framatome

DETAILS OF THE ACCIDENT PROGRESSION IN 1F1

EMUG 2019

BRAUN, Matthias

Switzerland, 3rd -5th April 2019

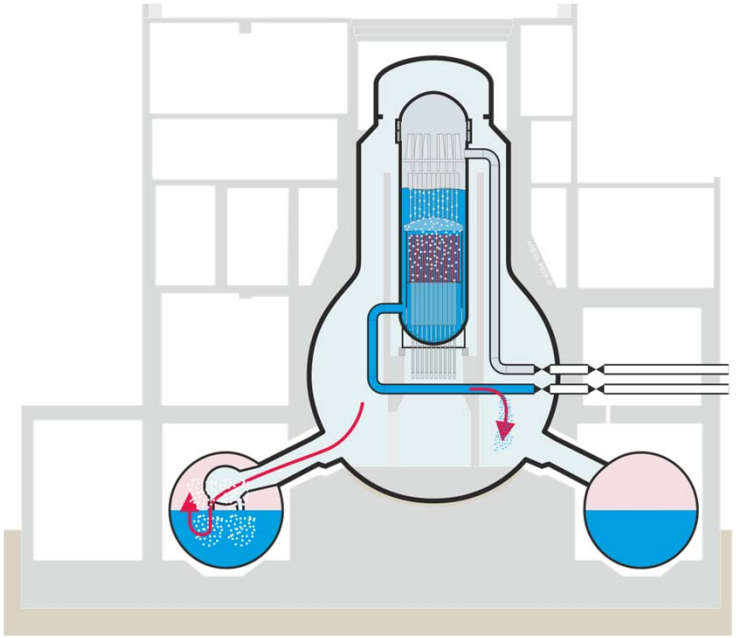
MELCOR 1.8.6 Model for 1F1

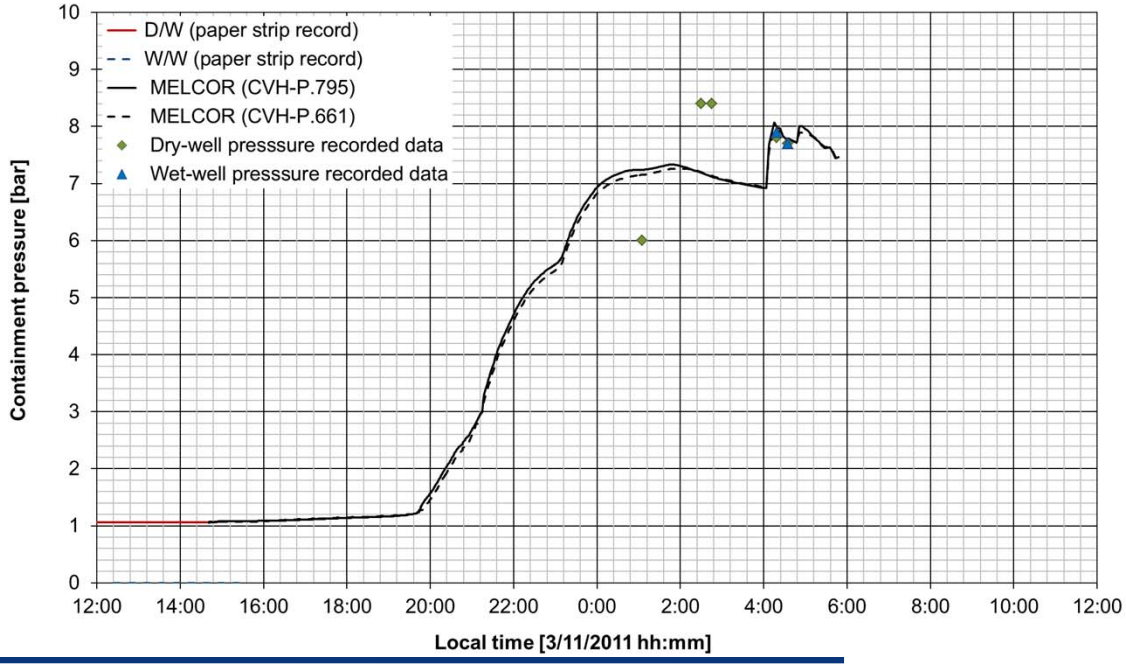
- **Not part of the BSAF OECD Benchmark Project**
  - Relying exclusively on publically available input data
  - No legal restraints for usage & publication (**project and export control**)
- **Aim is to reproduce 1F1 accident with low (minimum) number of fit parameters**
  - Prefer physical models over forced boundary conditions
  - No 1:1 correspondence to measured data desired
- **TEST MODEL – not a HOW-TO – Handle with care**
  - Alternative untested / not recommended modelling techniques
  - Test base for conversion 1.8.6 to 2.x
- **Model & description report freely distributed to MELCOR community (FGF_D02-ARV-01-111-828)**
  - **Revision B** (hardcopy) on EMUG2018
  - **Revision C** the MELCOR input model at CSARP/MCAP 2018
  - **Revision D planned end 2019**

framatome

RCS Leakage before RPV Failure? (I of II)

- **Containment pressure 6 bar-abs at 12th March 01:00**
  - Likely that RPV failure occurs afterward
  - A discharge only via open SRV into the W/W would require > 1500 kg H2 (100% core oxidation) to fill W/W and D/W
  - A steam leak in the D/W compresses N2 + H2 into the W/W requiring ~ 500-800 kg H2





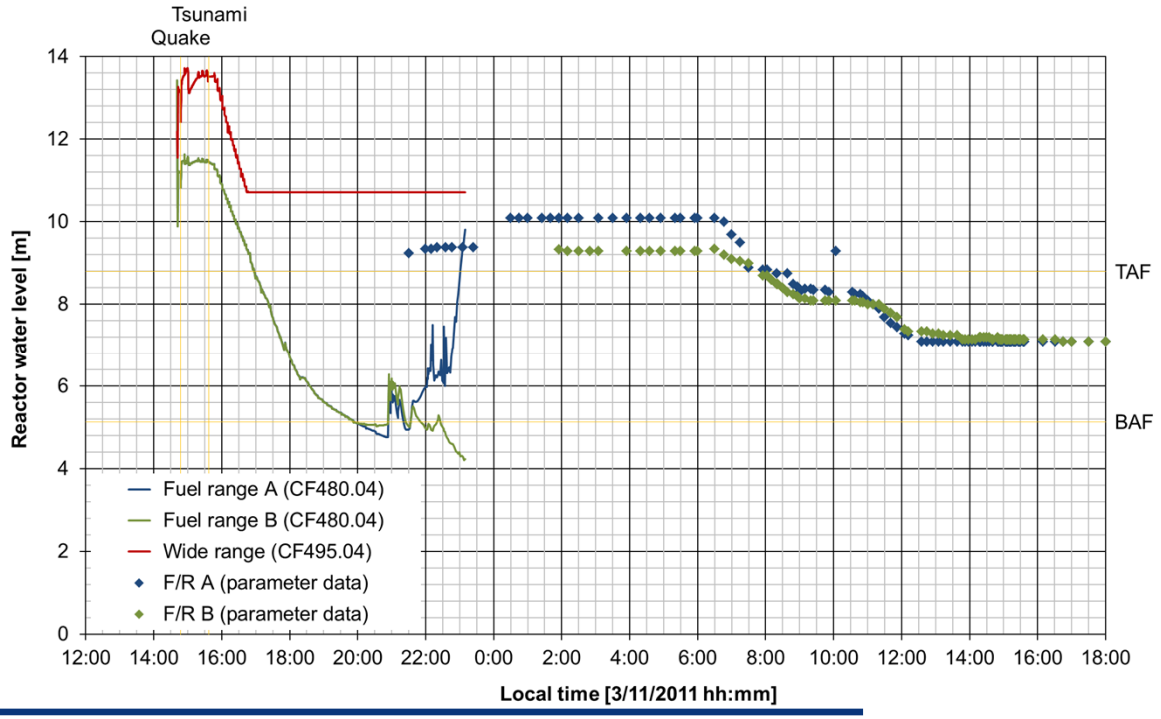
Plant Data published by TEPCO https://www4.tepco.co.jp/en/nu/fukushima-np/index10-e.html

framatome

RCS Leakage before RPV Failure? (II of II)

- **Malfunctioning of RPV water level measurement**
  - Containment heat-up via insulated RCS unlikely to be sufficient to cause this malfunctioning
  - **RCS leakage before 11th March 21:30**
  - Dry-out of upper reference line,
    and very late dry-out of lower sensing line

  -► Leak can not be too large



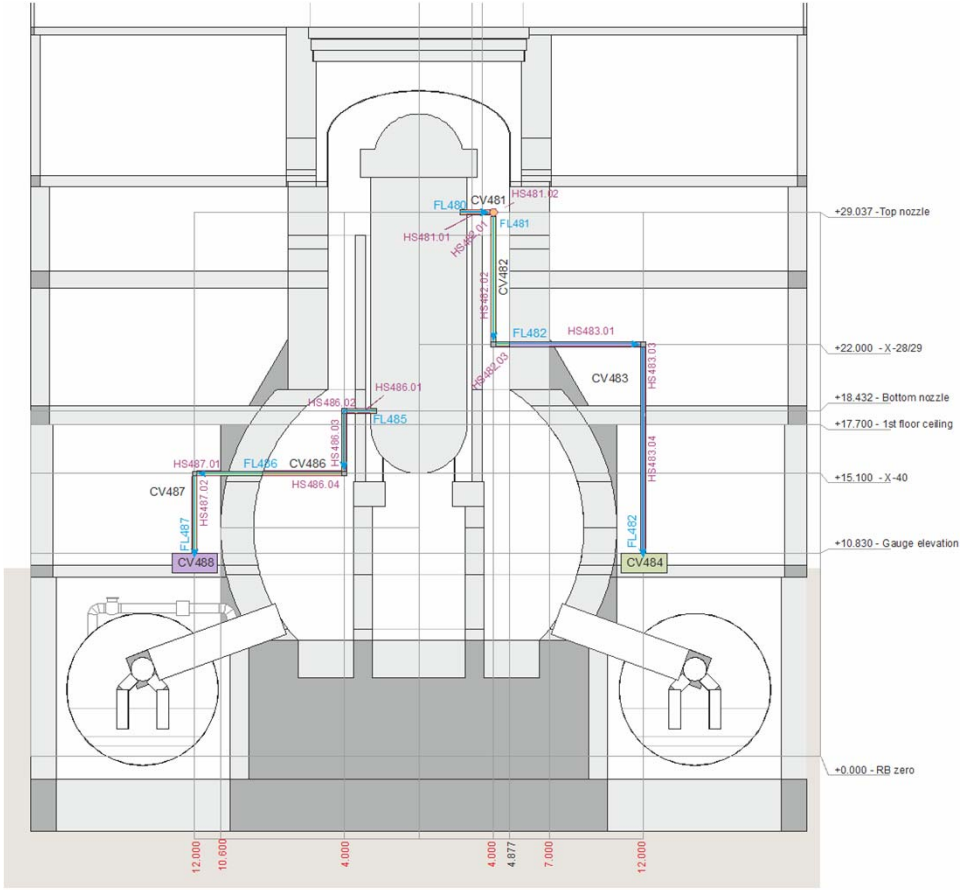
Plant Data published by TEPCO https://www4.tepco.co.jp/en/nu/fukushima-np/index10-e.html

framatome

Test Leakage Scenarios via Response of the RPV Level Measurement

- **Modelling of RPV water level measurement**
  - Generic 0.5 inch schedule 80 piping
  - No detailed information about piping routing available
  - Limited accuracy !!!!

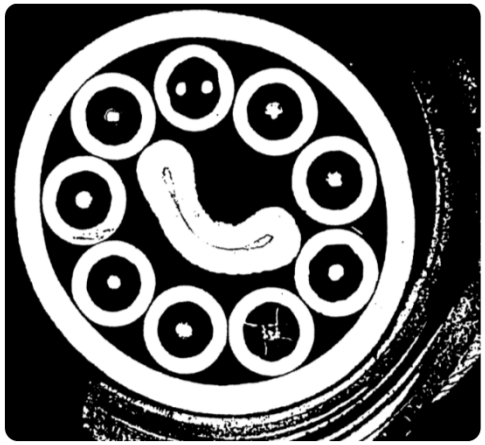
- **Complementary to**
  TEPCO 5th Progress Report Attachment 1-6
  Gothic simulation of containment
  https://www7.tepco.co.jp/newsroom/press/archives/2017/1485273_10469.html
  https://www4.tepco.co.jp/en/press/corp-com/release/betu17_e/images/171225e0213.pdf

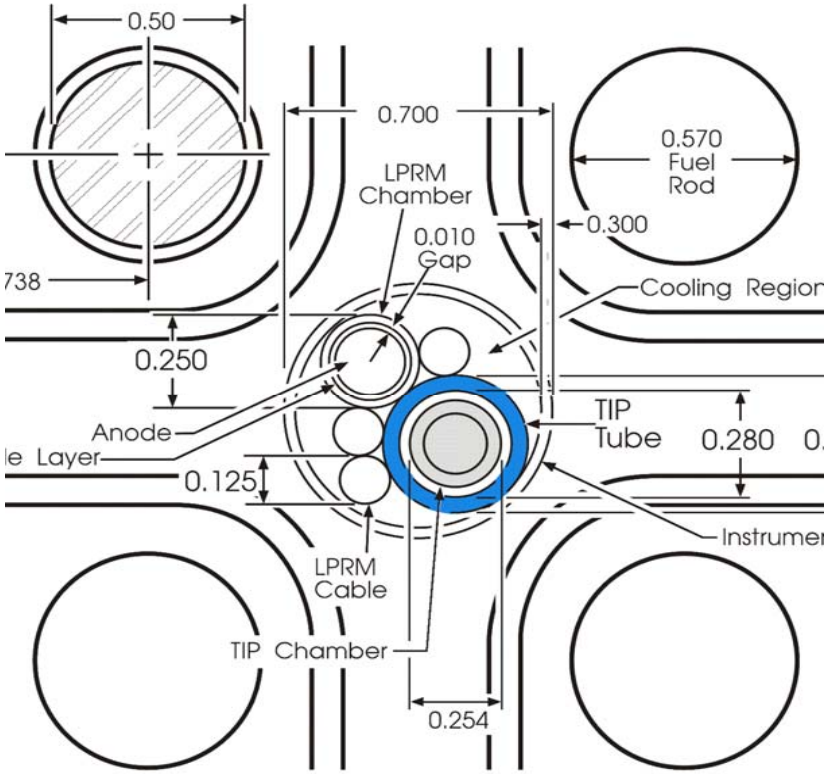


framatome

Failure of In-core Dry Tubes (I of II)

- **TIP dry tube failure?**
  - Dry tubes open to containment, reach from below into core regions
  - Free cross section of 22 lances ~9 cm^2
  - Highly likely that these dry-tubes get damaged by core overheating
  - Uncertain what real leakage cross section is



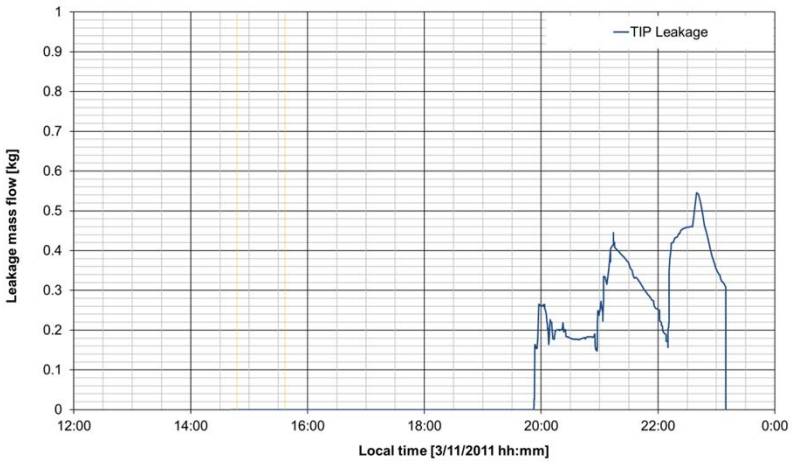


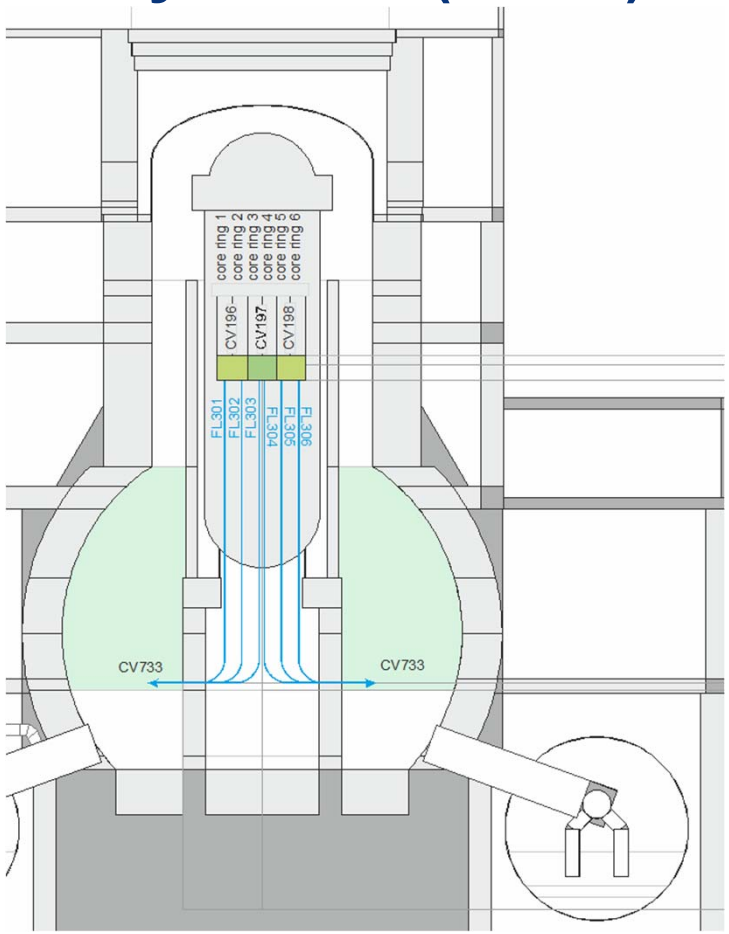
Three Mile Island Accident of Knowledge Database NUREG/KM-0001, https://www.nrc.gov/reading-rm/doc-collections/nuregs/knowledge/km0001/r1/

framatome

Failure of In-core Dry Tubes (II of II)

- **TIP dry tube failure?**
  - Dry tubes fail in ring when bypass fluid temperature > 1400°C
  - Steam leakage
  - Leakage of failed tubes: 10% of free area (bounding high assumption)
  - Pipe length ~20 m, squeezed over first 20 cm, DHYD = 0.001



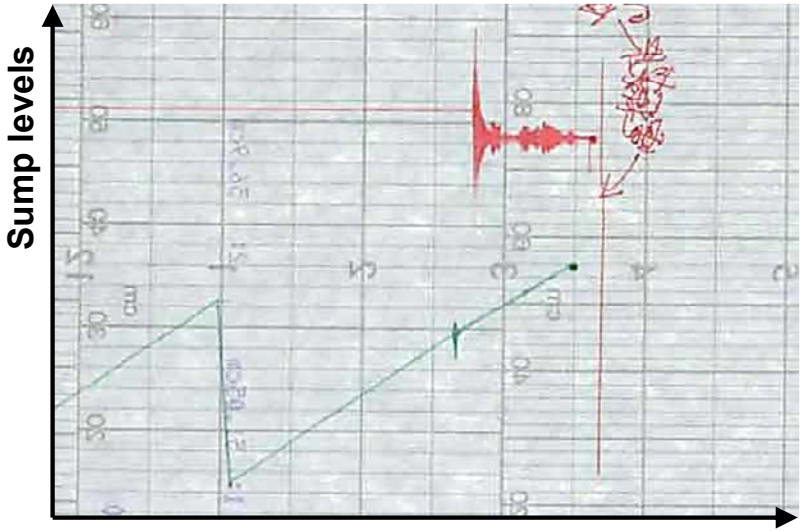


-► **Highly likely that leakage occurs, but flow is expected to be too small to cause level measurement malfunctioning**

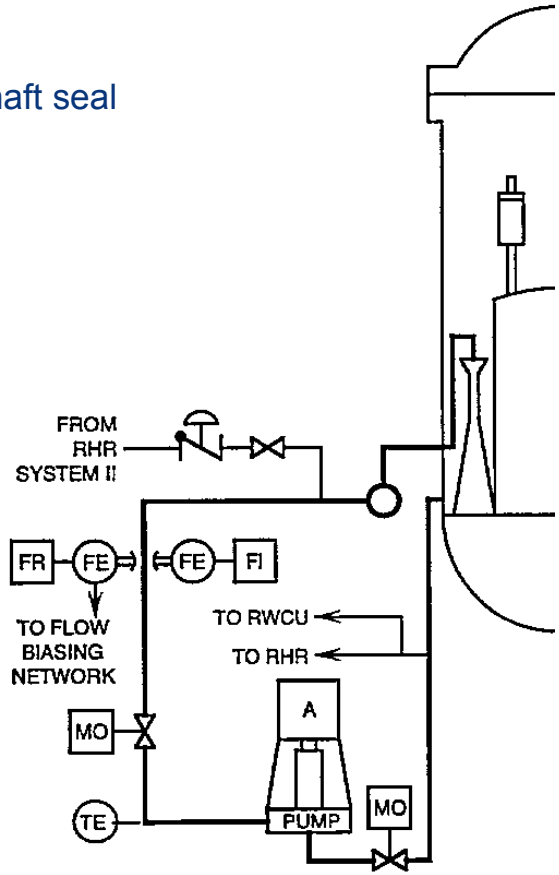
framatome

Recirculation Pump Seal Leakage (I of II)

- **Recirculation pumps seal failure?**
  - Control rod drive hydraulic system injects ~3 gpm cold water per pump into shaft seal
  - Most enter RCS, some leaks to the outside
  - Leakage low / high alarm < 0.25 / > 0.9 gpm per pump
  - 1F1 equipment sump level rise -> 0.71 gpm => 0.04 kg/s per pump



Plant Data published by TEPCO https://www4.tepco.co.jp/en/nu/fukushima-np/index10-e.html

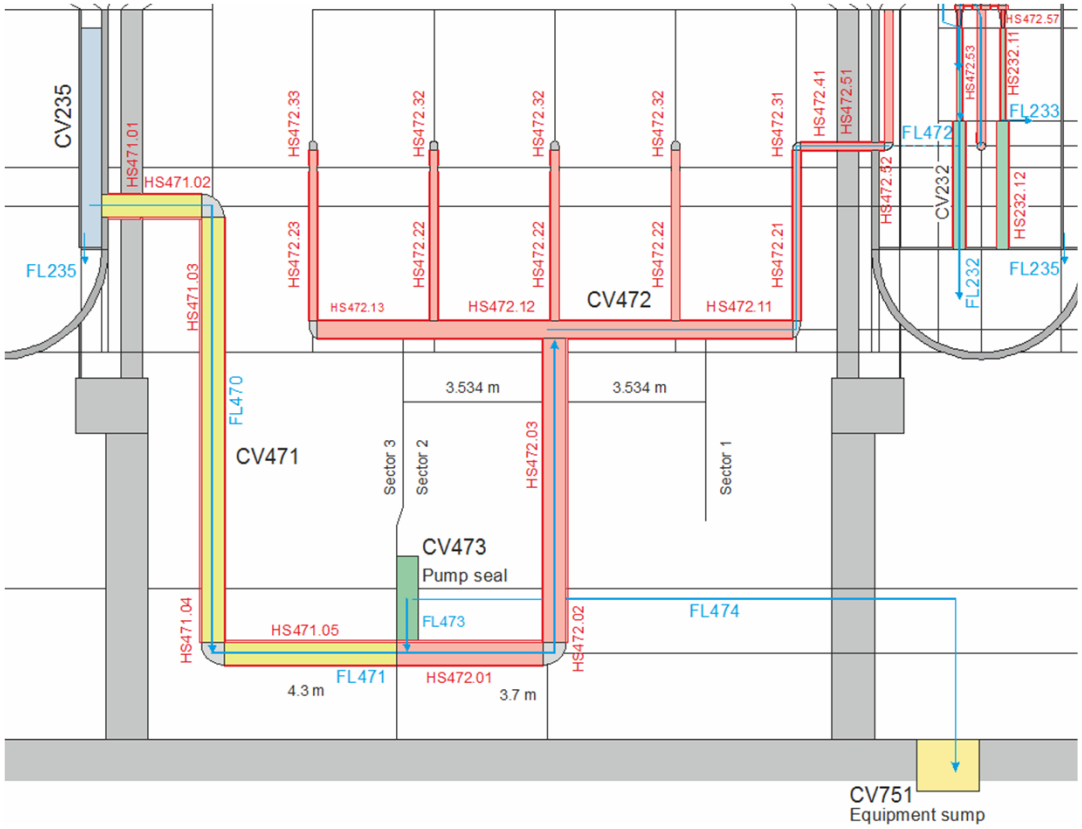


framatome

Recirculation Pump Seal Leakage (II of II)

- **In SBO condition**
  - Pump seals designed for 160°F ~71°C
  - With loss of AC power pump seal cooling stops, possibility causing thermal damage of seals
  - In SBO / overheating tests, no significant leakages were observed (NUREG/CR-4821)
  - Theoretical max. leakage 100 gpm / 6 kg/s
  - Observed operational BWR seal leakages (NUREG-1401) mostly < 10 gpm / 0.6 kg/s

- **Steam leakage would be saturated**
  - Can not cause a dry-out of the RPV liquid level measurement

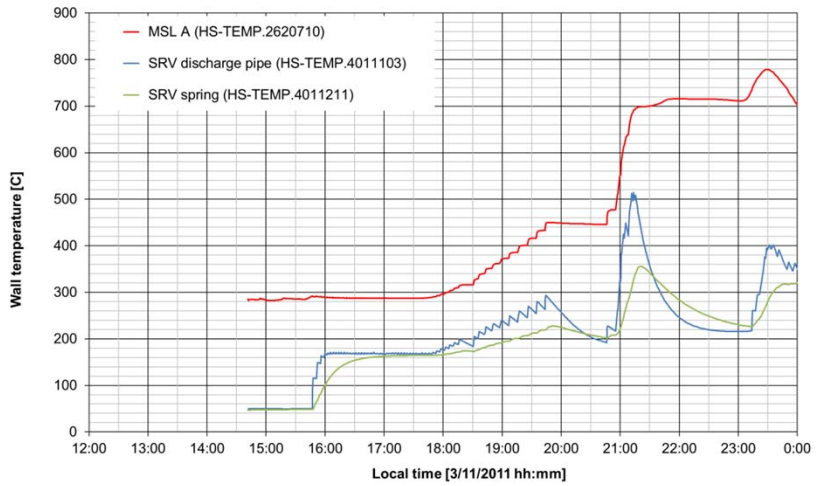


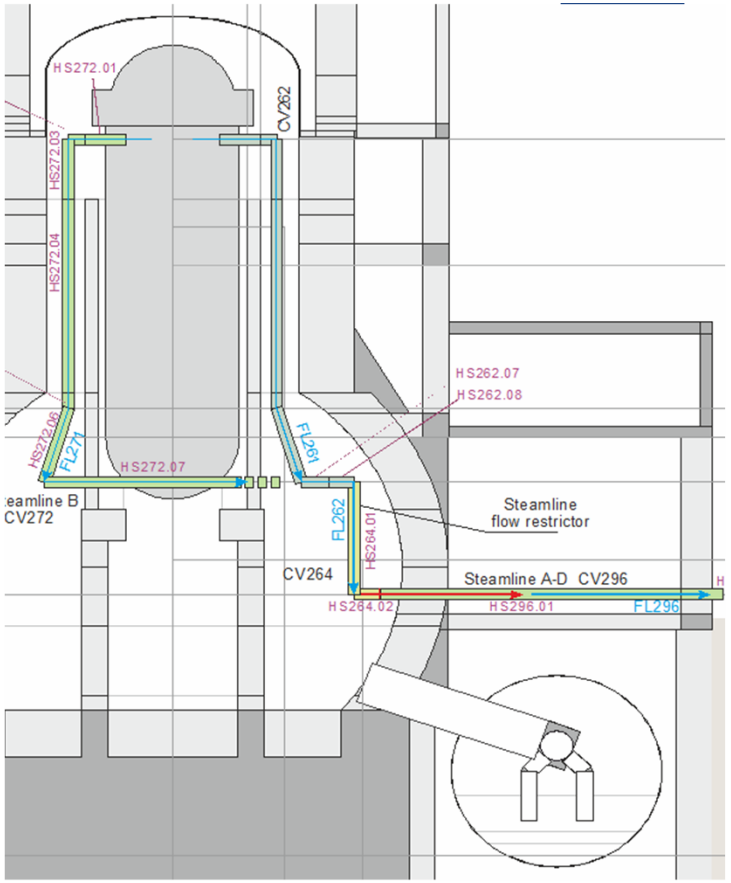
-► Increase of pump seal leakage in 1F1 appears currently unlikely, but not finally resolved, but it cant cause dry-out of level measurement lines

framatome

Creep Rupture of Main Steam Pipe (I of II)

- **Main steam lines**
  - Transports steam from RPV to turbine
  - 18 inch schedule 80 piping, thermally insulated
  - Closed off by main steam isolation valves
  - Reach ~700°C up to 21:30 on the March 11th
  - No continuous flow from RPV
    -► superheated core gas can cool in steam separator & dryer



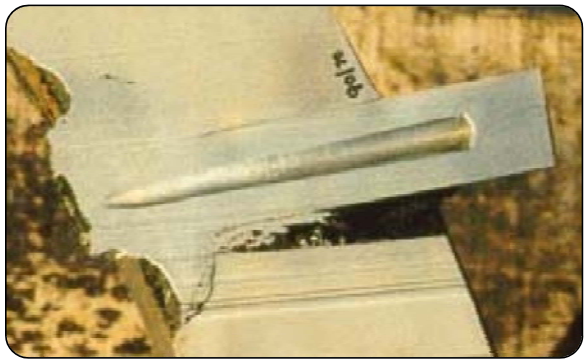


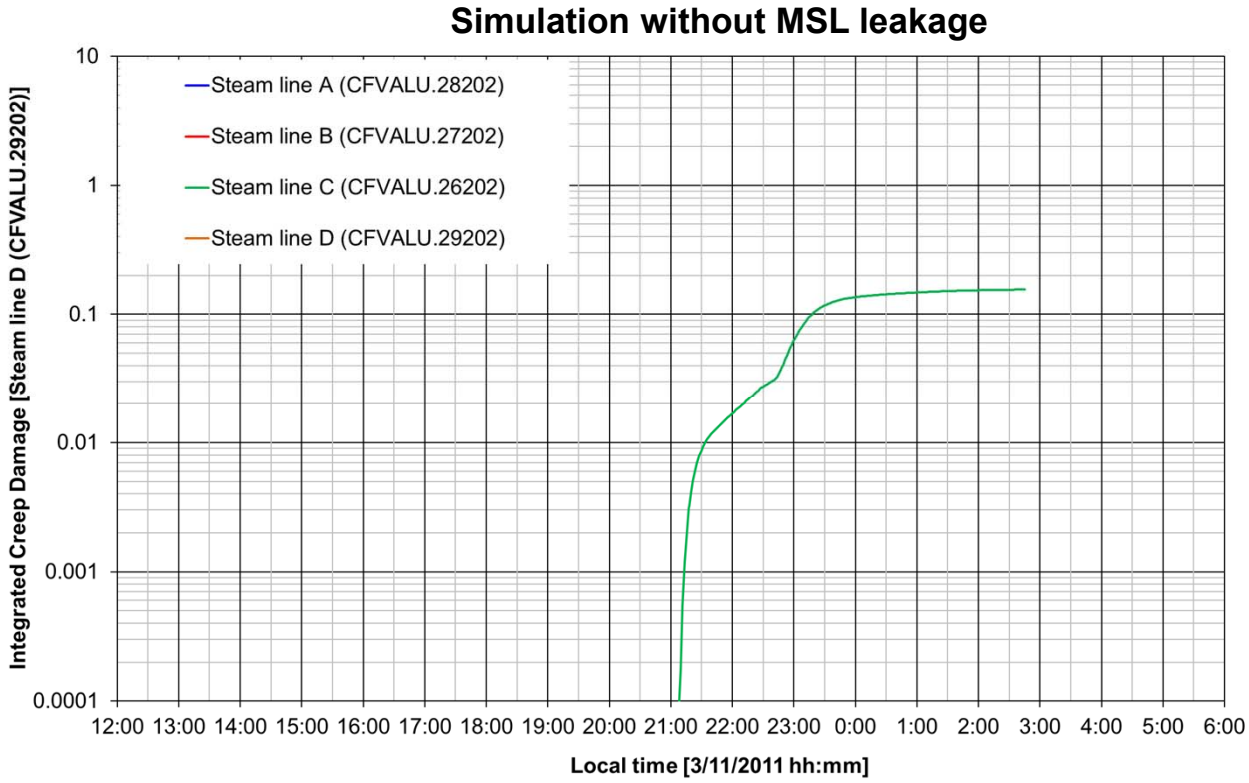
framatome

Creep Rupture of Main Steam Pipe (II of II)

- **At ~ 700°C only limited creep damage**
  - ~1% creep damage up to 21:30
  - unlikely that pipe failed that early

-► If main steam pipe failed early on, then likely not by rupturing but at measurement penetrations (compare LHF4, OLHF4) resulting in small leakage

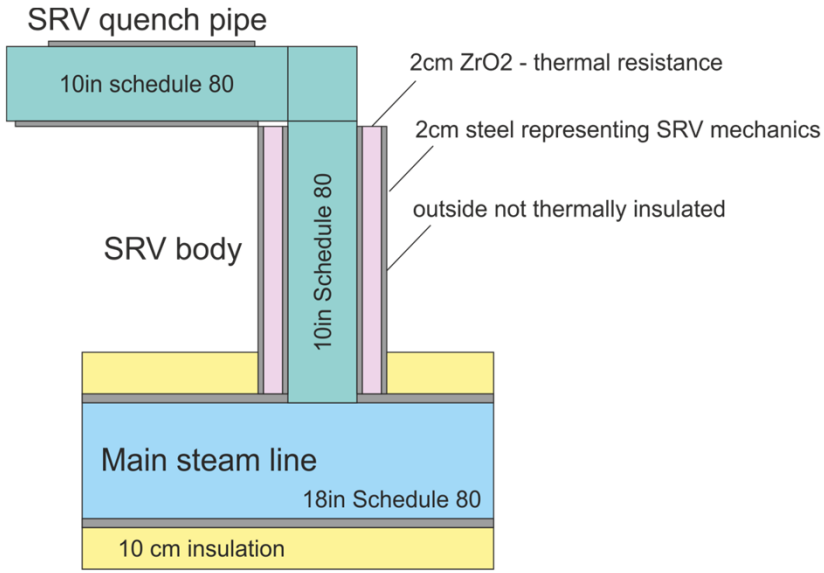




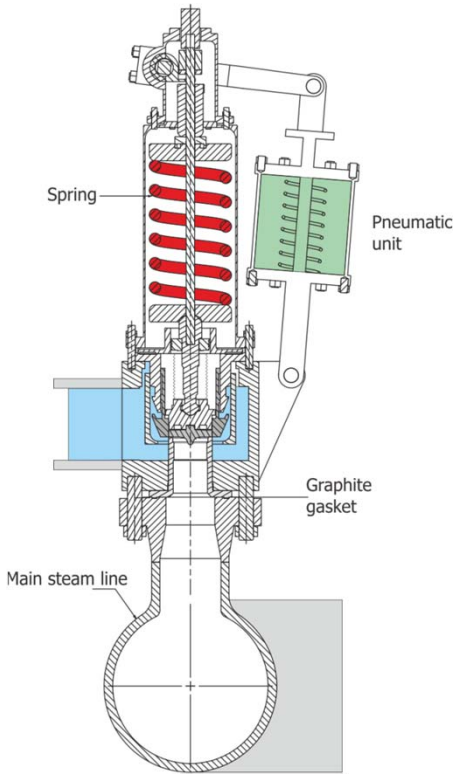
framatome

Failure of Safety Relief Valves (I of V)

- **Safety relief valves**
  - Relief function by pneumatic cylinder
  - Safety function by spring
  - Flanged with graphite gasket (design temperature 450°C)
  - Dump steam into suppression pool via 10 inch pipes



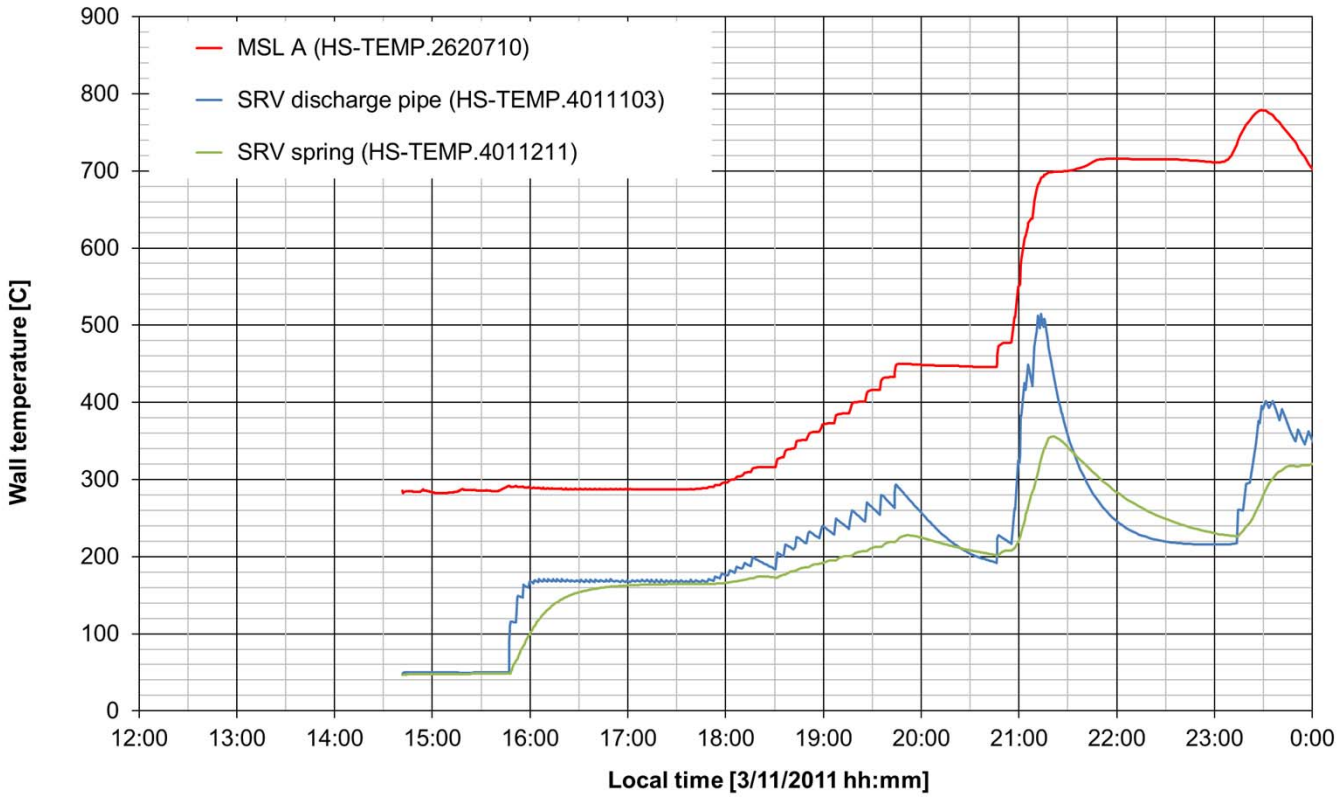
TEPCO Photo & Video Library
https://www7.tepco.co.jp/library/index-e.html



framatome

Failure of Safety Relief Valves (II of V)

- **Simulation temperatures**
  - SRV body shortly above 500°C
  - SRV mechanics cooler ~200°C up to 20:00
- **Why so "low" temperatures**
  - Non-insulated -► heat loss to PCV
  - No continuous flow from RPV -► superheated core gas can cool in steam separator & dryer

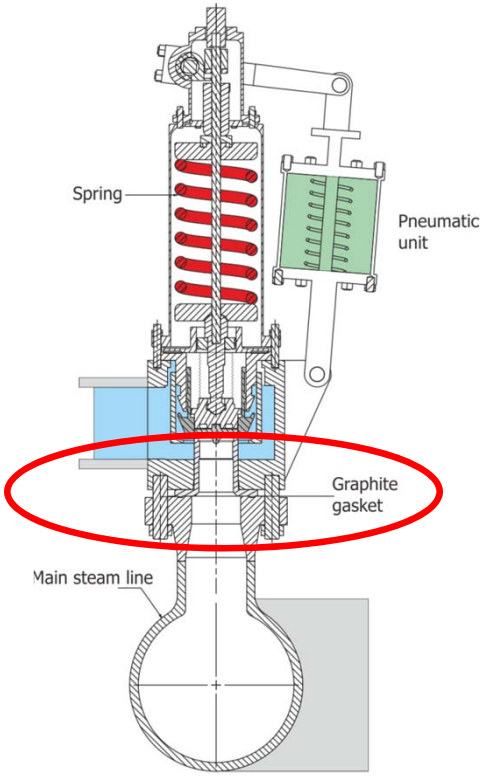


framatome

Failure of Safety Relief Valves (III of V)

- **SRV gasket failure?**
  - In simulation, SRV temperature (450°C) exceeded for < 15 min
  - **Exceeding the design does not mean failure**
  - > 700°C graphite gets oxidized (slowly) by steam

-► Highly unlikely that SRV gasket started leaking



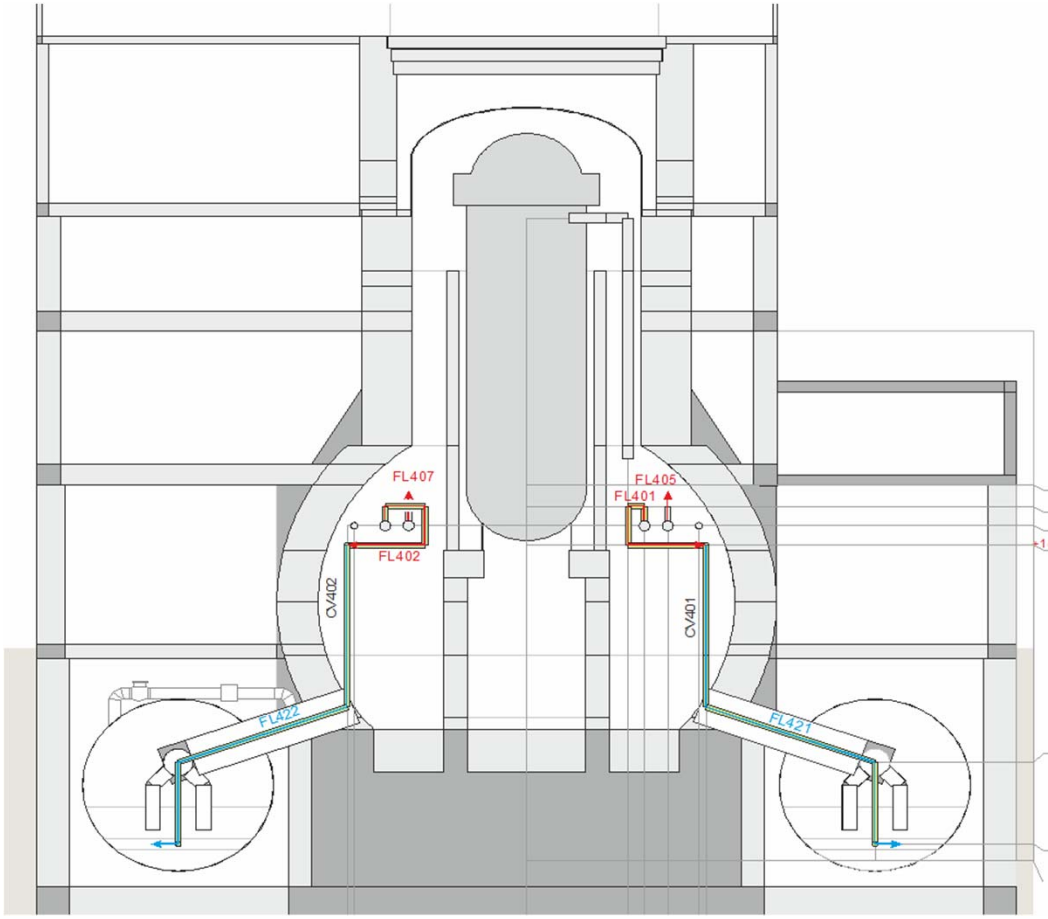
GRAFOIL® Flexible Graphite Engineering Design Manual
In gasketing conditions, the 975°F (525°C) temperature should not be considered a maximum use temperature in air but merely a "caution flag" that requires further examination of the operation. The thin-edge exposure of GRAFOIL packings and gaskets has successfully withstood extended periods of exposure to air at process fluid temperatures up to 1500°F (815°C).

framatome

Failure of Safety Relief Valves (IV of V)

- **SRV stuck-open?**
  - In simulation, SRV body > 450°C for < 15 min
  - Design exceeding, but probably able to stand heat load
  - Stuck-open failure would not lead to a heat-up of the PCV atmosphere
  - Inconsistent to high containment pressure

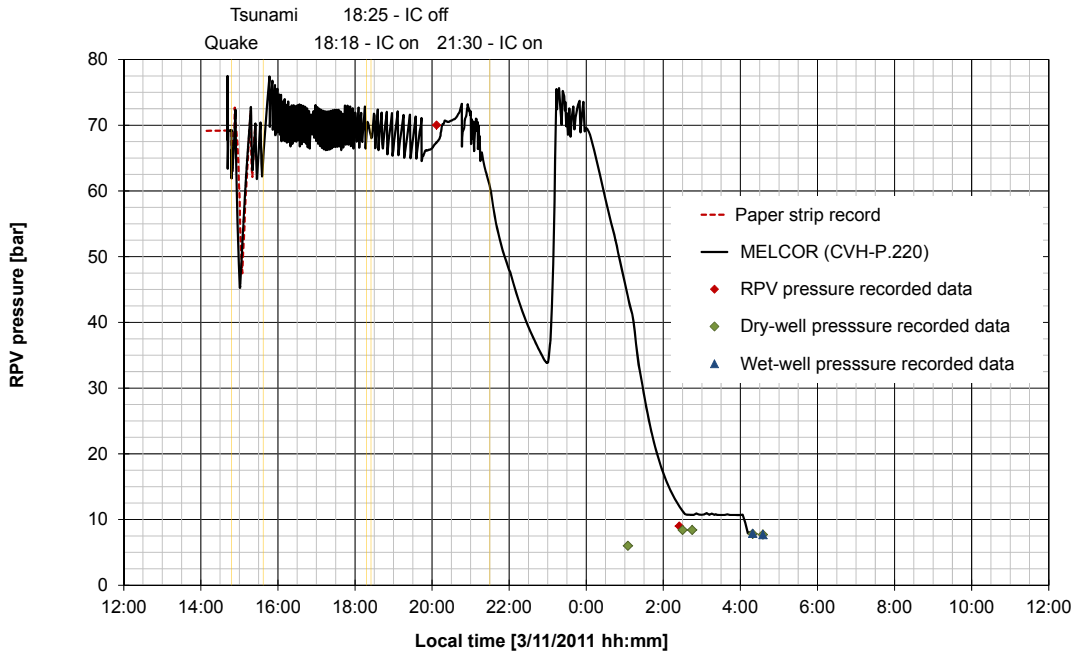
-► Appears unlikely that SRV failed in open position



framatome

Failure of Safety Relief Valves (V of V)

- **Shift of actuation pressure?**
  - Relief function open **72.7** barg / close **69.7** barg relative to environment
  - Safety function open **76.4** barg / close **68.8** barg relative to containment (PCV) atmosphere
  - Pressure measurement at 20:07 **69** barg
  - Measured pressure just at the lower edge of the SRV safety opening band (possible but unlikely)
  - When pressure is kept via safety valves, PCV pressure causes rise in RPV pressure
  - Safety function defined by steel spring
  - Heat-up reduces steel Youngs module ~ 4%/100K
  - RPV spring temperature 150°C -> 250°C -> SRV set-points ~73 barg and 66 barg



-► Likely that heat-up of SRV body caused slight decrease in actuation pressure

framatome

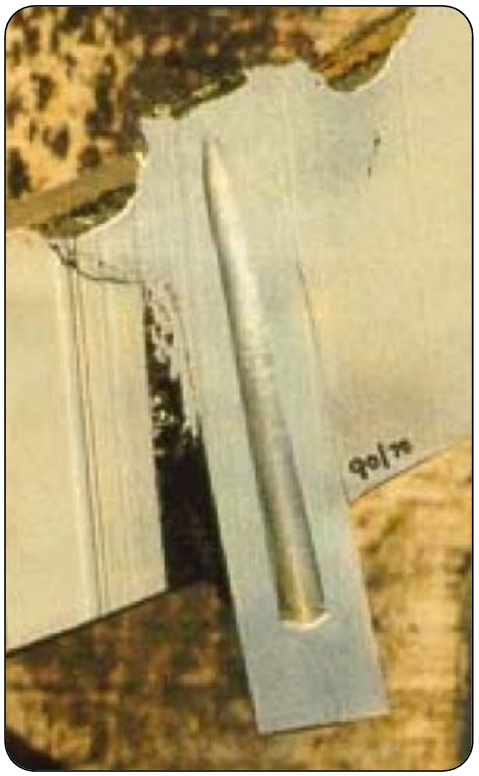
Summary (I of II)

- **Indications for RCS failure long before RPV failure**
  - Malfunctioning of the RPV liquid level measurement at March 11th 21:30
  - Containment pressure buildup to 6 bar-abs at 12th March 01:00, thus before RPV failure was likely
- **Damage to the TIP dry tubes**
  - Highly likely that damage occurred as these pipes reach within the core
  - Unknown cross section after squeezing flat
  - TIP failure alone cannot explain the faulty level measurement
- **Failure of the pump seals**
  - Currently appears unlikely, but inconclusive
  - Releases steam < 180°C, can contribute to pressure buildup, but not to dry-out of RPV level sensing lines
- **Failure of the SRV graphite gaskets**
  - Occurrence is highly unlikely due to temperature resistance of gaskets

framatome

Summary (II of II)

- **Failure of SRV in open position**
  - More unlikely as no extremely high temperature loads
  - No indications of this occurrence in the containment response
  - A fail-open would not lead to the observed liquid level measurement failure
- **Large Rupture of main steam line due to creep**
  - Appears unlikely, especially in the early stages
  - Can not explain the liquid level measurement failure at 21:30
- **Most Likely: Instrumentation penetration failure of the main steam line**
  - Small leakage of few cm^2 sufficient to cause level measurement failure when failure location in the upper containment
  - Consistent scenario with the TEPCO Gothic analysis
- **Additionally: Shift of the SRV pressure set-points due to heat-up**
  - Can explain the 69 bar RPV pressure measurement at 20:07
  - Will not lead to a substantial depressurization of the RCS, not to level malfunctioning and not to containment pressure rise



OECD Lower Head Failure Project
https://www.oecd-nea.org/nsd/docs/2002/csni-r2002-27.pdf

framatome

framatome

Thank you!