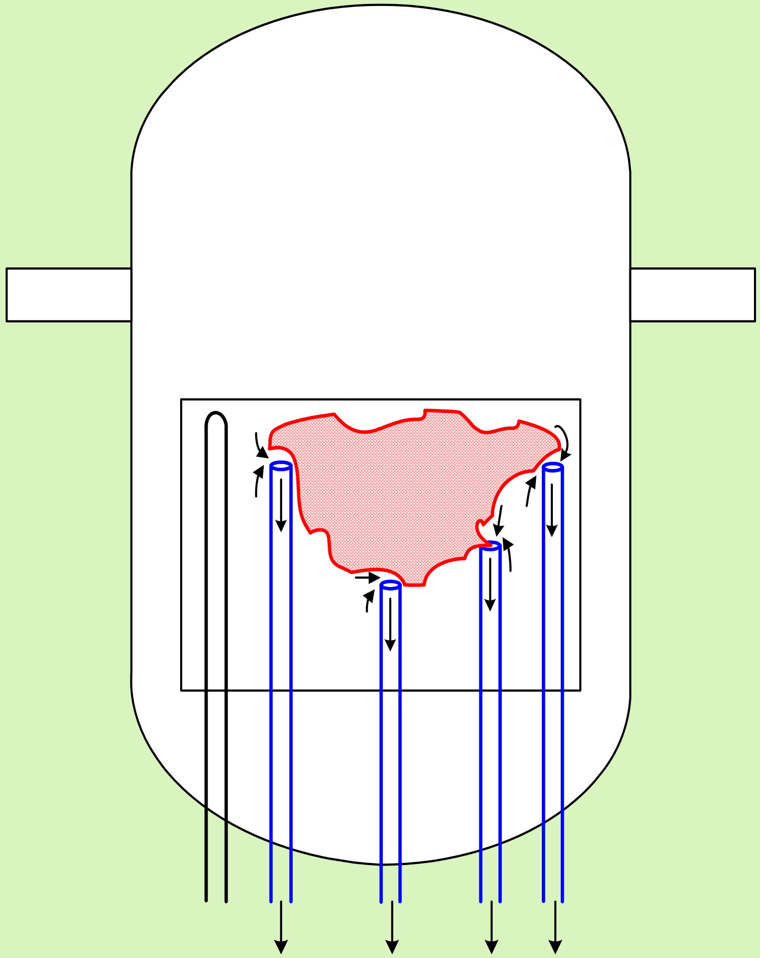


Modeling Approach (Cont.)

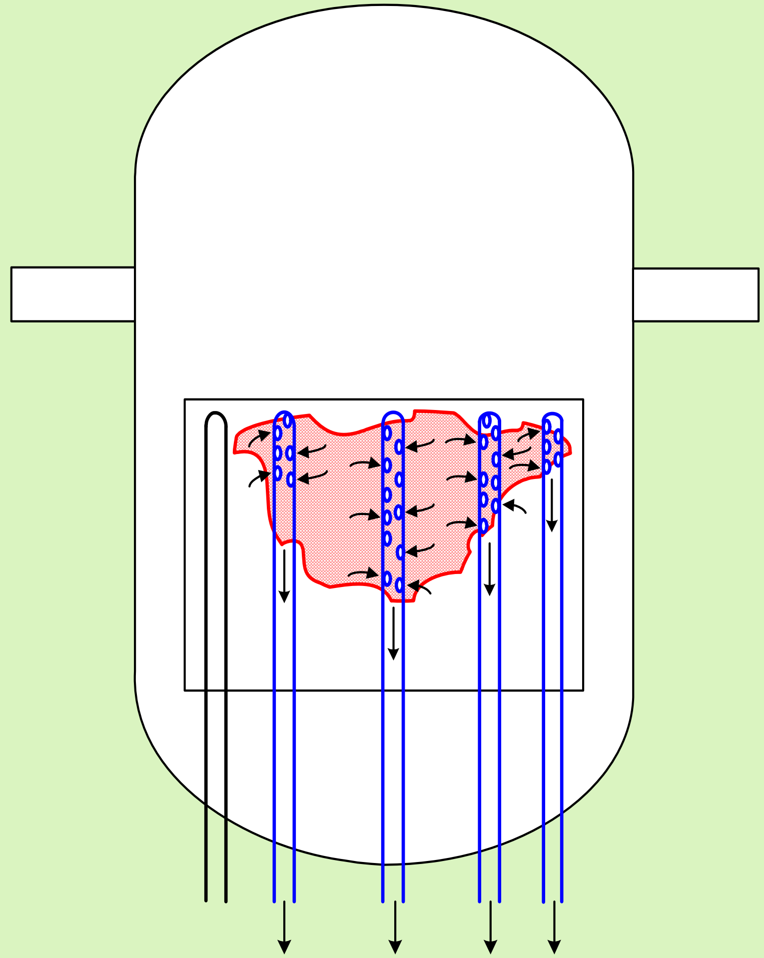
- Failure of Instrumentation Tubes - Introduced additional flow paths in the core region that open to containment when steam temperature reaches user defined "threshold" (e.g., melting temperature of Inconel)

- Plugging of Failed Instrumentation Tubes – Either:
  - Core reflood (freezing of molten debris) due pump restart (TMI-2) or accumulator injection
  - "Significant" core damage resulting in self-plugging of tubes (i.e., specified fraction of UO_2 converted into particulate debris)

Modeling Approach (Cont.)



Failure by Melting

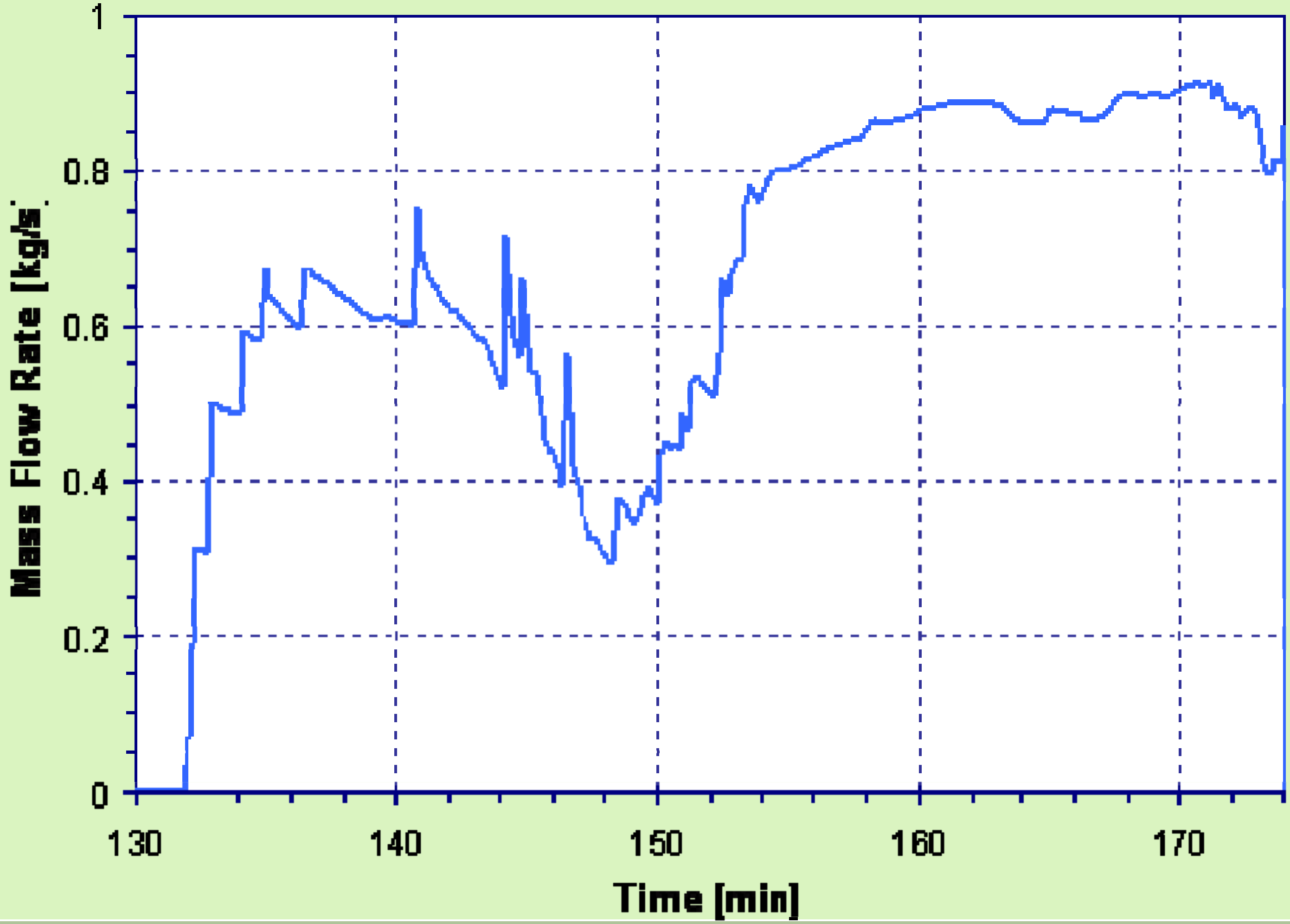


Failure by Perforation

Results (TMI-2)

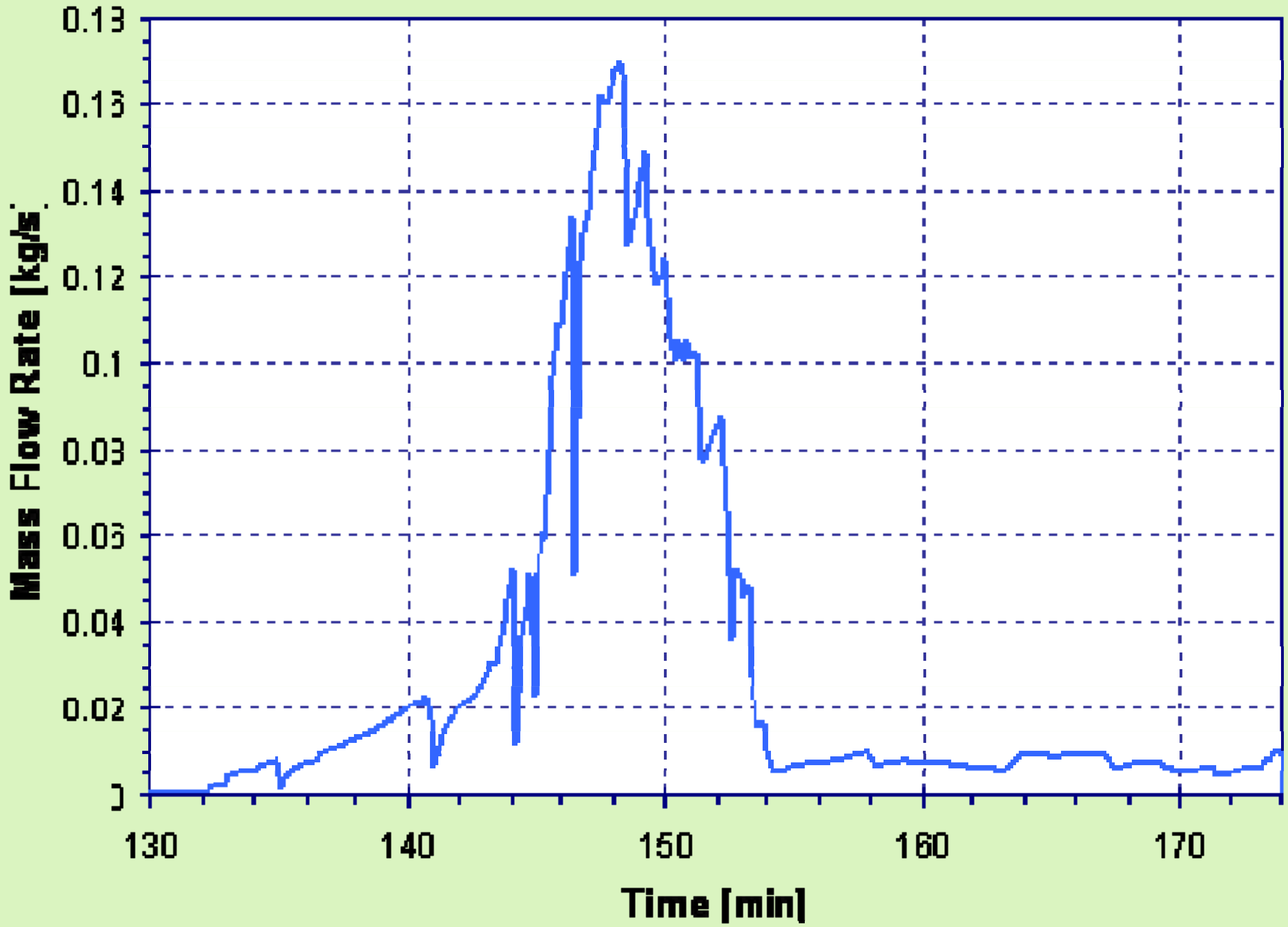
- Base Case - failure of instrumentation tubes assumed to occur at 1300K (low temperature failure)
  - Starting at 137 until 174 minutes, all 52 instrumentation tubes are calculated fail (but tubes of each computational ring are considered to vent at different axial levels as failure threshold in different levels are reached).
  - For all computational rings, the lowest level is the last to fail and in case of the outermost ring, this occurs only a few seconds before the time of the RCP-B restart
- Plugging of failed instrumentation tubes occurs upon core reflood (restart of RCP-B at 174 minutes)

Results (TMI-2) – Cont.



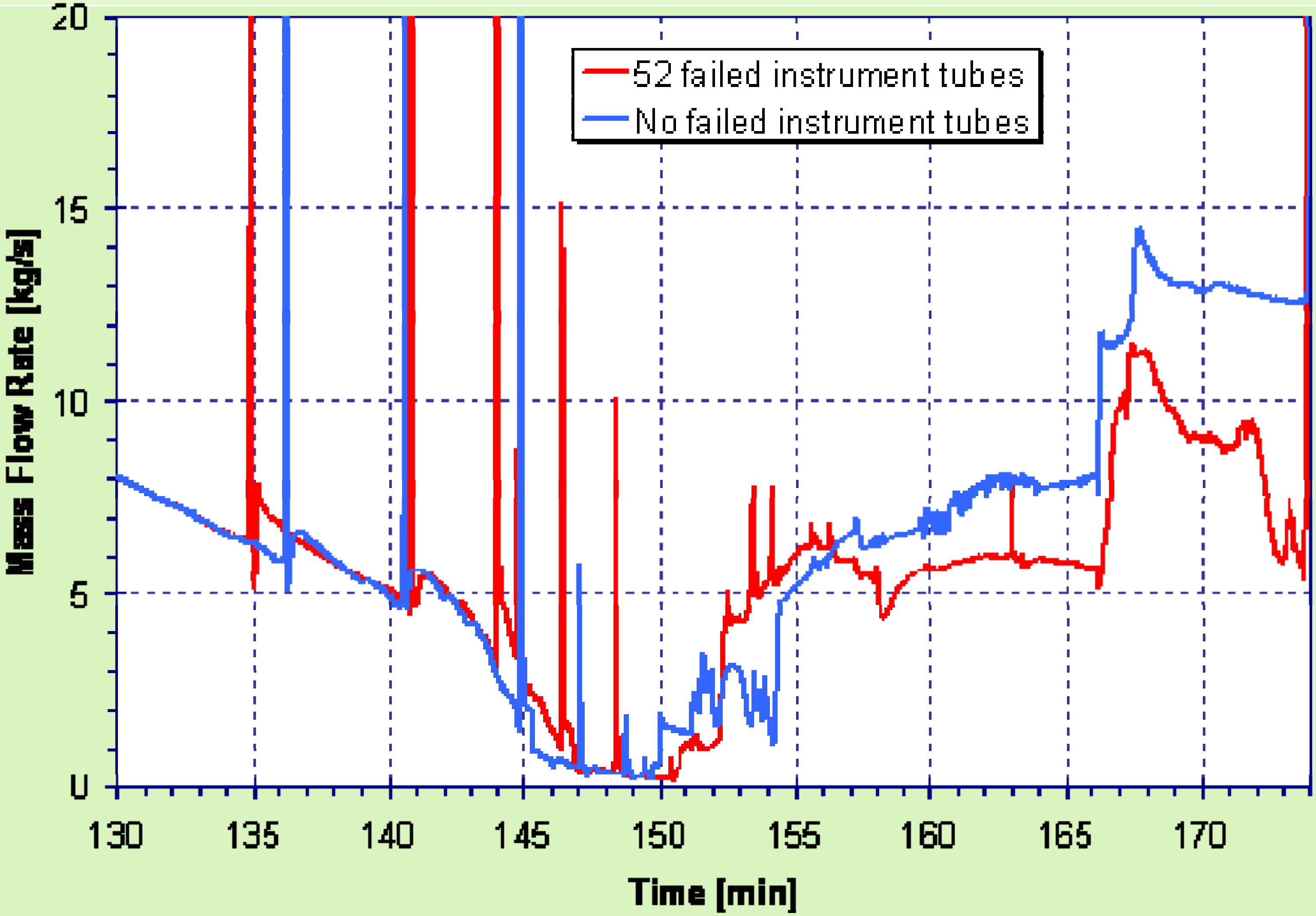
mass flow rate of steam and hydrogen through the failed instrumentation tubes

Results (TMI-2) – Cont.



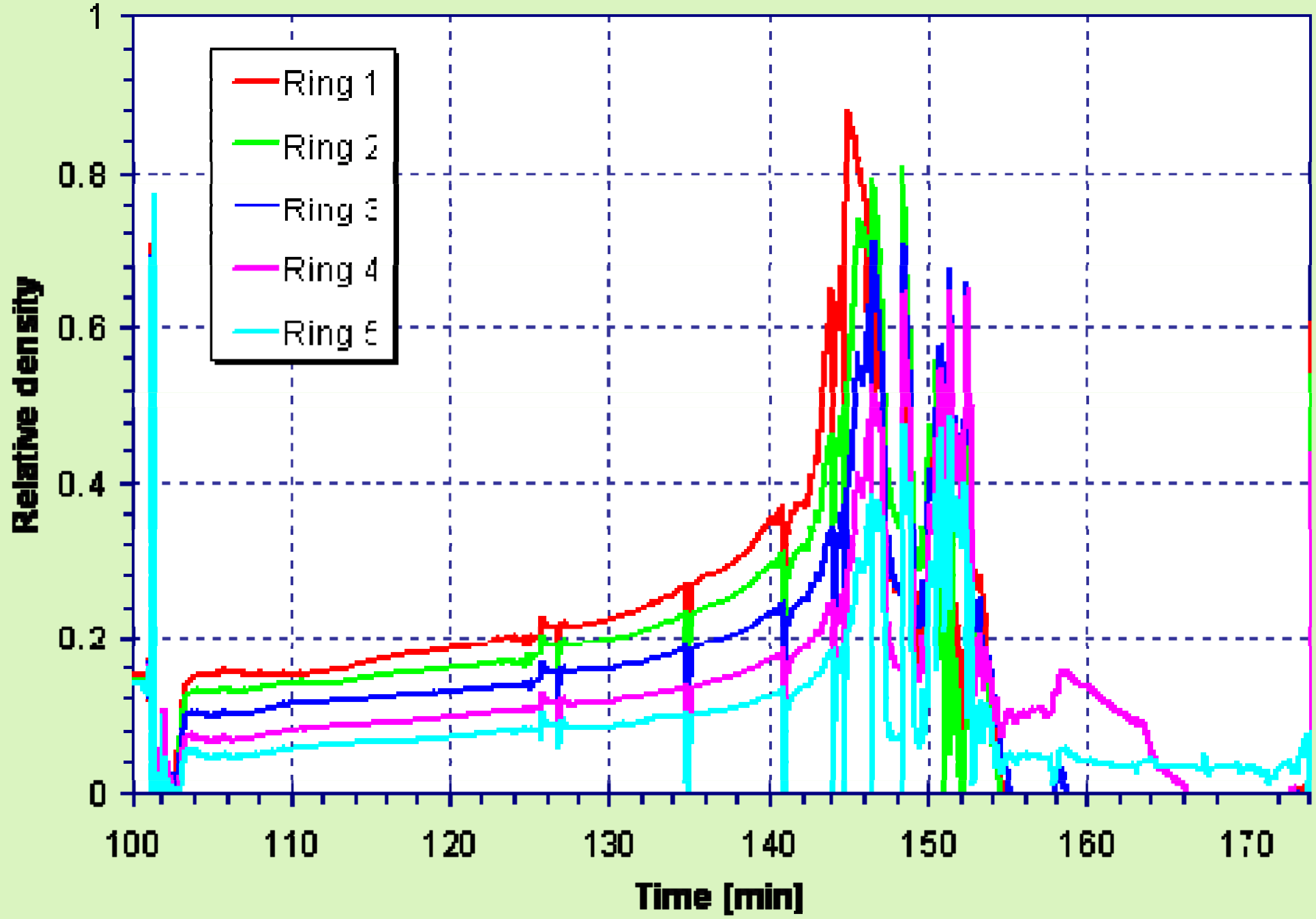
Net mass flow of hydrogen through failed instrumentation tubes

Results (TMI-2) – Cont.



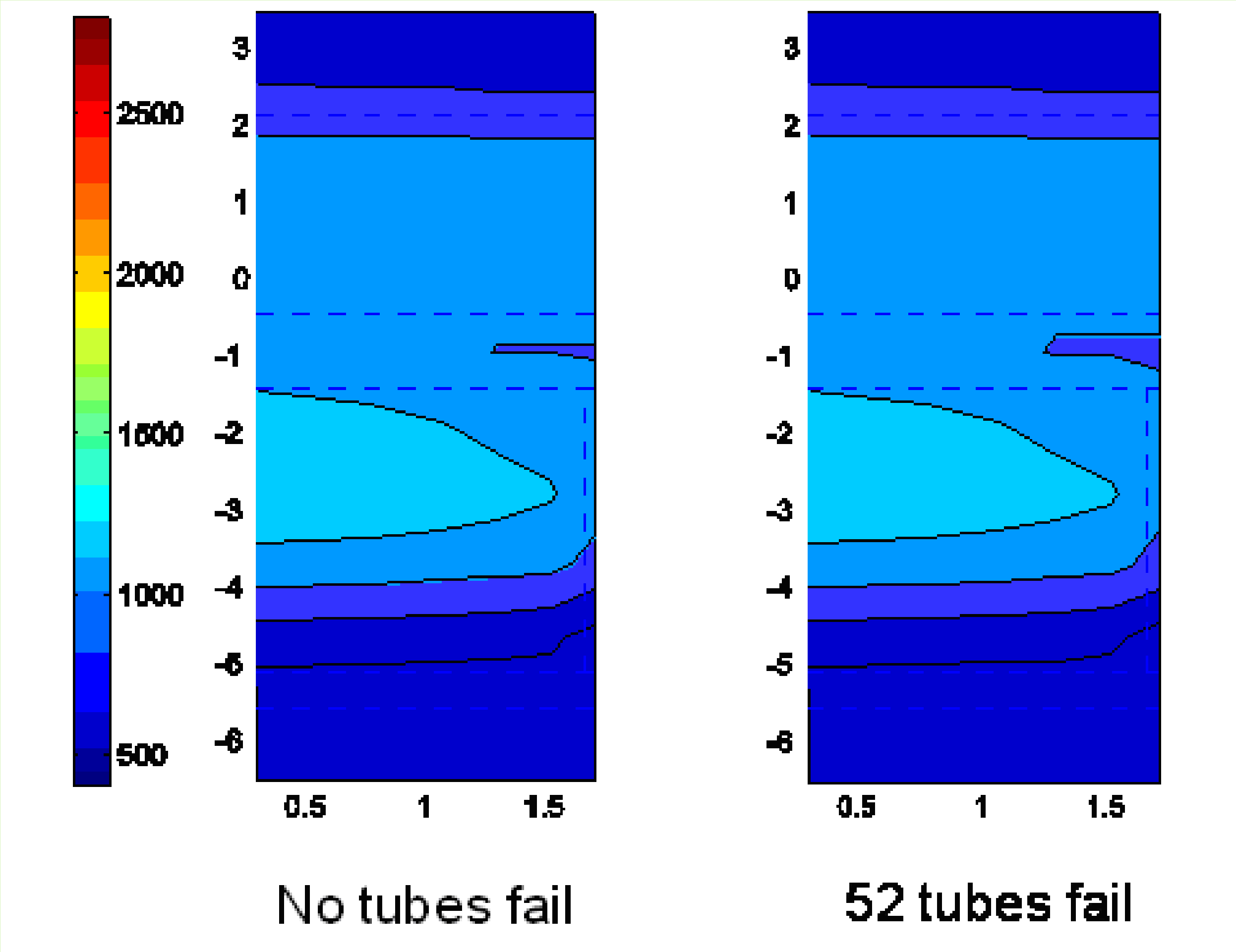
Recirculation flow rates (core-to-upper plenum) with & without inst. tube failure

Results (TMI-2) – Cont.



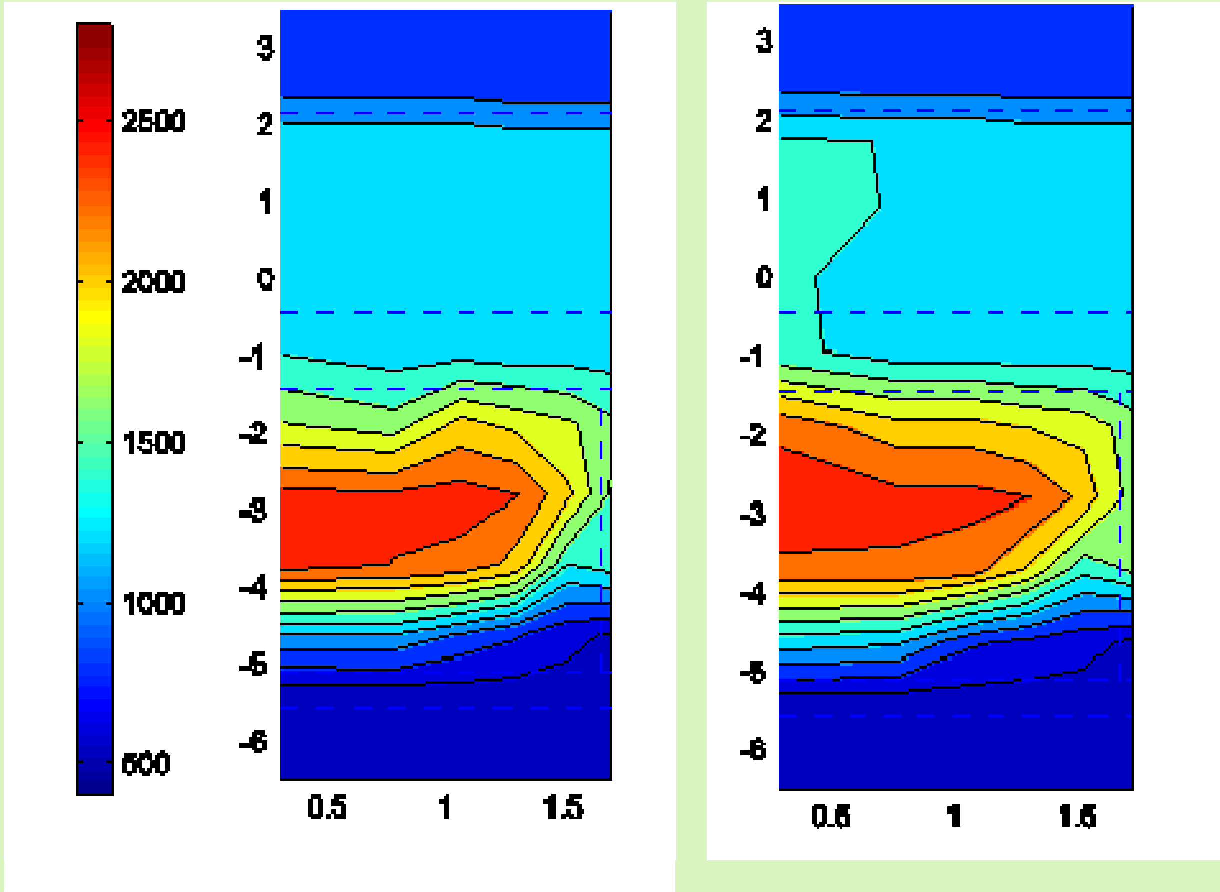
Fluid densities relative to bypass at top axial level of the core and bypass

Results (TMI-2) – Cont.



Gas temperature profile in the RPV (at 133 minutes)

Results (TMI-2) – Cont.

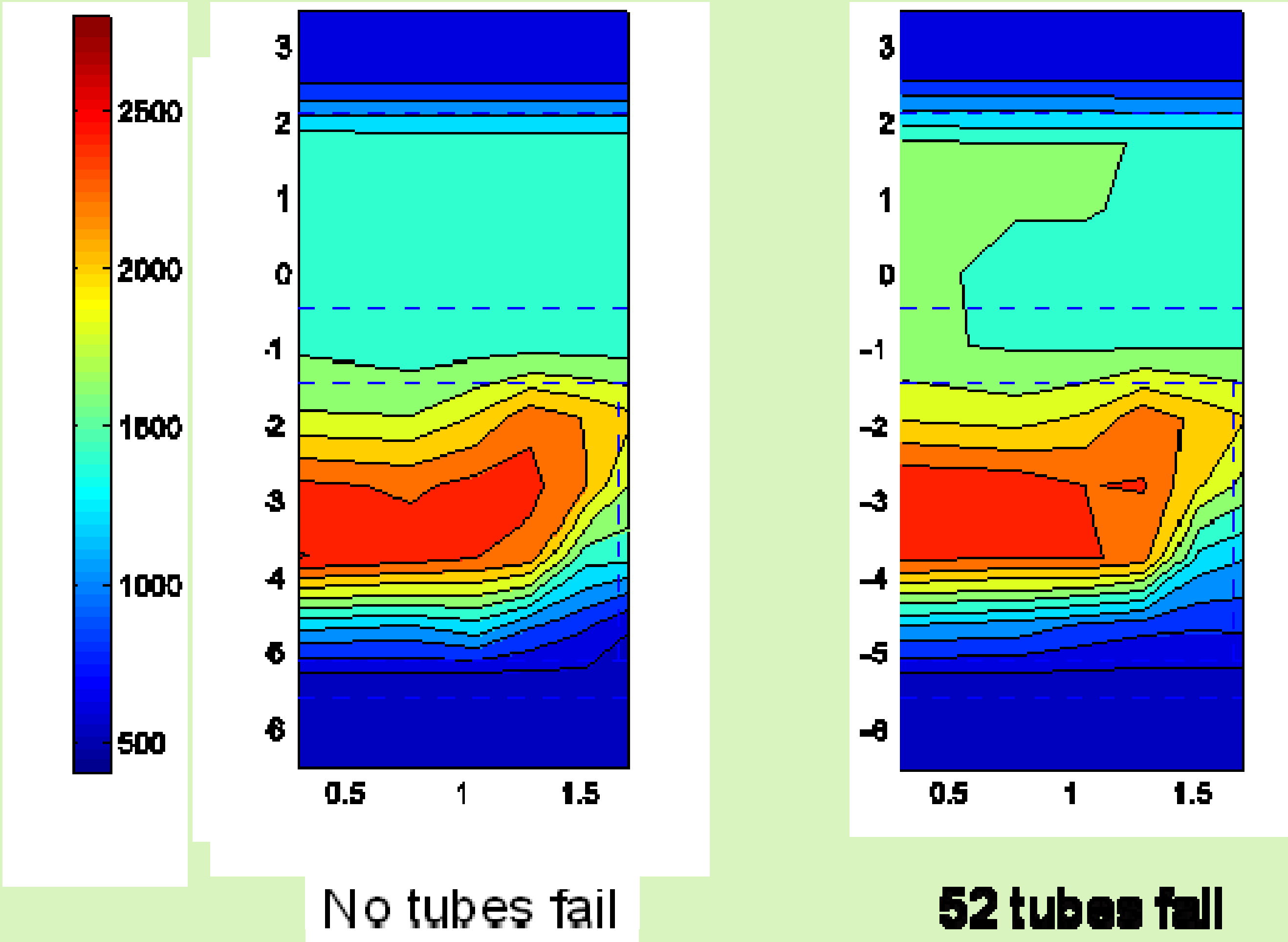


No tubes fail

52 tubes fail

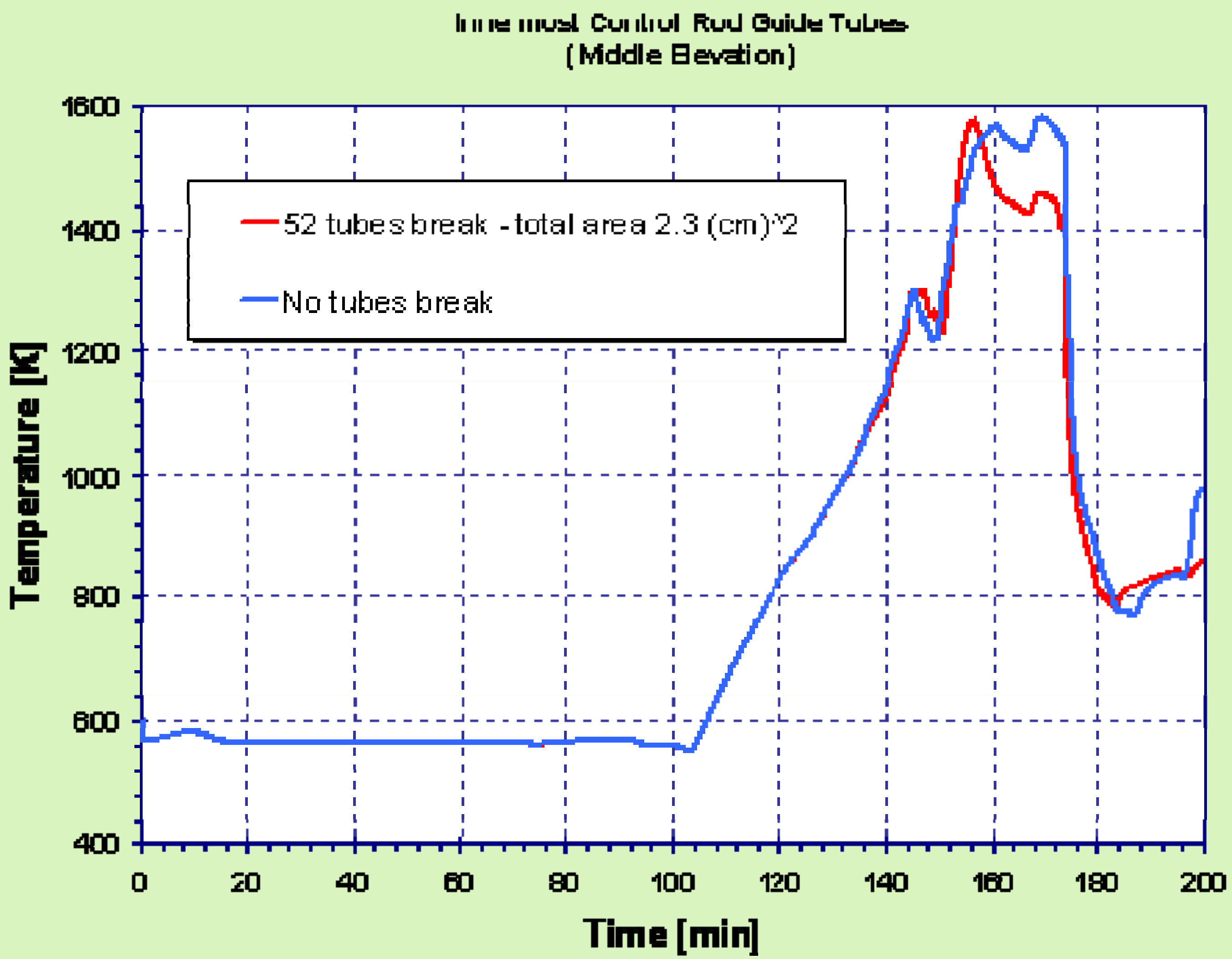
Gas temperature profile in the RPV (at 151 minutes)

Results (TMI-2) – Cont.

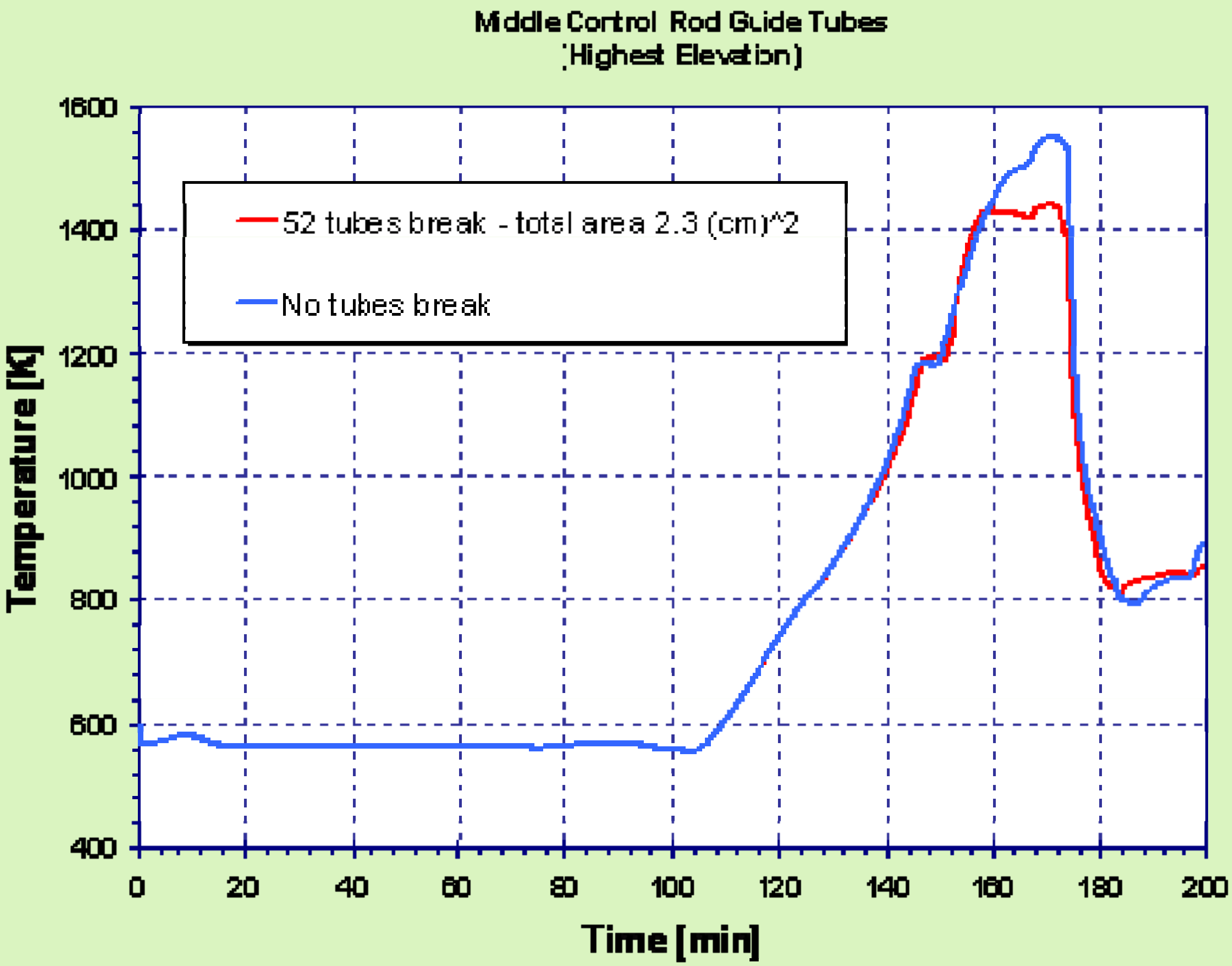


Gas temperature profile in the RPV (at 166 minutes)

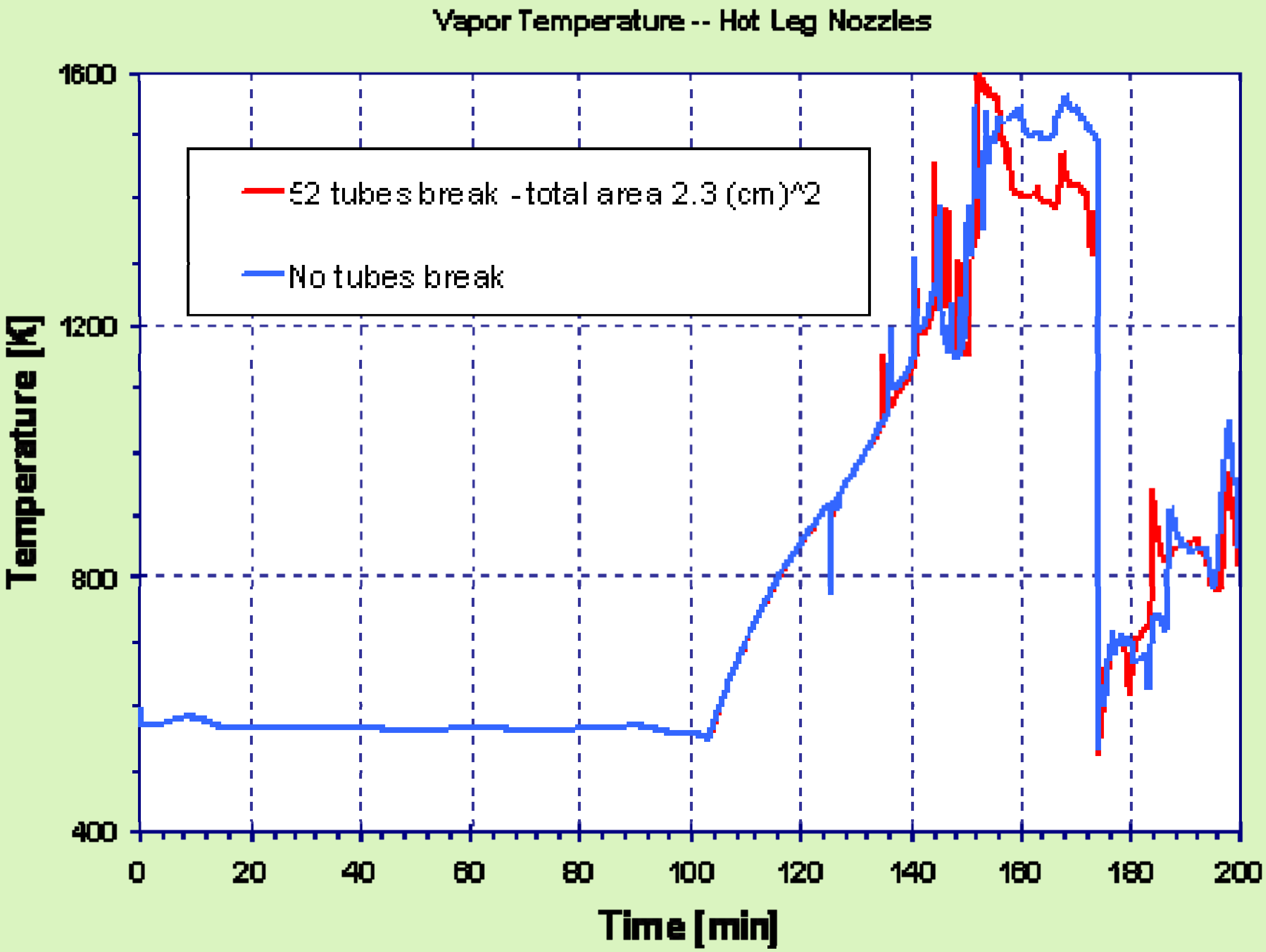
Results (TMI-2) – Cont.



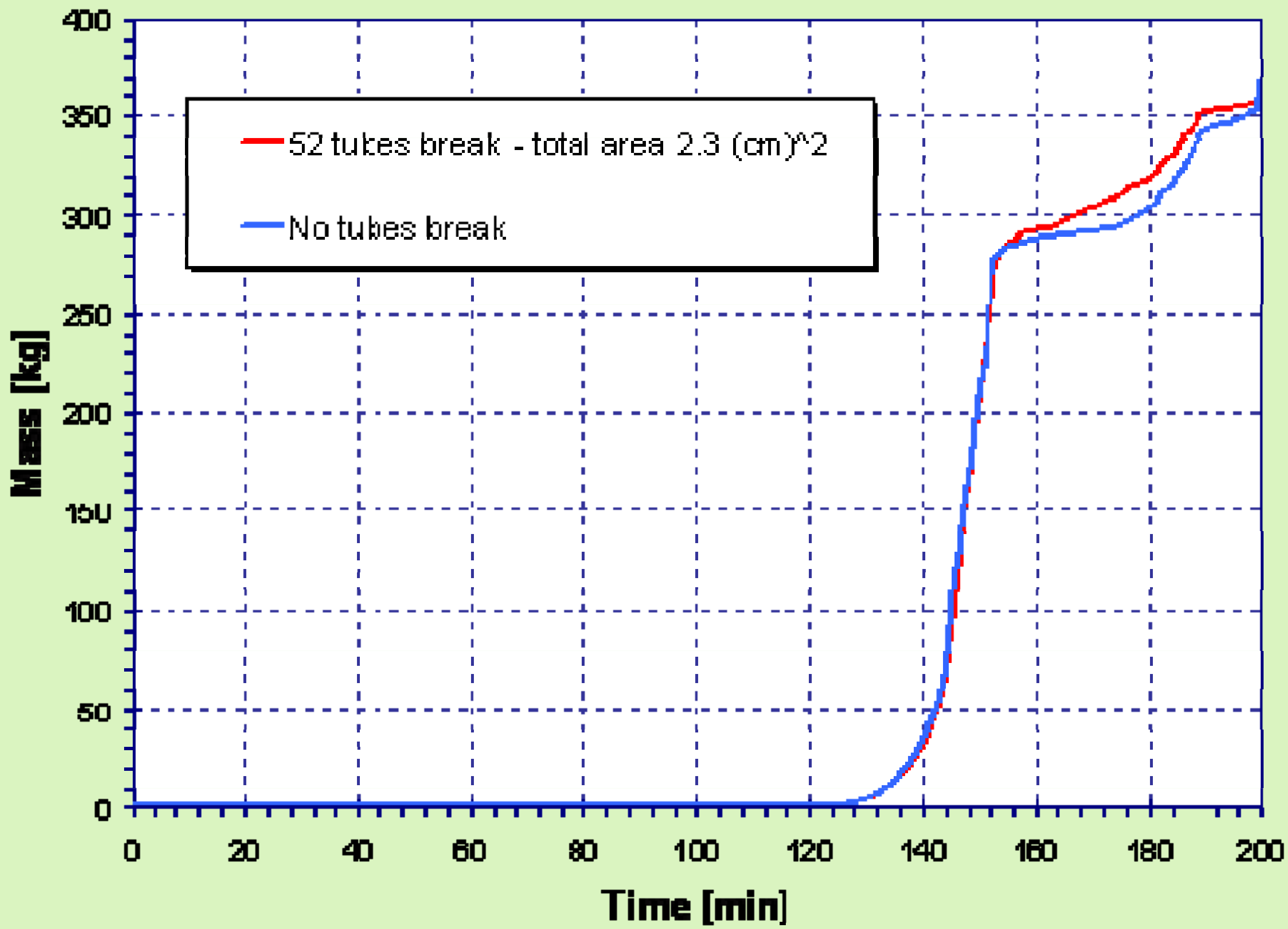
Results (TMI-2) – Cont.



Results (TMI-2) – Cont.

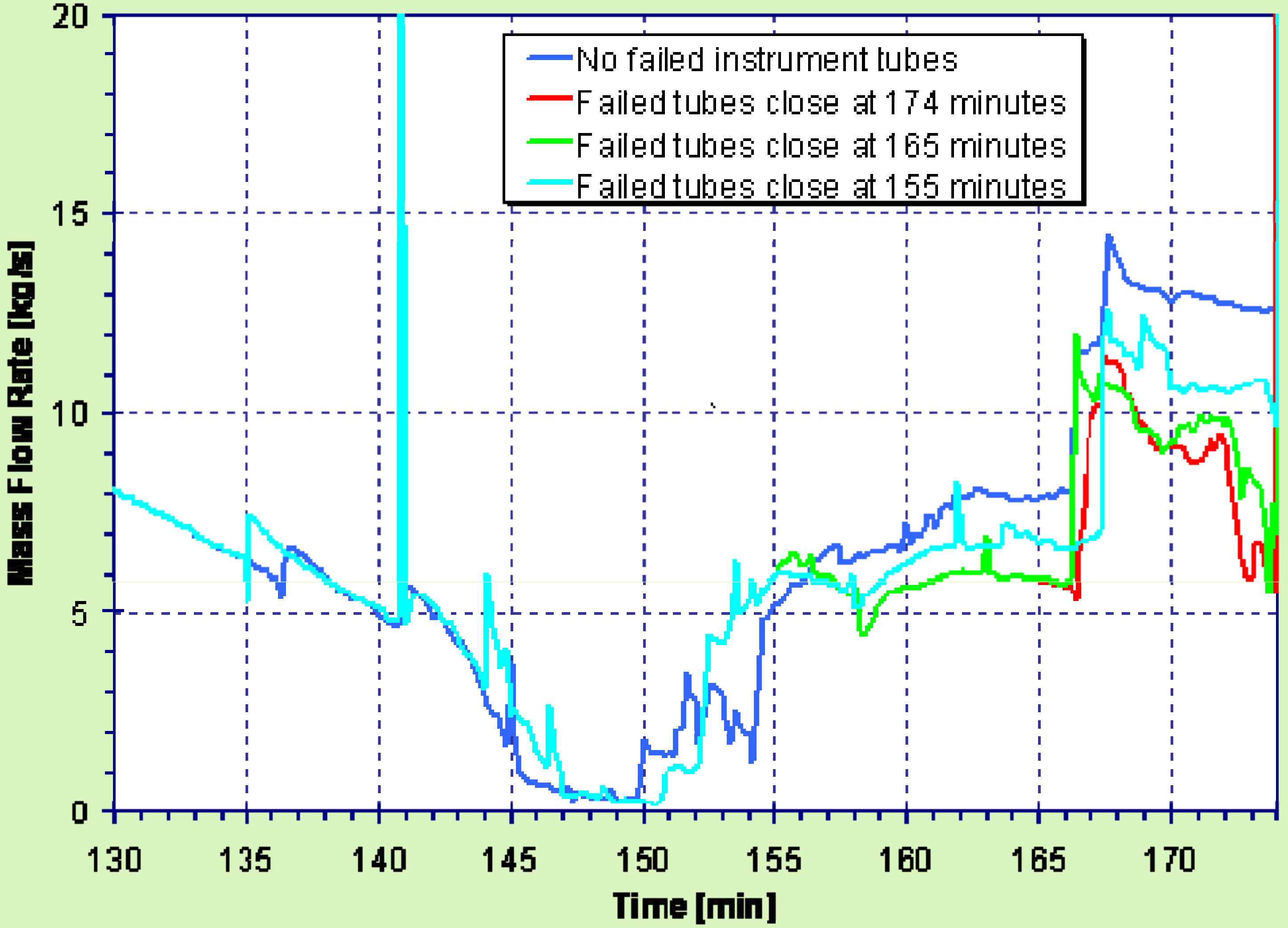


Results (TMI-2) – Cont.



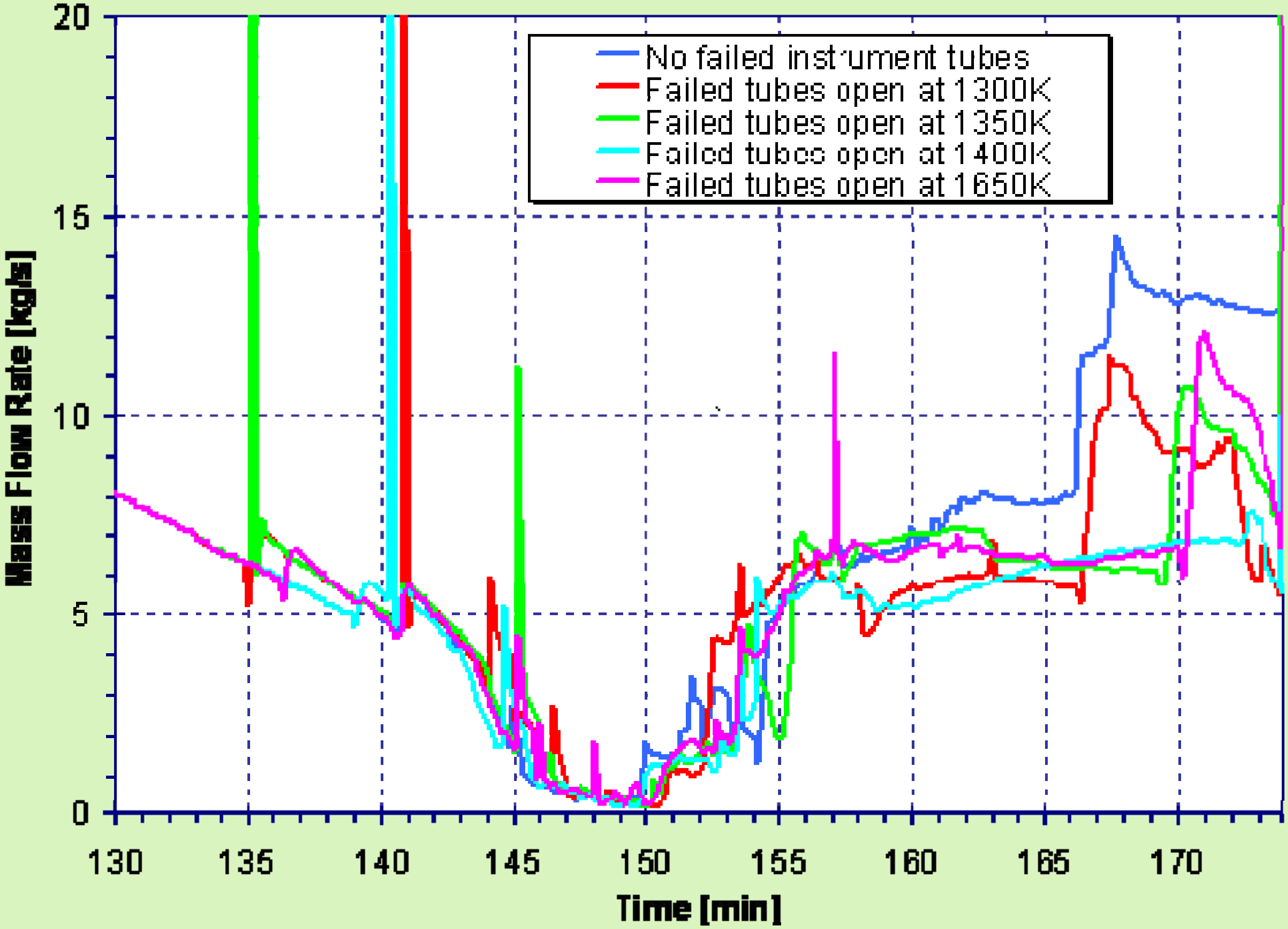
Cumulative in-vessel hydrogen production

Results (TMI-2) – Sensitivity Studies



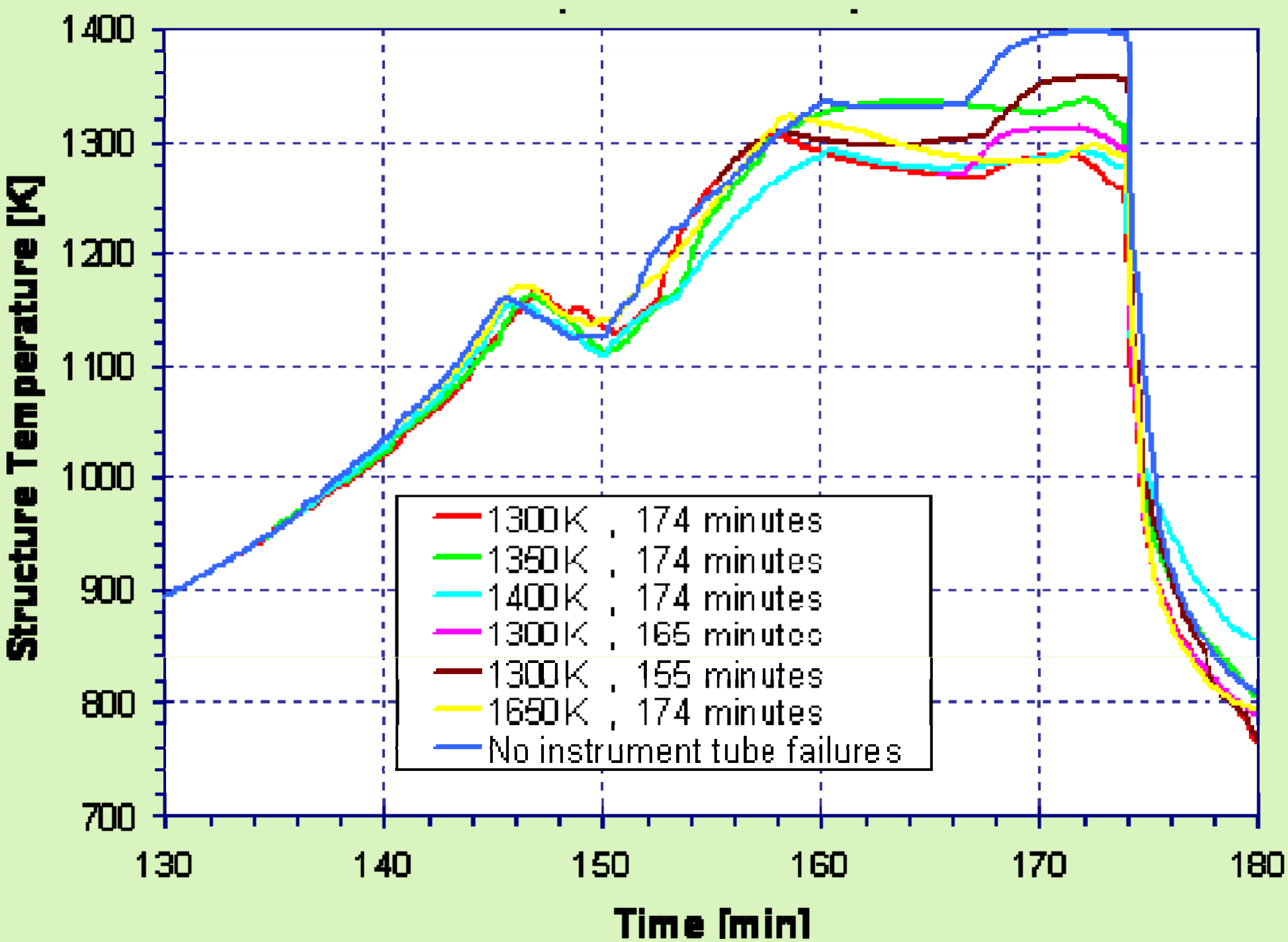
Sensitivity to instrumentation tube plugging time (duration of RPV venting)

Results (TMI-2) – Sensitivity Studies



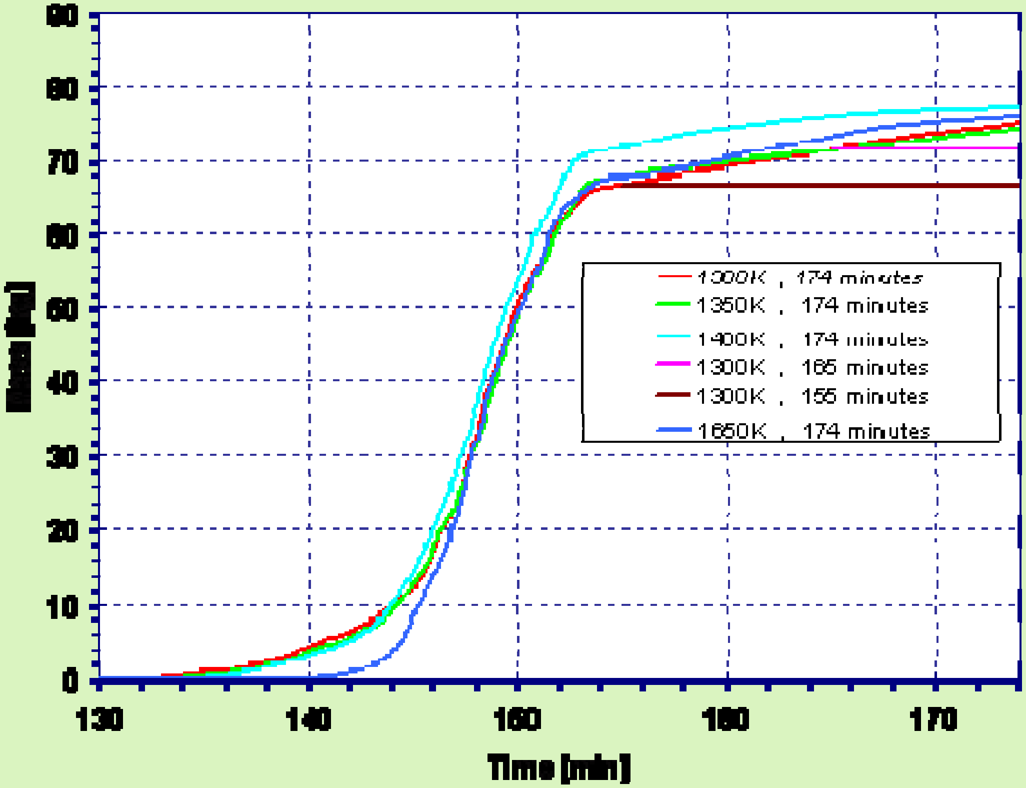
Sensitivity to instrumentation tube failure temperature

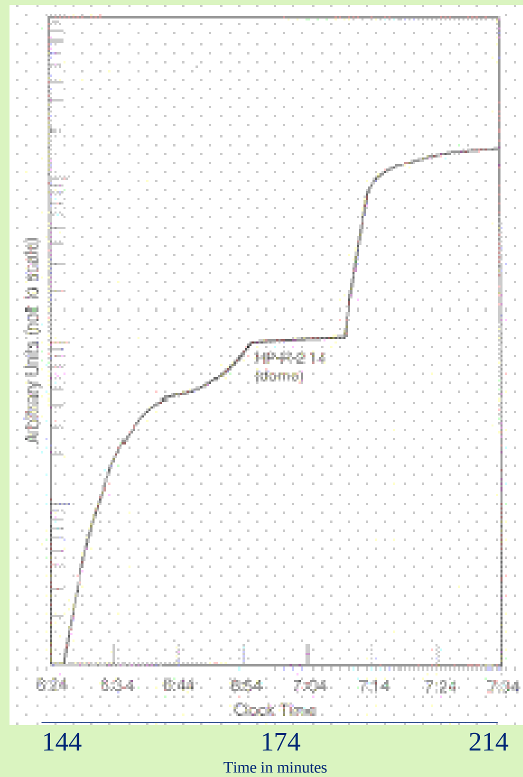
Results (TMI-2) – Sensitivity Studies



Sensitivity of control rod guide tube temperature to failure temperature & venting duration

Results (TMI-2)





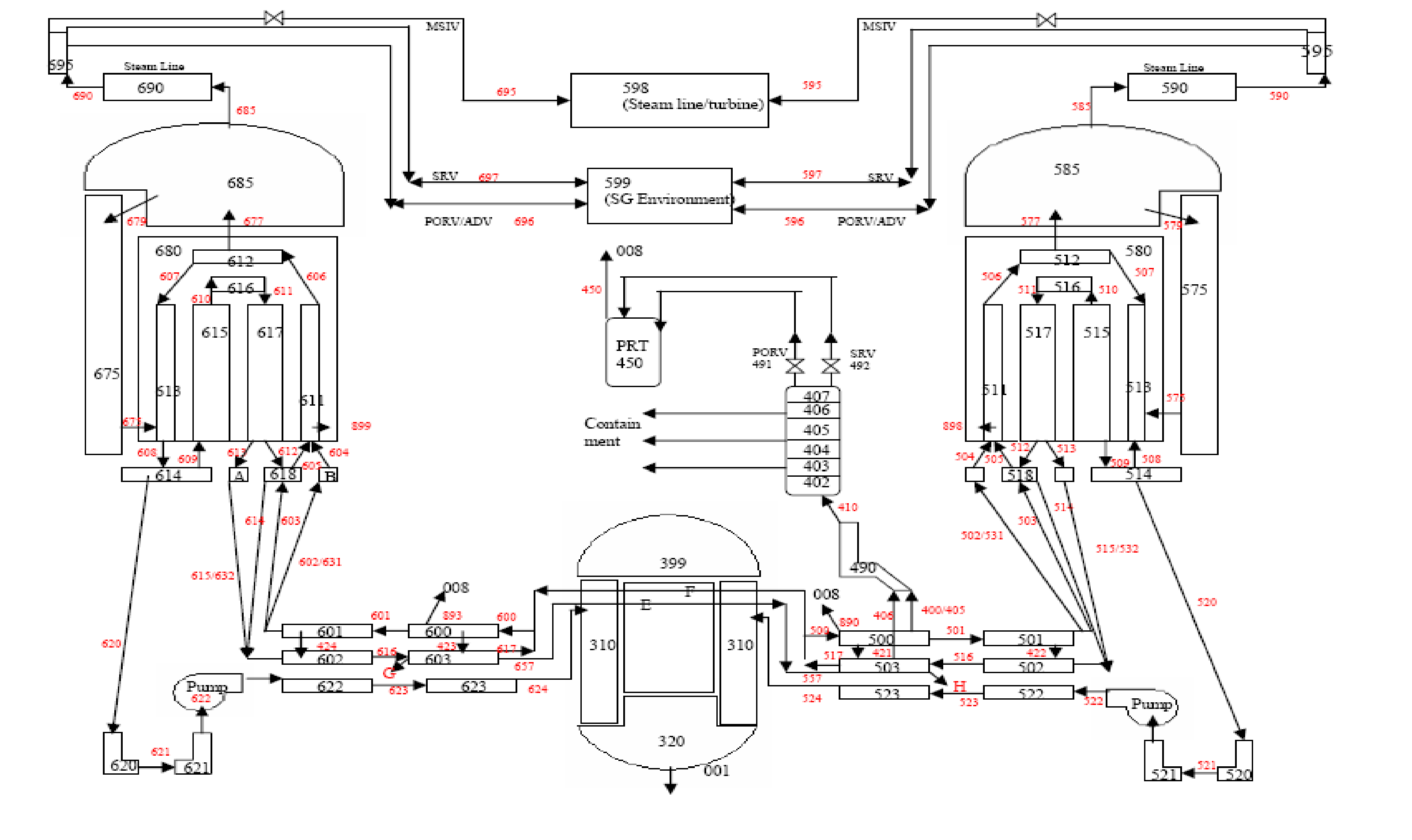
PWRs with U-Tube Steam Generators

- Natural circulation between core-to-upper plenum, and upper plenum, to hot leg, and steam generator tubes redistributes the core generated heat (decay and chemical) to:
  - Hot leg nozzles
  - Hot leg pipe
  - Surge-line (most affected by flow through PORV)
  - Steam generator tubes

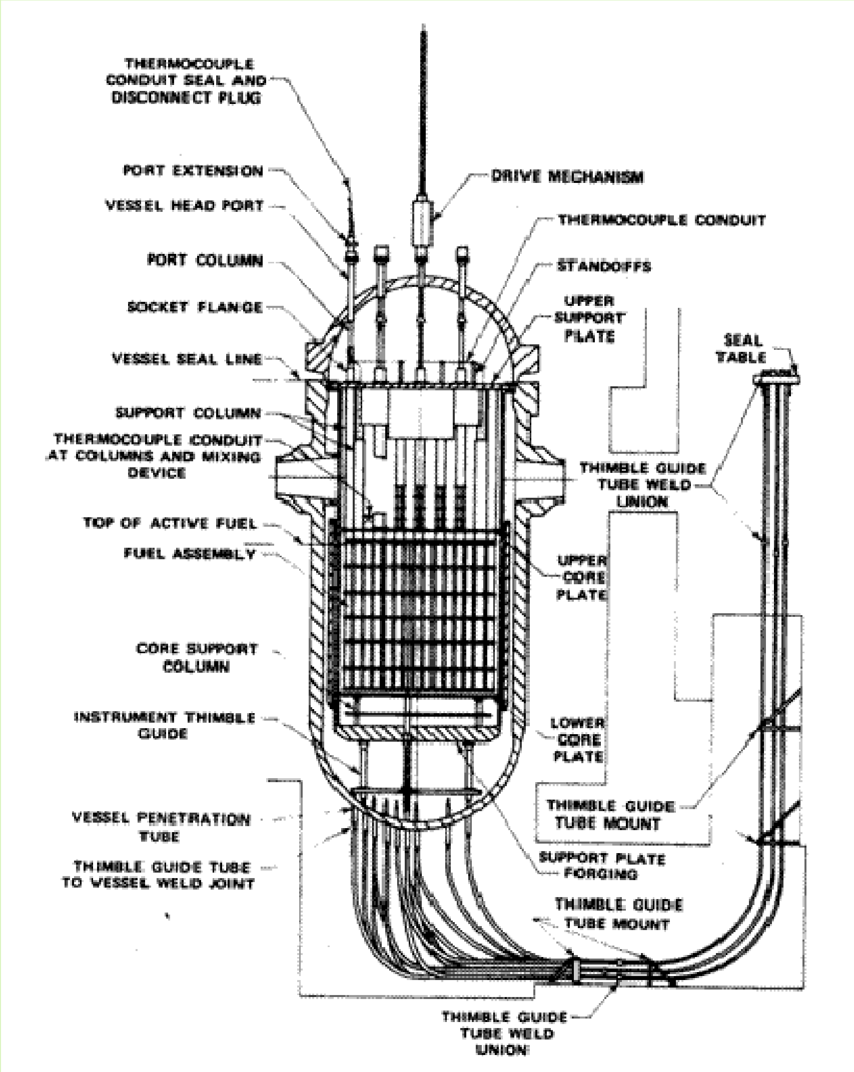
- At high pressure, creep-rupture of reactor coolant system boundary at these locations:
  - Beneficial Effect ("natural" thermal fuse that results in reactor coolant system depressurization) – eliminating potential for early containment failure due to "Direct Containment Heating".
  - Detrimental Effect – Creep rupture of SG tubes, can result in release of radioactivity to environment ("Containment Bypass")

Modeling Approach

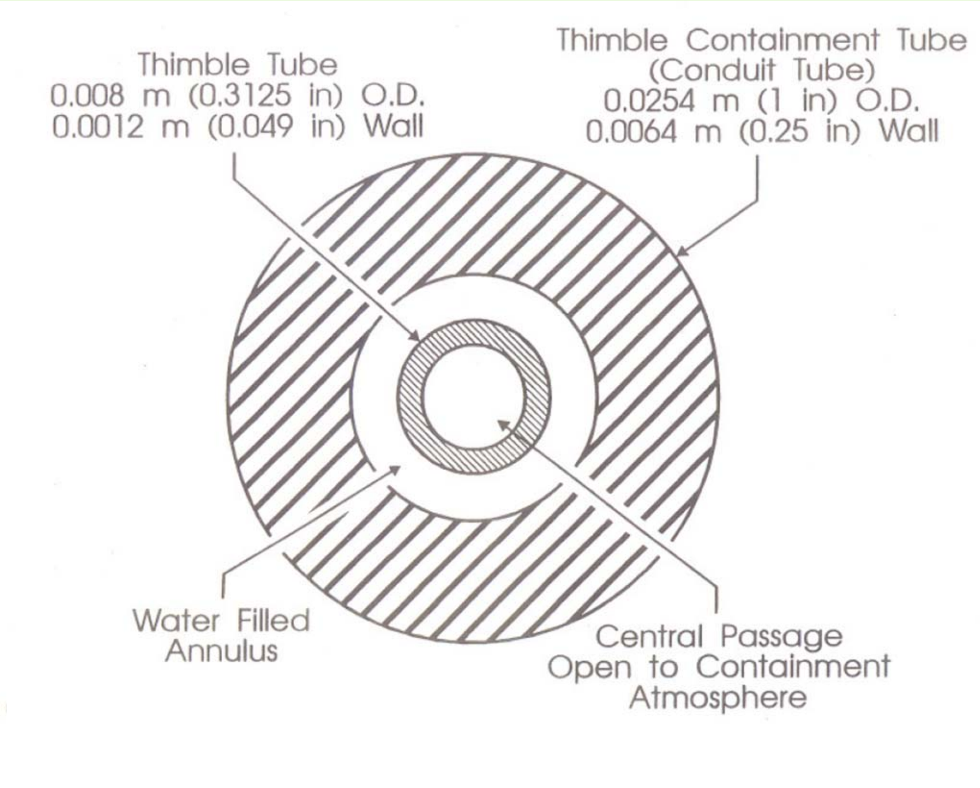
- MELCOR 1.8.6
- Tube failure modeling identical to that of TMI-2



In-Core Instrumentation Tubes



In-Core Instrumentation Tubes



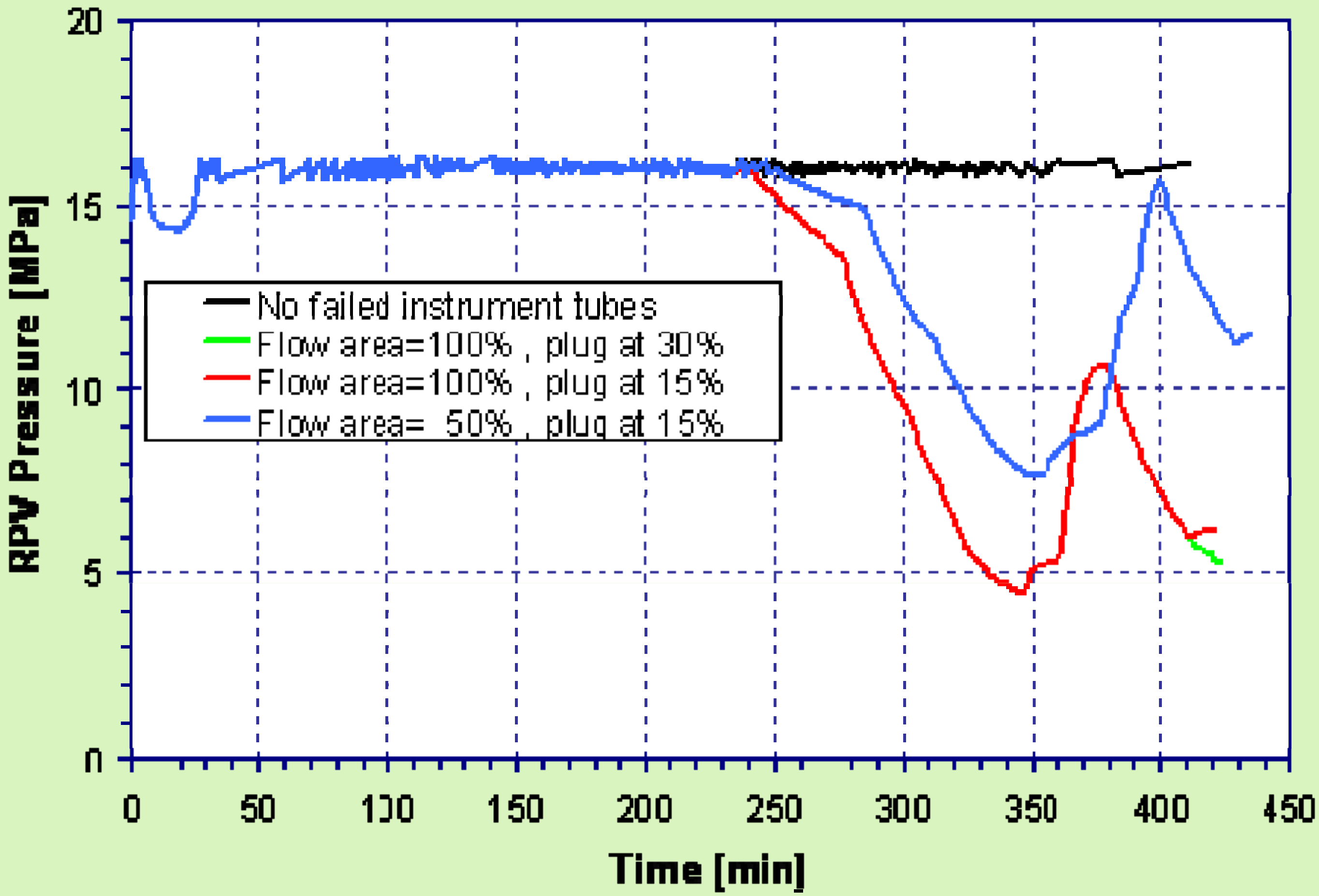
In-Core Instrumentation Tubes

- Typical Westinghouse plant (Zion):
  - 58 instrumented fuel assemblies
  - Diameter of inner part of instrumentation tubes (which is at containment pressure) is 5 mm
  - Therefore, flow area resulting from failure of all tubes is ~1.15×10^{-3} m^2 or ~5 times larger than TMI-2 (2.27×10^{-4} m^2).

Accident Scenario

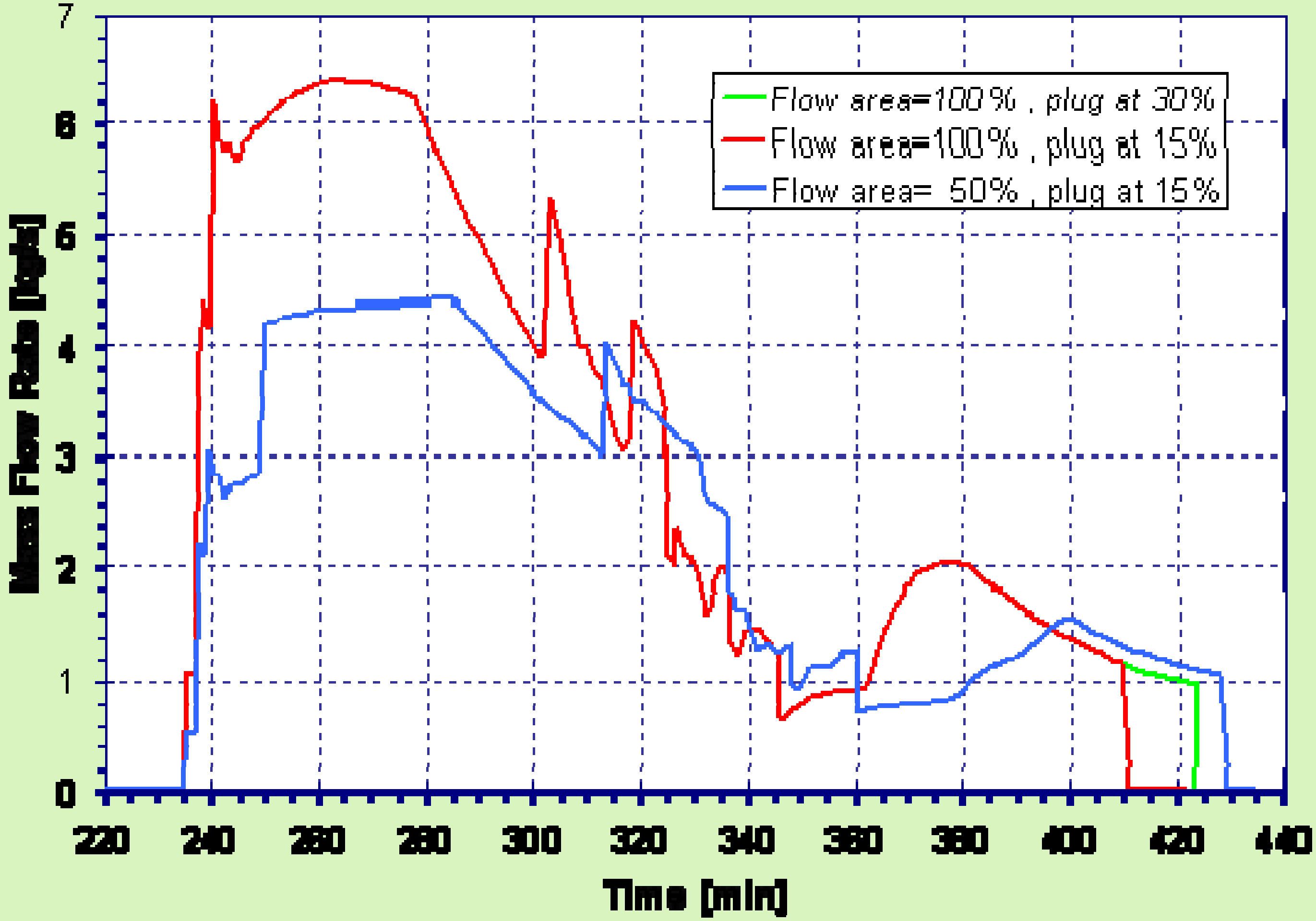
- Station Blackout Scenario
  - Base case – assumes the steam generator safety valve "sticks open" (depressurizing the secondary system) after lifting on one of the steam generators (on the pressurizer loop). This results in the most limiting tube-wall temperature.
  - Sensitivity case assuming the steam generators remain at the safety relief valve pressure.

Results (PWR with U-Tube SGs) – Base Case



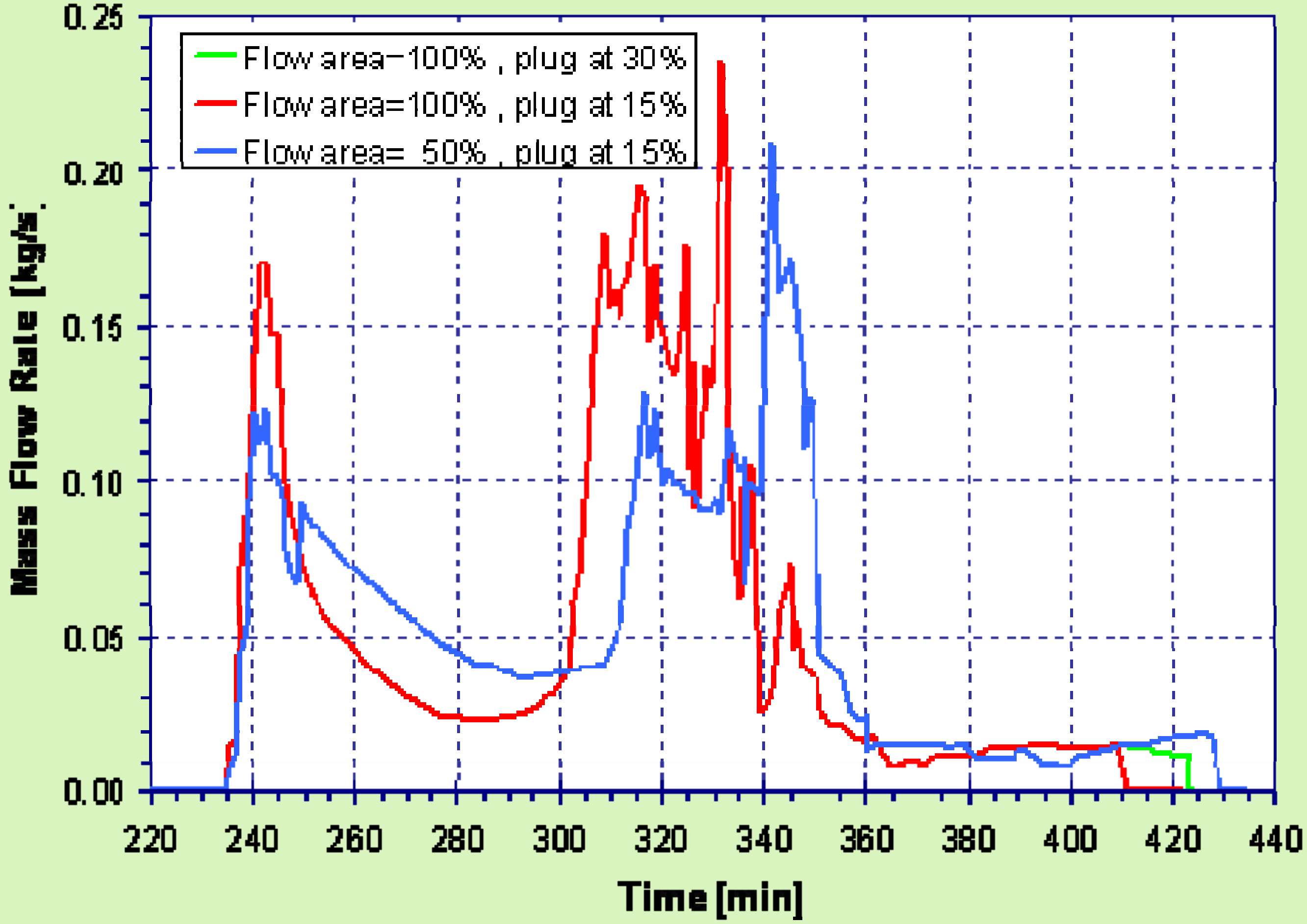
Primary System Pressure

Results (PWR with U-Tube SGs) – Base Case Cont.



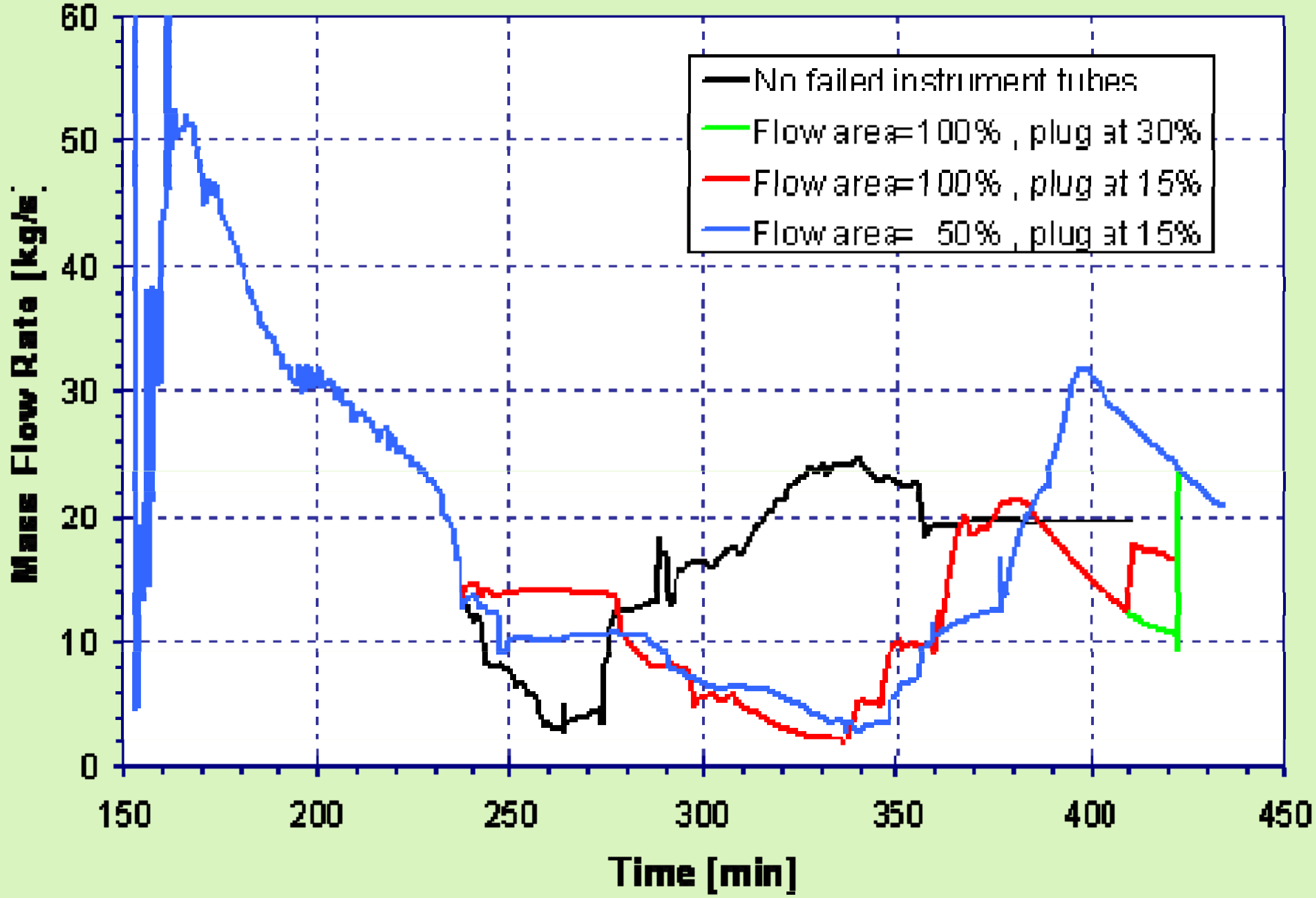
mass flow rate of steam and hydrogen through the failed instrumentation tubes

Results (PWR with U-Tube SGs) Base Case - Cont.



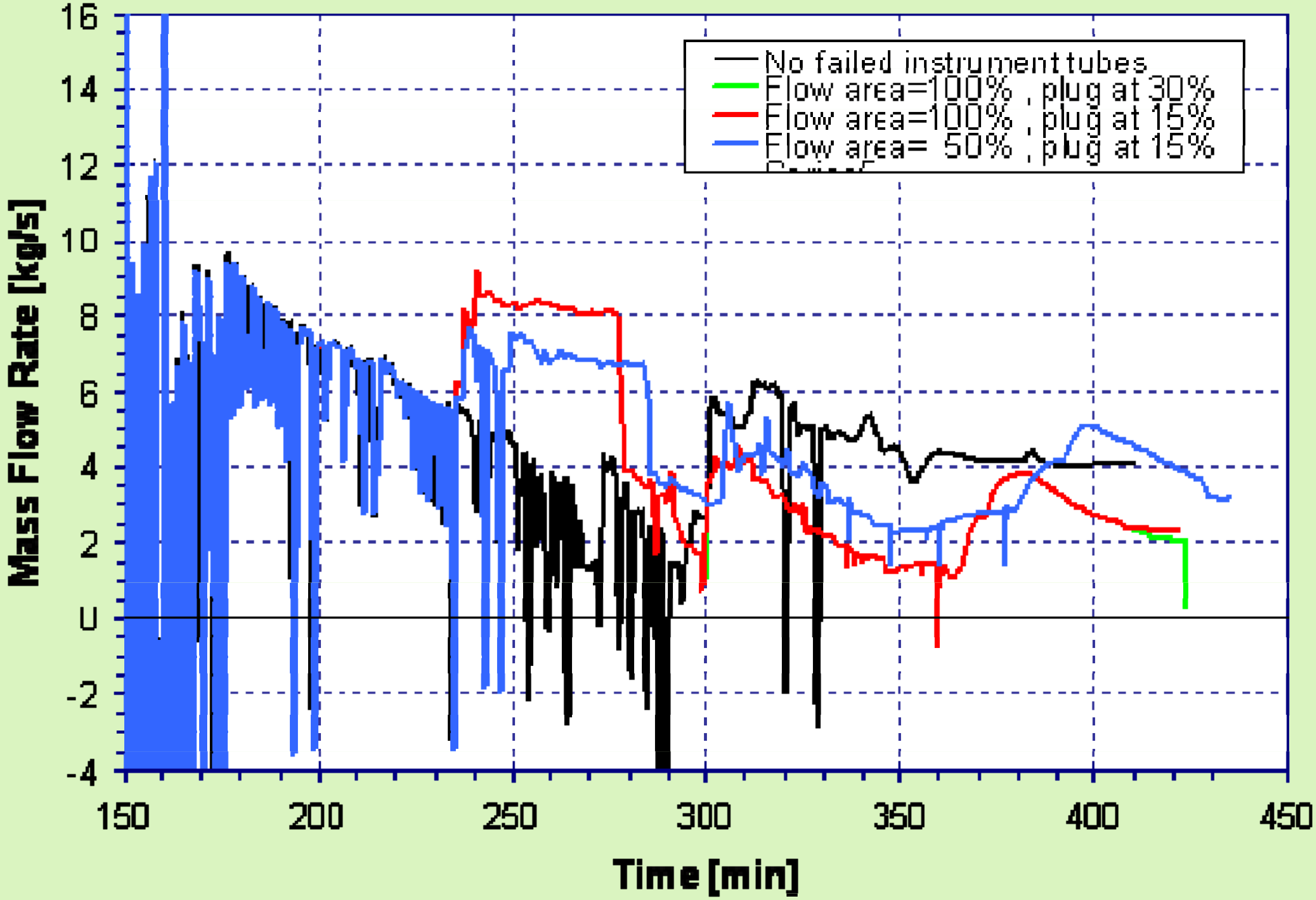
Net mass flow of hydrogen through failed instrumentation tubes

Results (PWR with U-Tube SGs) Base Case - Cont.



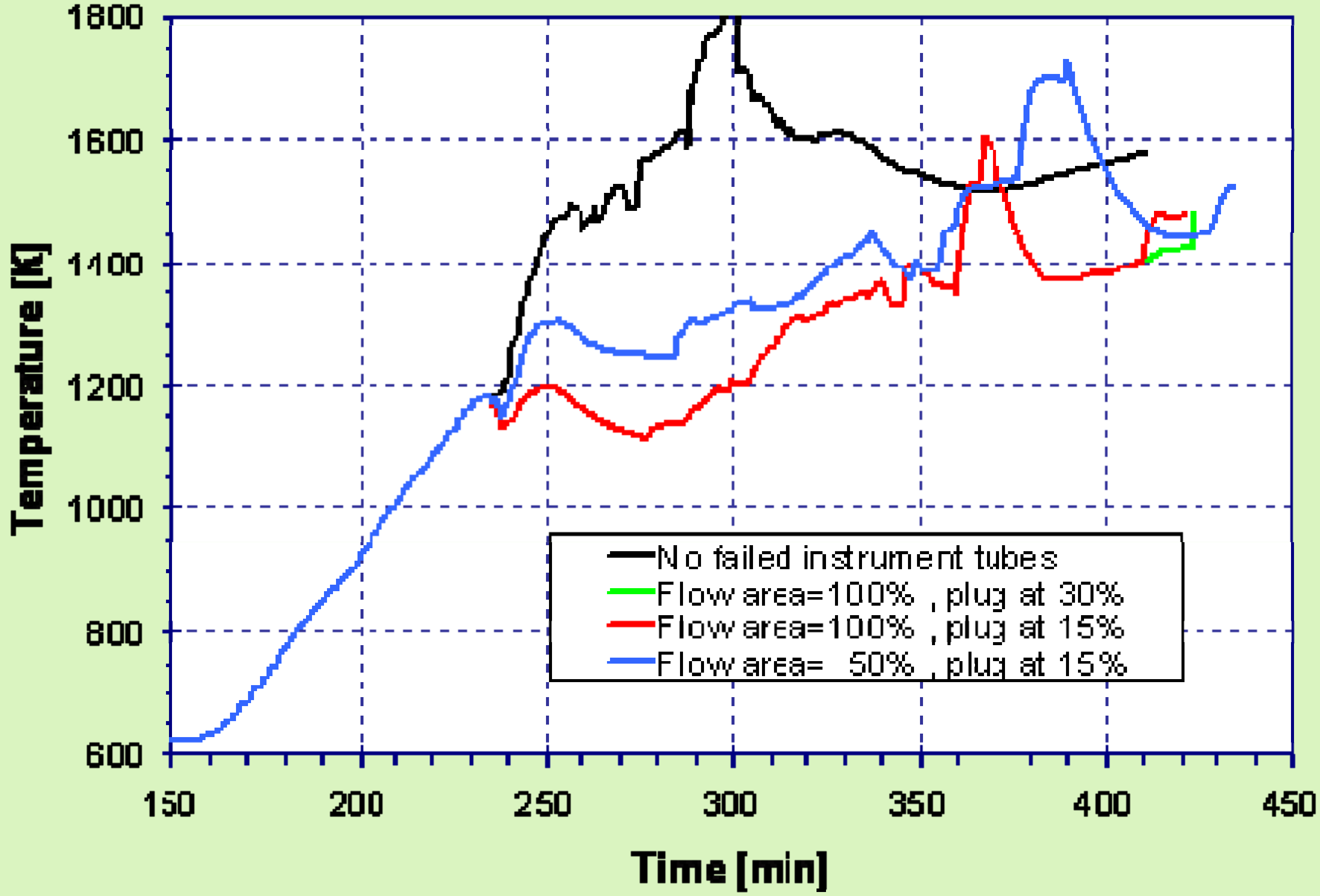
Recirculation flow rates (core-to-upper plenum) with & without inst. tube failure

Results (PWR with U-Tube SGs) Base Case - Cont.



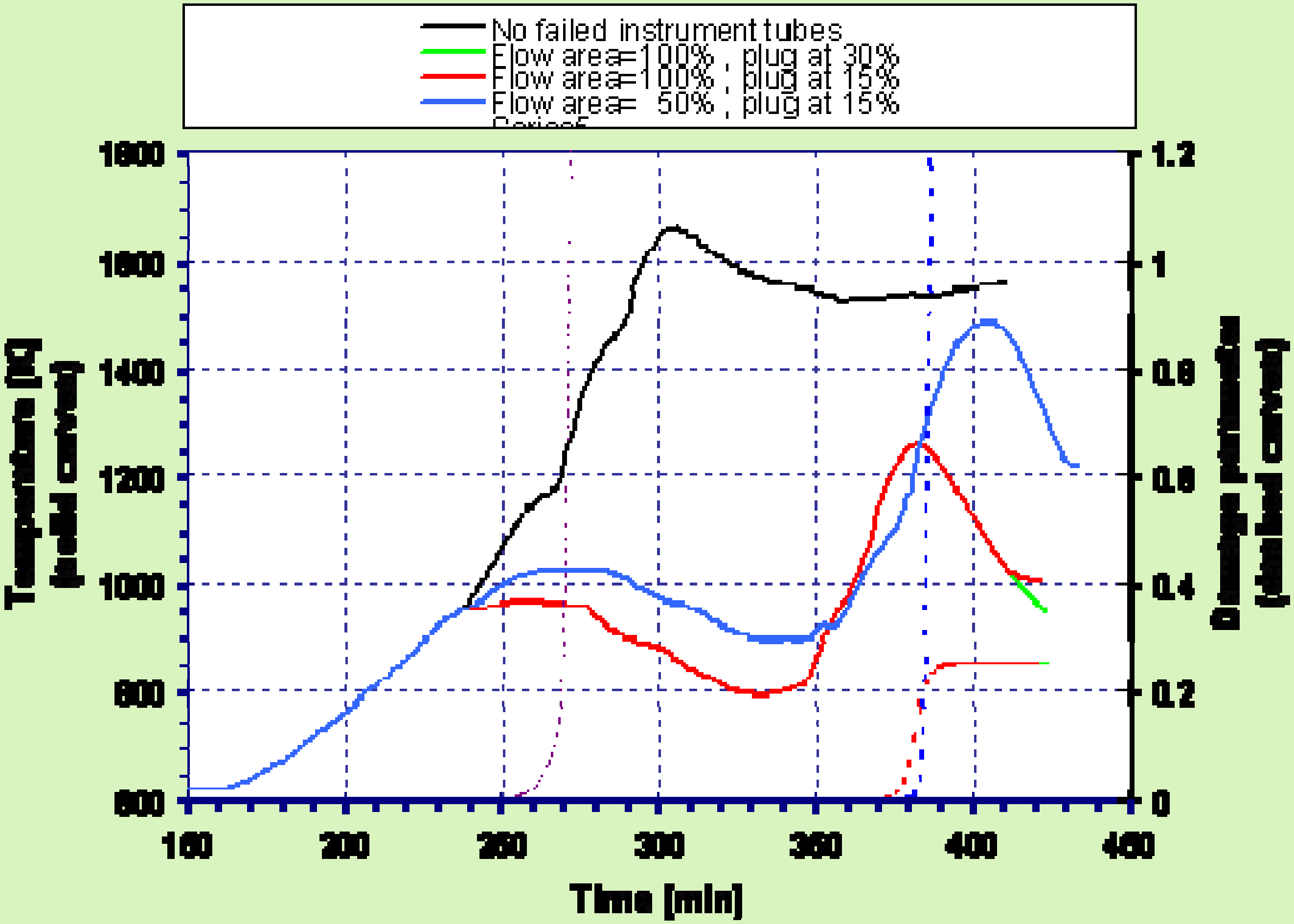
Counter-current coolant mass flow rate in the pressurizer hot leg

Results (PWR with U-Tube SGs) Base Case - Cont.



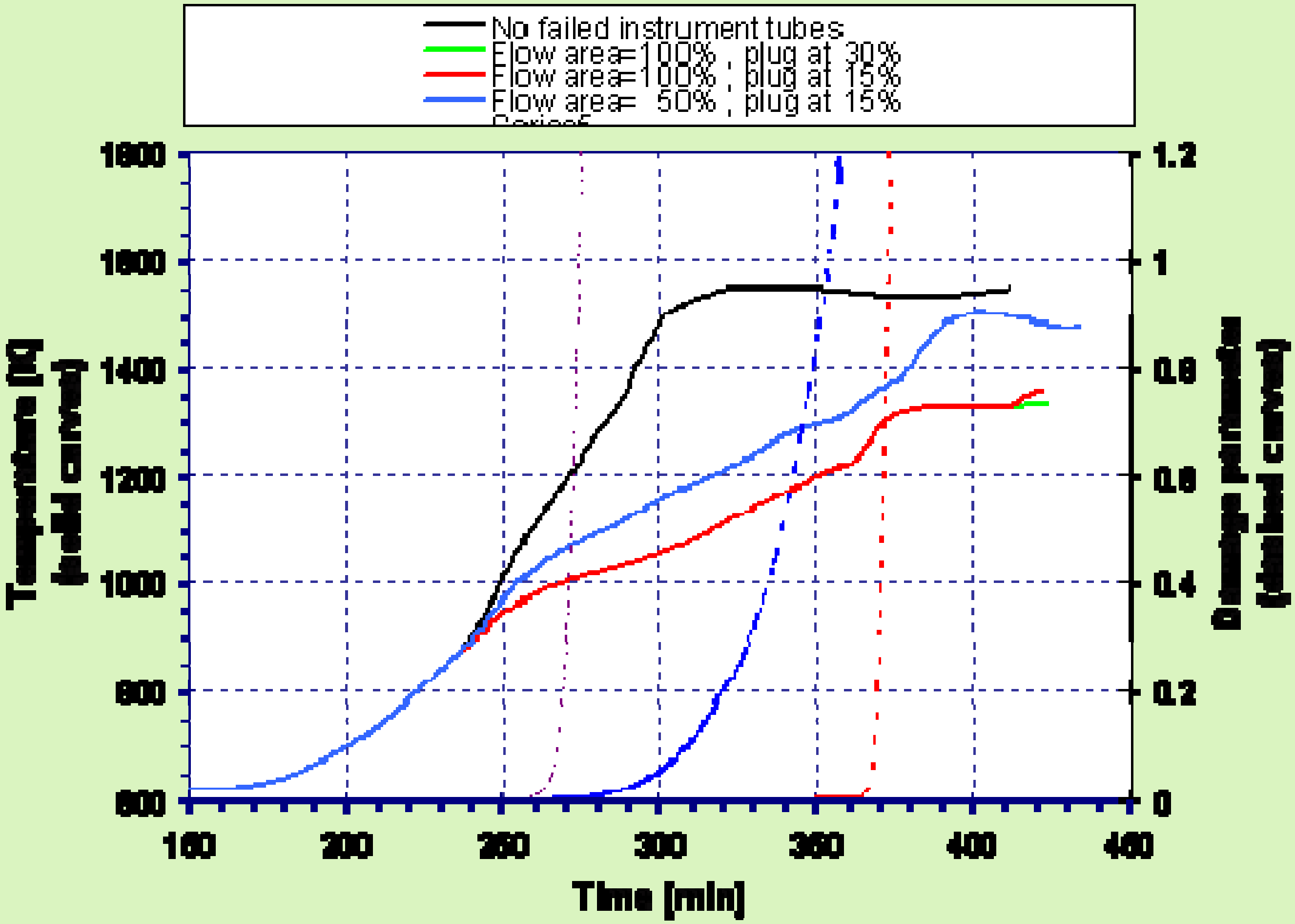
Vapor temperature at the hot leg nozzles

Results (PWR with U-Tube SGs) Base Case - Cont.



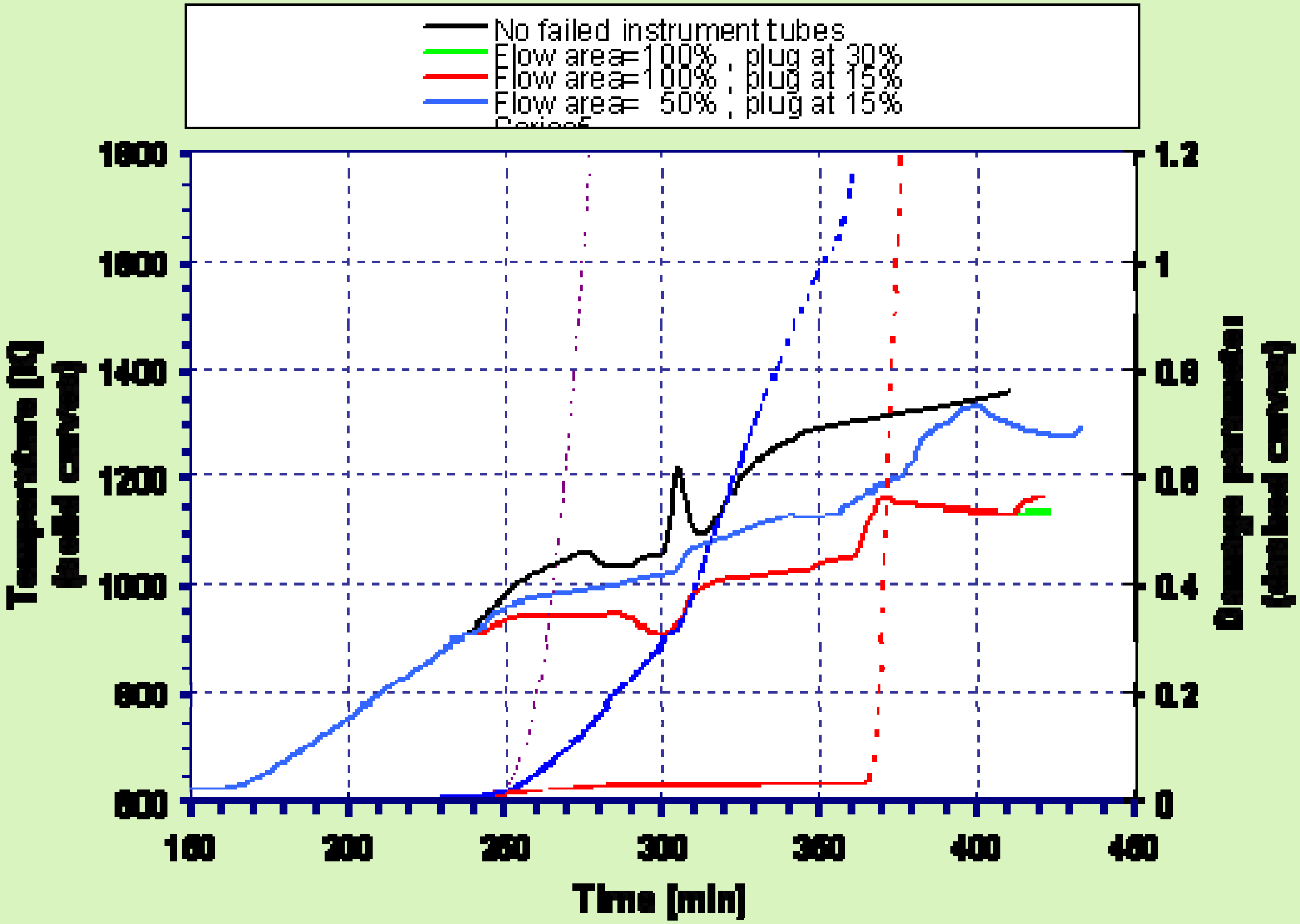
Pressurizer surge Line structure and damage parameter

Results (PWR with U-Tube SGs) Base Case - Cont.



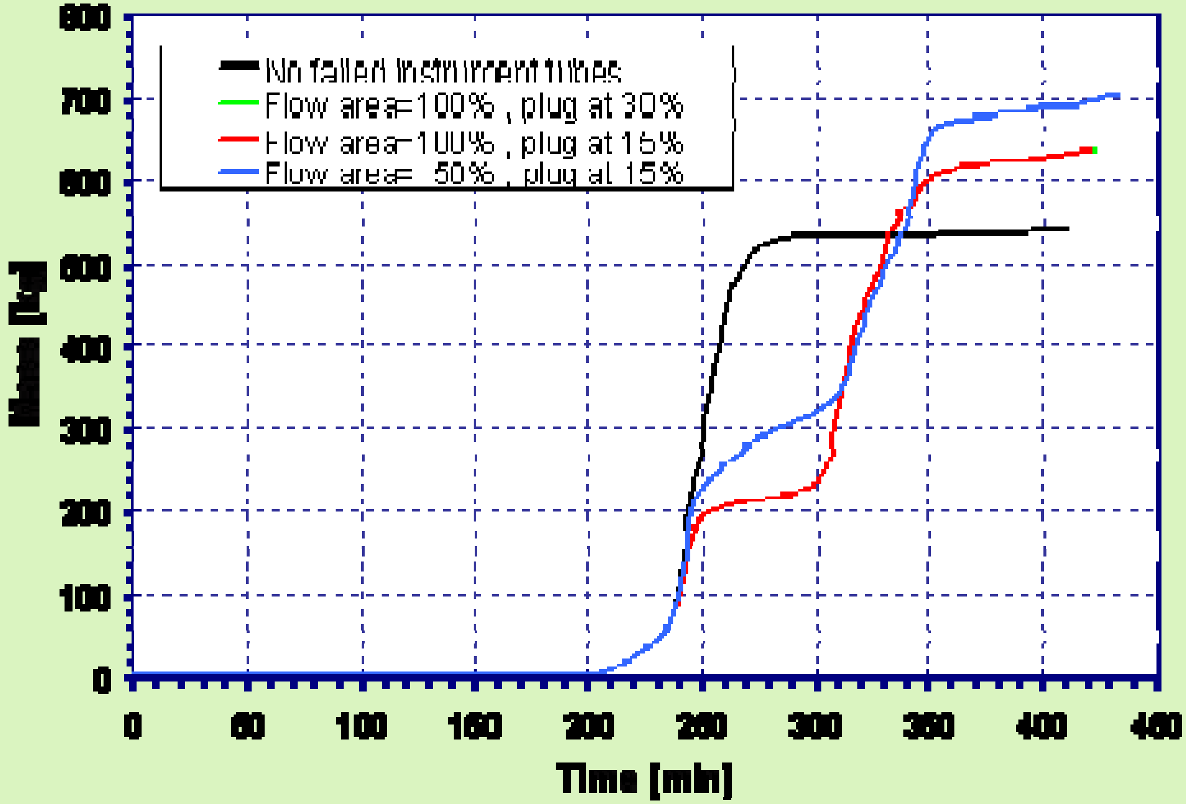
Hot Leg structure and damage parameter

Results (PWR with U-Tube SGs) Base Case - Cont.



Steam generator tube structure and damage parameter (pressurizer loop)

Results (PWR with U-Tube SGs) Base Case - Cont.

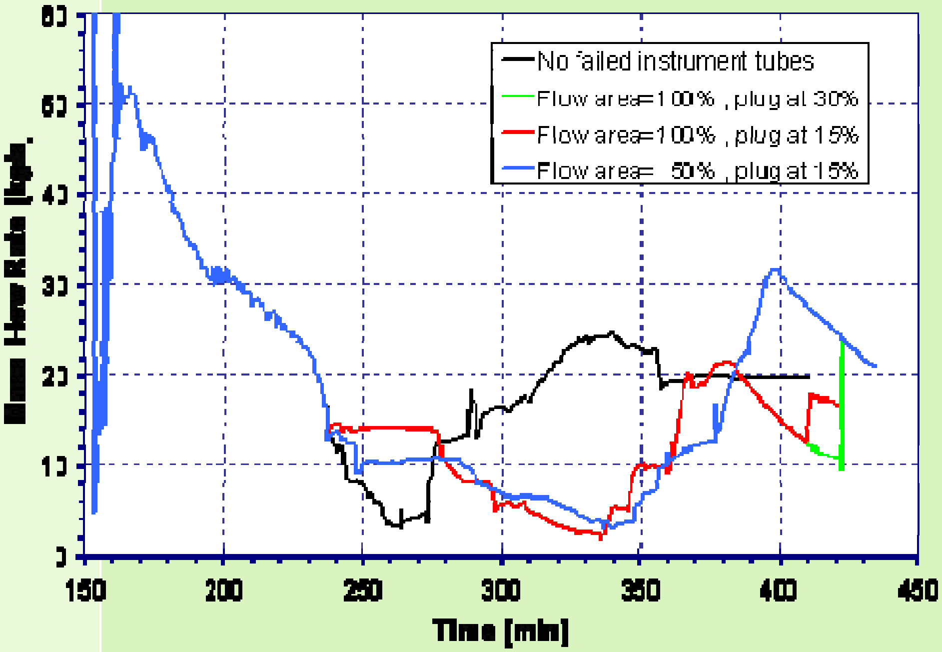


Total In-Vessel Hydrogen Generation

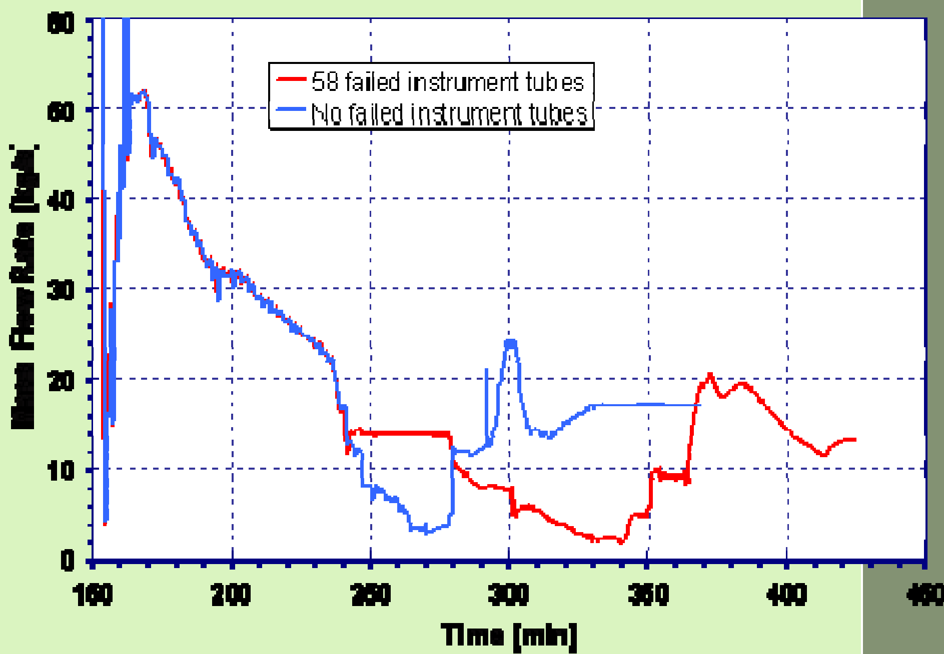
Results (PWR with U-Tube SGs)
Sensitivity to SG Secondary Pressure - Cont.

SG S/RV on pressurizer loop

Stuck open

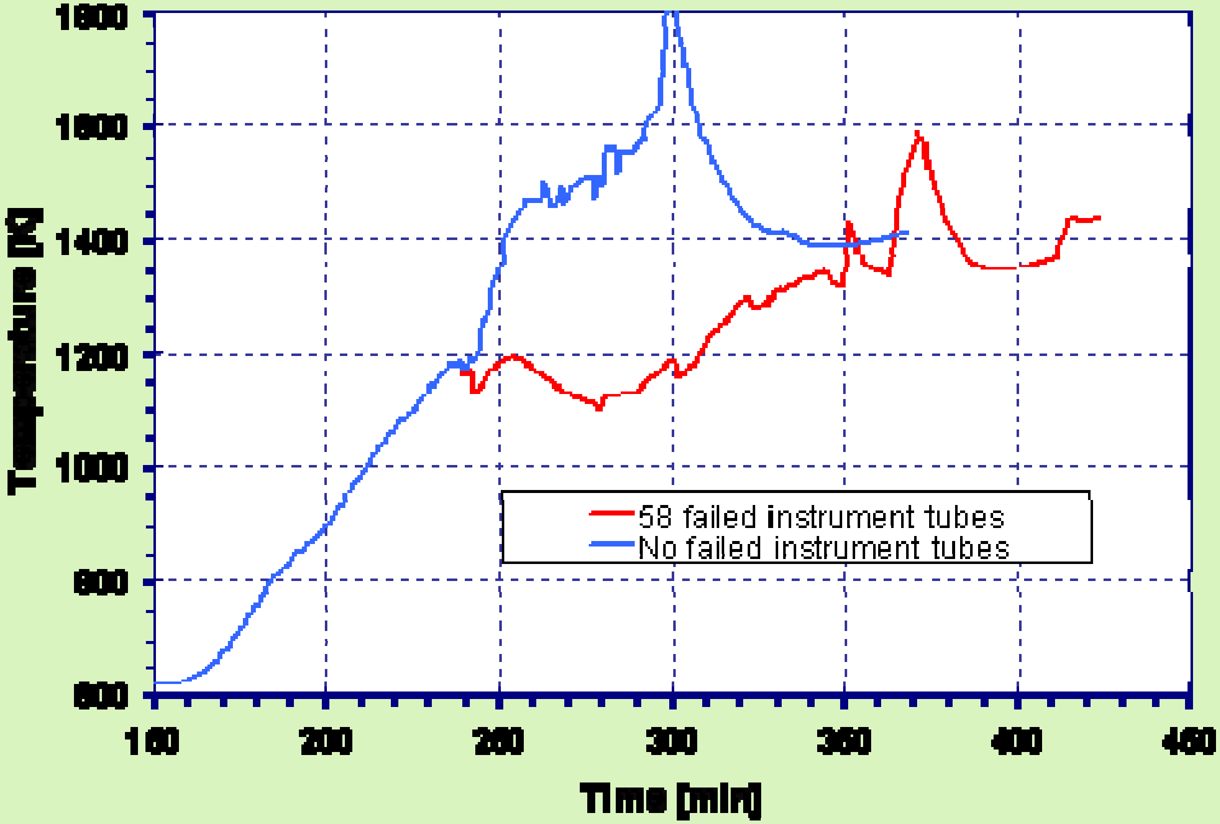


SG S/RV Operating



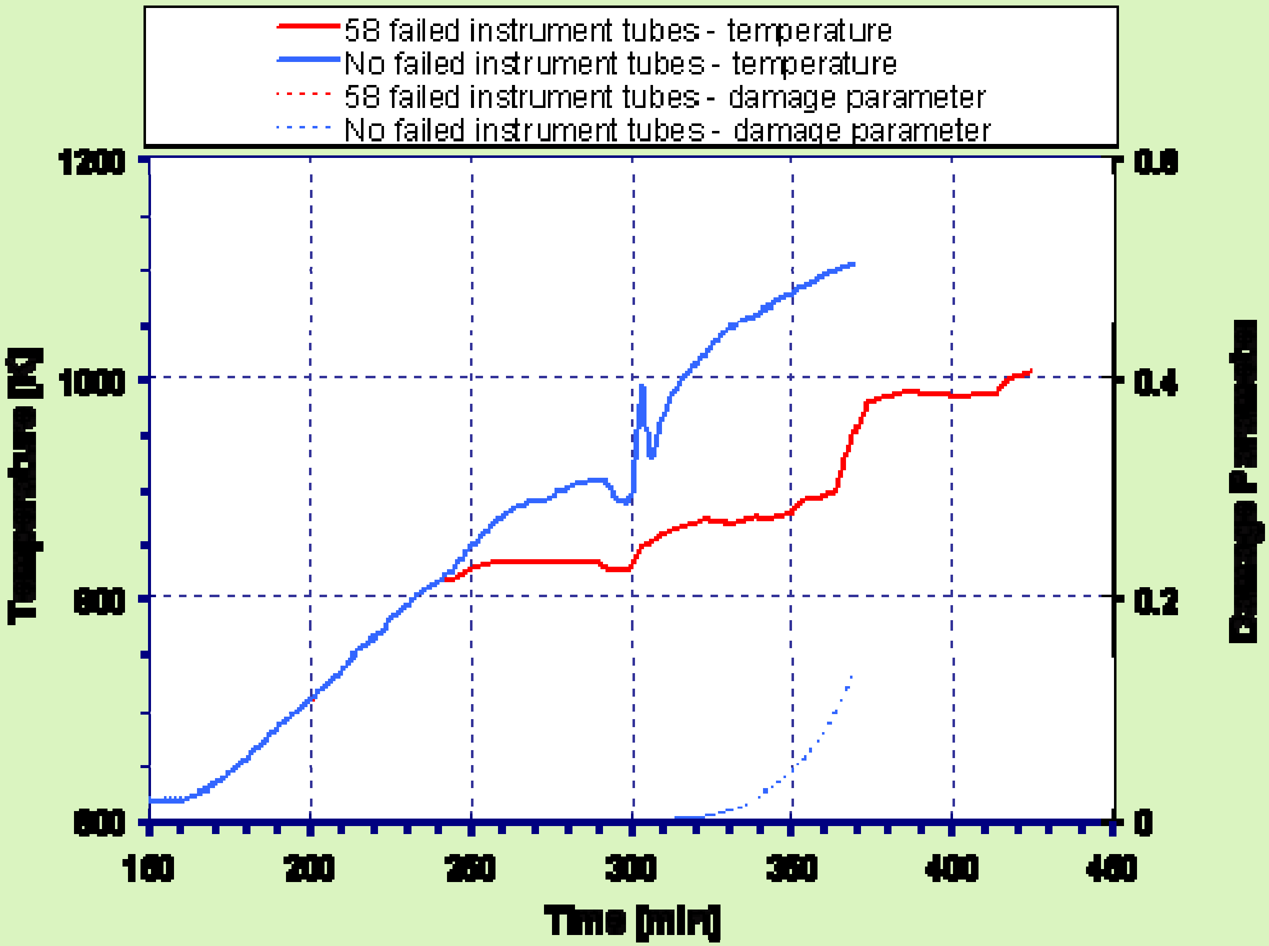
Recirculation flow rates (core-to-upper plenum)

Results (PWR with U-Tube SGs) Sensitivity to SG Secondary Pressure - Cont.



Vapor temperature at the hot leg nozzles

Results (PWR with U-Tube SGs) Sensitivity to SG Secondary Pressure - Cont.



Steam generator tube structure and damage parameter

Summary & Conclusions

- Failure of instrumentation tubes resulting in venting of steam and hydrogen to containment have a marked impact of natural circulation:
  - TMI-2 (One-through SGs)
    - Venting does not impact reactor coolant system pressure due to smaller/thinner instrumentation tubes.
    - Core-to-upper plenum recirculation generally suppressed
    - Structures (e.g., control rod guide tube) temperature lowered by as much as 100K
    - Total in-vessel hydrogen generation not significantly affected.

Summary & Conclusions - Cont

- PWR with Inverted U-Tube SGs
  - Large venting through failed instrumentation tubes sufficient to partially depressurize the reactor coolant system
  - Core-to-upper plenum recirculation suppressed significantly until the time of fuel relocation into lower plenum water and system repressurization.
  - Hot-leg to steam generator recirculation suppressed significantly (by a factor ~3) due to failure of instrument tubes
  - Temperatures of nozzles, surge line, hot leg pipe, and steam generator tubes significantly reduced (at least by as much as 500K) due to failed instrumentation tubes.
  - Failure of instrumentation tubes shifts the location of RCS failure to hot leg nozzles.

Summary & Conclusions - Cont

- Uncertainties:
  - Incipient instrumentation tube failure criterion
  - Failure location, and
  - Extent of available area for steam and hydrogen venting
  - Plugging of failed tubes due to damage progression.

- Nonetheless, over the range of parametrics, analyses show:
  - Degradation in core-to-upper plenum natural circulation is significant
  - Significant impact in terms of reduction of the potential for steam generator tube rupture for PWRs with inverted U-tubes SGs.
  - All previous studies have over estimated the likelihood of induced SGTR