**REDUCTION OF RADIOLOGICAL ACCIDENT CONSEQUENCES**

| | |
|---|---|
| Title: | **Re-evaluation of cladding failure criteria in LOCA within H2020 project** |
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| Affiliation: | VTT Technical Research Centre of Finland Ltd |
| Event: | SYP 2022 |
| When: | 02 November 2022 |
| Where: | Helsinki, Finland |

Commission européenne

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# Outline

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- R2CA project
- Implementation of new burst criteria in U.S.NRC's FRAPTRAN code
- Modification of FRAPTRAN's mechanical models
  - Phase transition
  - High-temperature creep laws
  - Burst criteria
- Results of LOCA validation matrix re-simulation
- Application of modifications to EPR LB-LOCA

# R2CA Project

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- The Reduction of Radiological Consequences of design basis and extension Accidents (R2CA) is an EU H2020 project coordinated by IRSN running from 2019 to 2023. The project is mainly funded by the European Commission, brings together 17 different organizations based in 12 countries.

- The aim of the R2CA project is to develop new calculation methodologies and updated computer codes in order to produce more realistic evaluations of radioactive releases resulting from such accidents.

- The purpose of VTT study is to improve the evaluation of the number of failing fuel rods in a whole core during the LOCA transient.

# Implementing IRSN's new burst criteria

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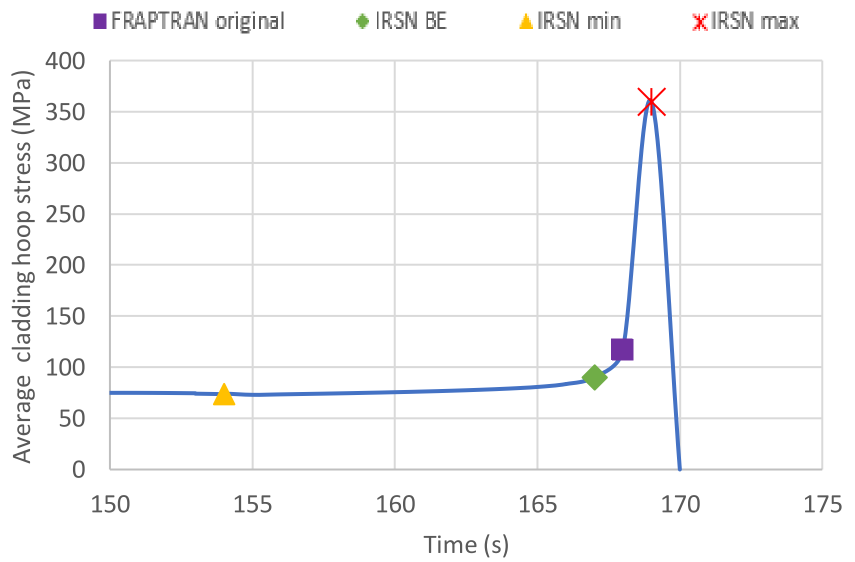
- Work was started by implementing new cladding burst criteria developed by IRSN
- 7 FRAPTRAN LOCA validation cases were simulated to compare the effect of implemented correlations (IRSN best estimate, min, max)
- Results showed that the code predictions (e.g., failure time) are not so sensitive in terms of failure criteria when the cladding hoop stress starts to increase exponentially

→ Update of cladding mechanical models

| | Time to failure (s) | | | | |
|---|---|---|---|---|---|
| Test | FRAPTRAN original | IRSN BE | IRSN min | IRSN max | Measured value |
| IFA-650.5 | 169 | 168 | 155 | 169 | 179 s |
| IFA-650.6 | 423 | 419 | 359 | 425 | 525 s |
| IFA-650.7 | 152 | 152 | 145 | 152 | 247 s |
| TREAT rod 16 and 17 | 26,4 | 26,4 | 26,3 | 26,4 | 30.3-37.5 |
| LOC-11C rod 3 | No Failure | No Failure | No Failure | No Failure | No Failure |
| LOC-11C rod 2 | 14,4 | 14,4 | 10,8 | 14,4 | No Failure |
| LOC-11C rods 1 and 4 | No Failure | No Failure | No Failure | No Failure | No Failure |

*FRAPTRAN LOCA validation matrix results with various failure criteria*




*Hoop stress during LOCA IFA-650.5*

# New models and criteria from open literature

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- New models have been implemented in FRAPTRAN for Zry-4 and Zr-1%Nb claddings
- Updated models for Zr-1%Nb are utilised in EPR simulation with M5 cladding

☑ A phase transformation model by Massih, 2009[1]

☑ Two separate high temperature creep models Kaddour et al, 2004[2] and Rosinger, 1984[3]

☑ Two new burst criteria:

- A new temperature burst limit by Meyer and Wiesenack 2022[4]
- Optimized Rosinger best estimate stress limit by Quantum Technologies 2021[5]

☑ The new models for phase transition and creep, and the burst limits have been verified by re-simulating the FRAPTRAN LOCA validation matrix

COMPLETED

# Code modifications: Mechanical deformation



- The modifications were implemented in *cstrni* subroutine that is used by the mechanical model *FRACAS-I* under open gap condition and *BALON2* model. This subroutine is relevant for high strain rates conditions.

- Plastic strain has been replaced by a high temperature creep law which is used in combination with the phase transformation model to calculate the strain rate according to equations (1) and (2).

$$\dot{\varepsilon} = \frac{A}{T}\sigma^{n}\exp\left(-\frac{Q}{RT}\right) \qquad (1)$$

Parameters (A, Q, n) in the alpha and beta phase are provided by (Kaddour et al, 2004) for both Zy-4 and Zr-1%Nb claddings, and only for Zry-4 claddings in (Rosinger, 1984) model

- In the mixed phase region (alpha + beta), linear interpolation is used:

$$\dot{\varepsilon}_{\alpha\beta} = \dot{\varepsilon}_{\alpha}(1-y) + \dot{\varepsilon}_{\beta}y \qquad (2)$$

# Code modifications: Phase transformation



- Massih (2009) phase transformation model was implemented in FRAPTRAN. The model solves the differential equation (3) to obtain the volume fraction of cladding beta phase $y$ after the onset temperature

$$\frac{dy}{dt} = k(T)[y_s(T) - y] \qquad (3)$$

$k(T)$ is the rate parameter, $y_s$ is the equilibrium b-phase volume fraction

- The onset temperature for the phase transition is a function of temperature and hydrogen content
  - For example: Zircaloy-4 under heating conditions:

$$T_{\alpha\to\alpha+\beta} = \begin{cases} 1083 - 0.152w & \text{for } 0 \leqslant Q < 0.1\text{K/s} \\ (1113 - 0.156w)Q^{0.0118} & \text{for } 0.1 \leqslant Q \leqslant 100\text{K/s} \end{cases} \qquad (4)$$

$Q$ is the heating rate and $w$ is the hydrogen content in wppm (weight parts per million)

# Implemented burst criteria from open literature

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## ❑ Temperature limit by Meyer and Wiesenack (2022):

$$T_{burst} = 1385\sigma^{-0.129} - 0.0057H^{1.49} + 1.845R - 29$$

T is temperature in [°C], σ is hoop stress [N/mm$^2$], H is hydrogen content [wppm], and R is the heating rate in [°C/s]

## ❑ Optimized Rosinger best estimate stress limit by Quantum Technologies (2021):

$$\sigma_{burst} = A_b e^{-B_b T} e^{-\left(\frac{x_{Met}}{C_b}\right)^2}$$

$x_{Met}$ is the cladding metal excess oxygen concentration; this parameter is calculated by the oxidation model

| Temperature region (K) | $A_b$ (Pa) | $B_b$ $(K^{-1})$ | $C_b$ |
|---|---|---|---|
| 873 to 1075 | $7.3757 \times 10^{10}$ | $5.9298 \times 10^{-3}$ | $5.888 \times 10^{-4}$ |
| 1075 to 1250 | $5.1513 \times 10^{12}$ | $9.8798 \times 10^{-3}$ | $5.888 \times 10^{-4}$ |
| 1250 to 1873 | $2.3301 \times 10^{7}$ | $3.4814 \times 10^{-5}$ | $5.888 \times 10^{-4}$ |

This burst limit was tested with Rosinger (1984) creep model since the limit was developed from the same experimental data

# Calculations results: FRAPTRAN original deformation model

| | FRAPTRAN original plastic strain model | | | | | | |
|---|---|---|---|---|---|---|---|
| Burst failure criterion / **Test** Parameters | **FRAPTRAN original burst criteria (stress +strain)** | **IRSN BE** | **IRSN min** | **IRSN max** | **Temperature limit (Meyer 2022)** | **Failure trigger in FRAPTRAN original** | **Measured value** |
| **IFA-650.5** | | | | | | Stress limit | |
| Time to cladding rupture (s) | **169** | **168** | **155** | **169** | **166** | | **179** |
| Burst Temperature (K) | 1005 | 1001 | 954 | 1005 | 994 | | 1023 |
| Max hoop strain % | 30 | 23 | 5 | 32 | 11 | | 16 % |
| Rod pressure (MPa) | 10.2 | 10.6 | 10.6 | 10.2 | 10.8 | | |
| **IFA-650.6** | | | | | | Stress limit | |
| Time to cladding rupture (s) | **423** | **419** | **359** | **425** | **419** | | **525** |
| Burst Temperature (K) | 1069 | 1067 | 1020 | 1071 | 1067 | | 1103 |
| Max hoop strain % | 38 | 29 | 5 | 40 | 29 | | 36 % |
| Rod pressure (MPa) | 8.3 | 8.6 | 8.4 | 8.3 | 8.6 | | |
| **IFA-650.7** | | | | | | Stress limit | |
| Time to cladding rupture (s) | **152** | **152** | **145** | **152** | **152** | | **247** |
| Burst Temperature (K) | 1221 | 1221 | 1197.2 | 1221 | 1221 | | 1373 |
| Max hoop strain % | 36 | 35.7 | 5 | 35.7 | 36 | | 24 % |
| Rod pressure (MPa) | 1.98 | | 2.1 | | 1.98 | | |
| **TREAT rod 16 and 17** | | | | | | Strain limit | |
| Time to cladding rupture (s) | 26.4 | 26.4 | 26.3 | 26.4 | 26.5 | | 30.3-37.5 |
| Burst Temperature (K) | 1263.5 | | | | 1260.8 | | 1478 to 1589 |
| Max hoop strain % | 68.6 | 117 | 9.6 | 248 | 99606 | | 58 % and 33 % |
| Rod pressure (MPa) | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | | |
| **LOC-11C rod 3** | No Failure | No Failure | No Failure | No Failure | No failure | N/A | No Failure |
| **LOC-11C rod 2** | | | | | | Strain limit | No Failure |
| Time to cladding rupture (s) | 14.4 | 14.4 | 10.8 | 14.4 | 14.4 | | |
| Burst Temperature (K) | 1017.7 | 1017.7 | 973.4 | 1017.7 | 1017.7 | | |
| Max hoop strain % | 90.4 | 38.156 | 5 | 1954 | 1960.9 | | |
| Rod pressure (MPa) | 8.4 | 8.4 | 11.3 | 8.4 | 8.4 | | |
| **LOC-11C rods 1 and 4** | No Failure | No Failure | No Failure | No Failure | No failure | N/A | No Failure |

In terms of failure time, FRAPTRAN orig, IRSN BE and IRSN max have similar results

***Note!*** FRAPTRAN strain limit was **enabled** in these simulations

# Calculations results:
# Phase transformation + Kaddour et al. (2004) creep model



| Test / Parameters (Burst failure criterion) | Phase transition + Kaddour et al 2004 creep model Zy-4 and Zr1NbO | | | | | |
|---|---|---|---|---|---|---|
| | **FRAPTRAN original stress limit** | **IRSN BE** | **IRSN min** | **IRSN max** | **Temperature limit (Meyer 2022)** | **Measured value** |
| **IFA-650.5** | | | | | | |
| Time to cladding rupture (s) | **184** | **182** | **166** | **184** | **167** | **179** |
| Burst Temperature (K) | 1057 | 1048 | 994 | 1054 | 998 | 1023 |
| Max hoop strain % | 32 | 22 | 5 | 32 | 5 | 16 % |
| Rod pressure (MPa) | 10.5 | | | | | |
| **IFA-650.6** | | | | | | |
| Time to cladding rupture (s) | **453** | **453** | **371** | **455** | **431** | **525** |
| Burst Temperature (K) | 1087 | 1087 | 1032 | 1087 | 1074 | 1103 |
| Max hoop strain % | 31 | 31 | 5 | 40 | 15 | 36 % |
| Rod pressure (MPa) | 8.837 | | | | | |
| **IFA-650.7** | | | | | | |
| Time to cladding rupture (s) | **175** | **175** | **173** | **175** | **156** | **247** |
| Burst Temperature (K) | 1298 | 1298 | 1292 | 1298 | 1234 | 1373 |
| Max hoop strain % | 31 | 36 | 5 | 36 | 36 | 24 % |
| Rod pressure (MPa) | 2.2 | | | | | |
| **TREAT rod 16 and 17** | | | | | | |
| Time to cladding rupture (s) | **46.5** | **45.5** | **45.5** | **46** | **29** | 30.3-37.5 |
| Burst Temperature (K) | 1601 | 1528 | | 1602 | 1369 | 1478 to 1589 |
| Max hoop strain % | 80.2 | 5 | 5 | 9 | 104 | 58 % and 33 % |
| Rod pressure (MPa) | 0.80 | | | | | |
| **LOC-11C rod 3** | No failure | No failure | No failure | No failure | No Failure | No Failure |
| **LOC-11C rod 2** | | | | | | |
| Time to cladding rupture (s) | | | **14.2** | | | |
| Burst Temperature (K) | No failure | No failure | 1015 | No failure | No failure | No Failure |
| Max hoop strain % | | | 5 | | | |
| Rod pressure (MPa) | | | | | | |
| **LOC-11C rods 1 and 4** | No failure | No failure | No failure | No failure | No failure | No Failure |

In terms of failure time, FRAPTRAN orig, IRSN BE and IRSN max have similar results

***Note!***
FRAPTRAN strain limit was **disabled** in these simulations

# Calculations results:
# Phase transformation + Rosinger (1984) creep model



| | Phase transition + Rosinger 1984 creep model<br>Zy-4 | | | | | | |
|---|---|---|---|---|---|---|---|
| Burst failure criterion<br>**Test**<br>Parameters | **FRAPTRAN original stress limit** | **SSM Zy-4 burst criterion 2021** | **IRSN BE** | **IRSN min** | **IRSN max** | **Temperature limit (Meyer 2022)** | **Measured value** |
| **IFA-650.5**<br>Time to cladding rupture (s)<br>Burst Temperature (K)<br>Max hoop strain %<br>Rod pressure (MPa) | **223**<br>1160.5<br>31.5 | **207**<br>1122<br>5<br>12.5 | **207**<br>1122<br>**5** | **207**<br>1122<br>5 | **223**<br>1160.5<br>31.5 | **207**<br>1122<br>5 | **179**<br>1023<br>16 % |
| **IFA-650.6**<br>Time to cladding rupture (s)<br>Burst Temperature (K)<br>Max hoop strain %<br>Rod pressure (MPa) | N/A | N/A | N/A | N/A | N/A | N/A | **525**<br>1103<br>36 % |
| **IFA-650.7**<br>Time to cladding rupture (s)<br>Burst Temperature (K)<br>Max hoop strain %<br>Rod pressure (MPa) | No failure | No failure | No failure | No failure | No failure | **248**<br>1391<br>5 | **247**<br>1373<br>24 % |
| **TREAT rod 16 and 17**<br>Time to cladding rupture (s)<br>Burst Temperature (K)<br>Max hoop strain %<br>Rod pressure (MPa) | No failure | No failure | No failure | No failure | No failure | No failure | 30.3-37.5<br>1478 to 1589<br>58 % and 33 % |
| **LOC-11C rod 3** | No failure | No failure | No failure | No failure | No failure | No failure | No Failure |
| **LOC-11C rod 2**<br>Time to cladding rupture (s)<br>Burst Temperature (K)<br>Max hoop strain %<br>Rod pressure (MPa) | No failure | No failure | No failure | No failure | No failure | No failure | No Failure |
| **LOC-11C rods 1 and 4** | No failure | No failure | No failure | No failure | No failure | No failure | No Failure |

False non-failures were predicted

***Note!***
FRAPTRAN strain limit was **disabled** in these simulations

# Calculations results: Time to burst

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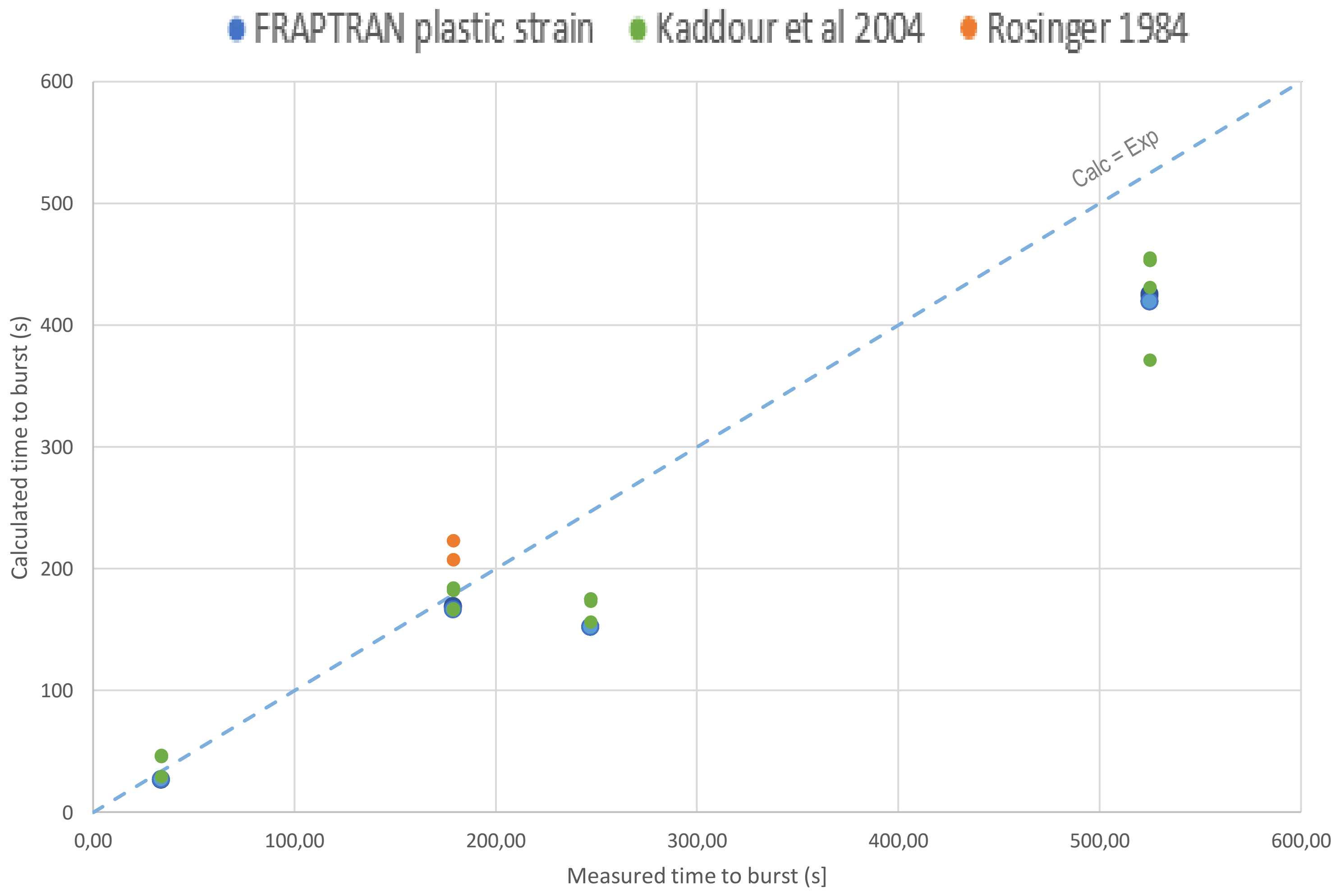
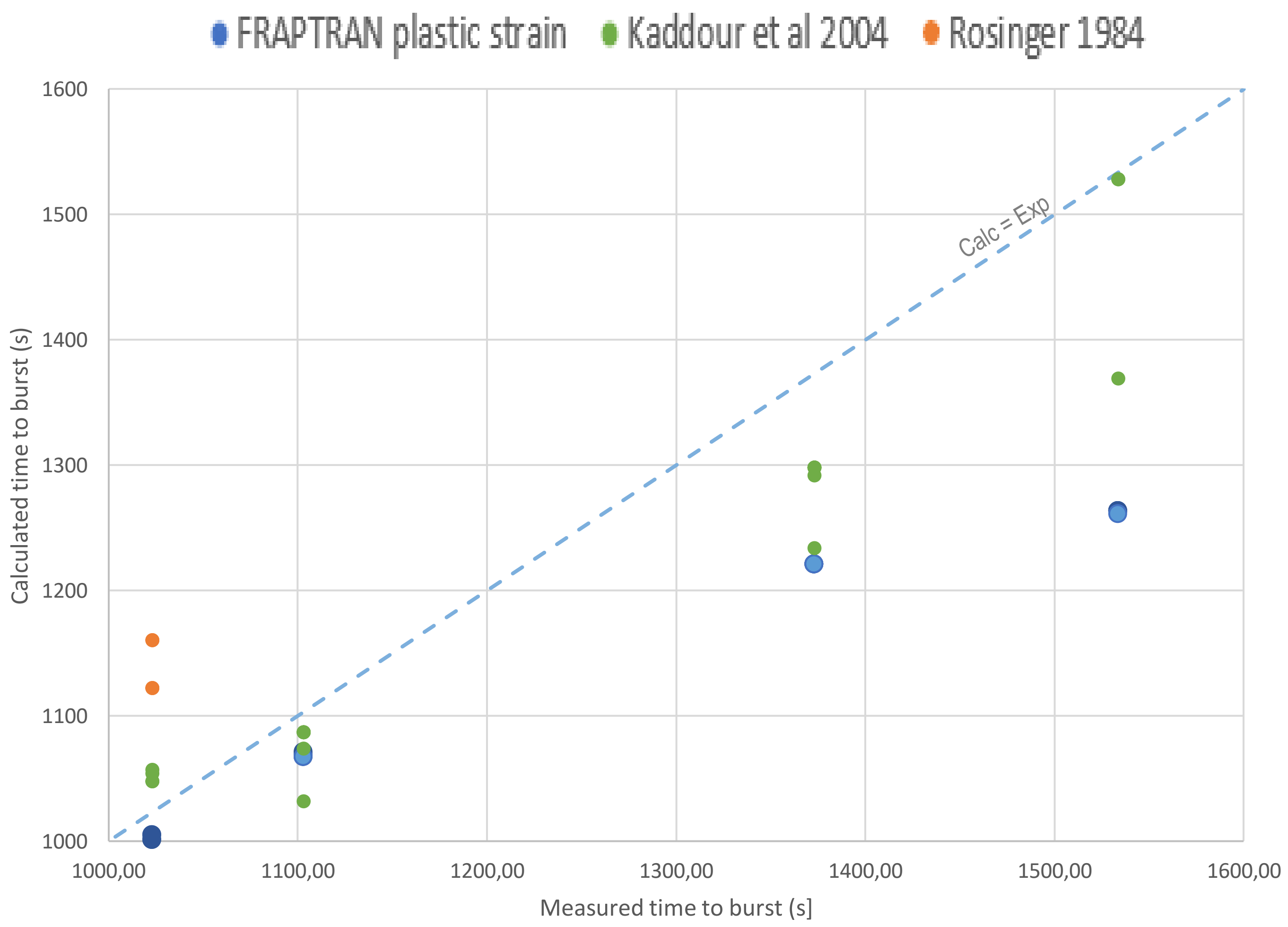


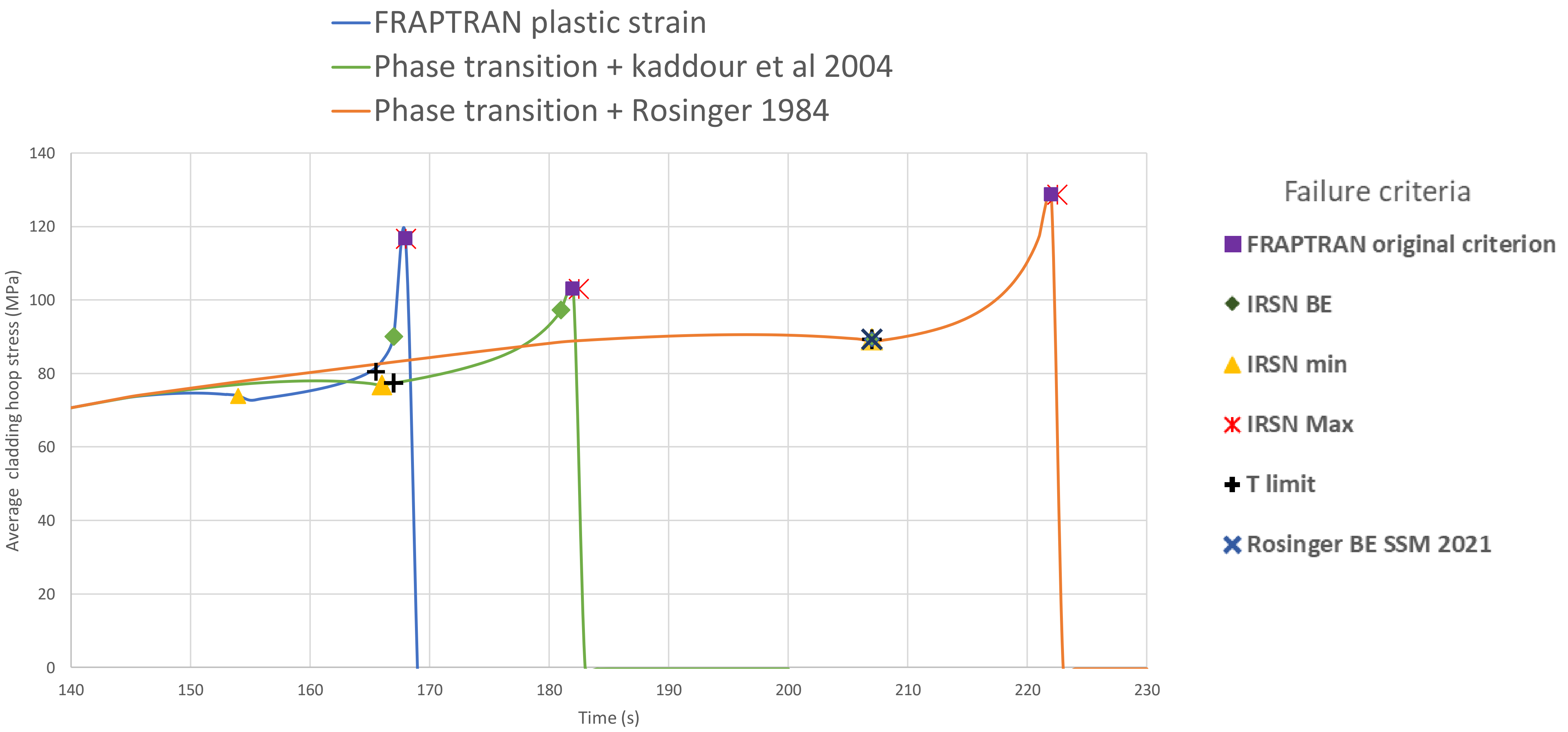
# Calculations results: Burst temperature

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS



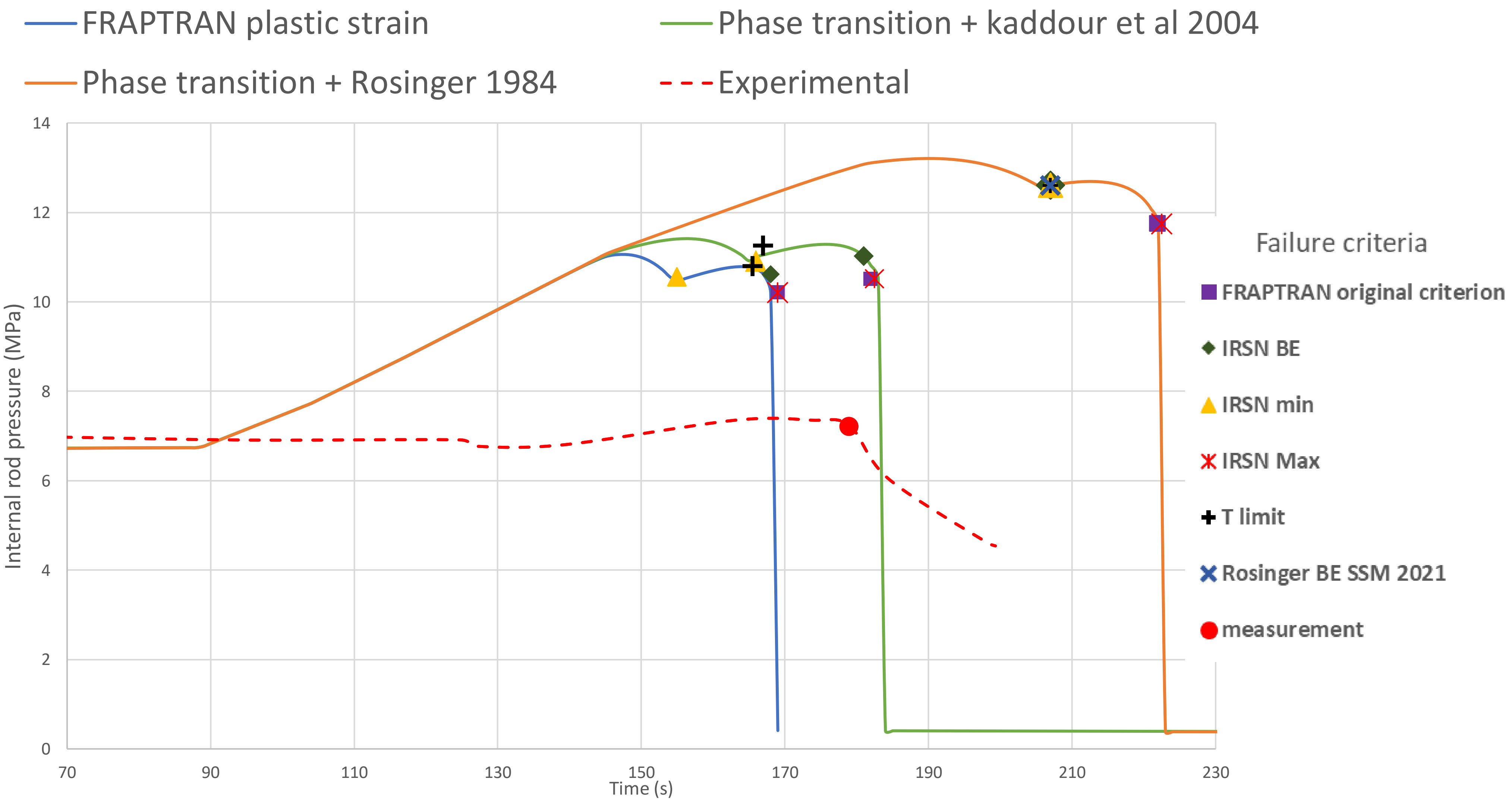
# IFA-650.5 LOCA results: hoop stress

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS




**NOTE! Plotted value is *averaged* over the ballooning node. Local calculations in the ballooning model divide the node into 16 x 16 subnodes, so the stress that triggers the failure criterion is different than in the average stress plot.**

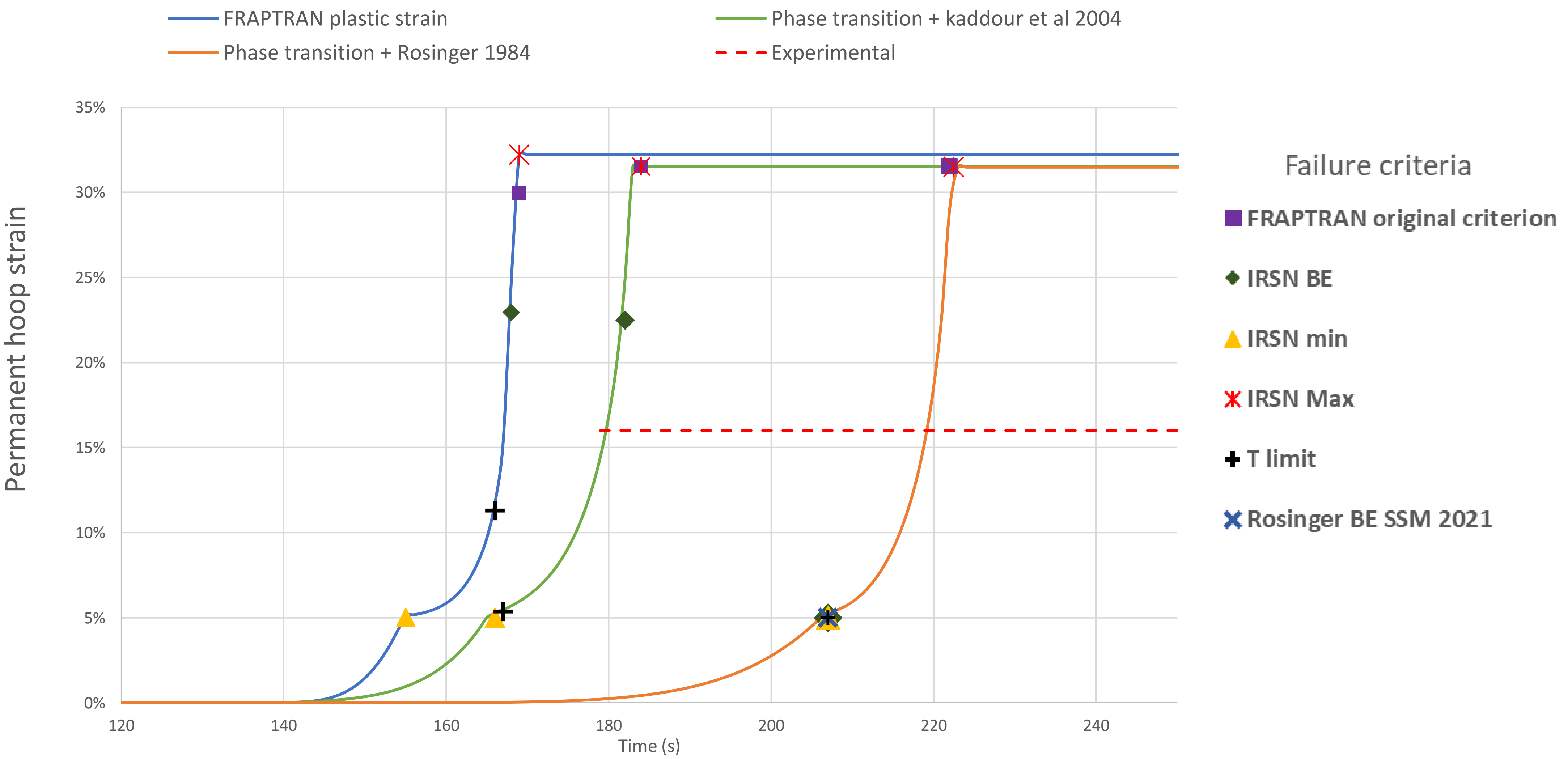
# IFA-650.5 LOCA results: rod internal press




REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

# IFA-650.5 LOCA results: plastic hoop strain

*REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS*



# Comparison of original and modified mechanical deformation models

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

| Test | | Average error | |
|---|---|---|---|
| | | Phase transition + Kaddour et al 2004 | FRAPTRAN original mechanical deformation |
| IFA-650.5 | Time | -1.3 % | -7.6 % |
| | Temperature | 0.7 % | -3.0 % |
| | | | |
| IFA-650.6 | Time | -17.6 % | -22.1 % |
| | Temperature | -2.7 % | -4.0 % |
| | | | |
| IFA-650.7 | Time | -30.9 % | -39.0 % |
| | Temperature | -6.5 % | -11.4 % |
| | | | |
| TREAT rod 16 and 17 | Time | 25.4 % | -22.1 % |
| | Temperature | -0.6 % | -17.7 % |
| | | | |
| LOC-11C rod 3 | | No Failure | No Failure |
| LOC-11C rod 2 | | No Failure ( False failure prediction only with IRSN min) | Incorrect failure prediction in all cases |
| LOC-11C rods 1 and 4 | | No Failure | No Failure |

$$\text{Average error (Parameter)} = \frac{Average\,(P_{FRAPTRAN\ burst\ criterion} + P_{IRSN\ BE} + P_{IRSN\ min} + P_{IRSN\ max} + P_{T\ limit}) - P_{measured}}{P_{measured}}$$

# On-going work

REDUCTION OF RADIOLOGICAL CONSEQUENCES
OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS


- A new validation case for M5 cladding is being simulated to validate the implemented models for M5
  - IFA-650.15 with M5 cladding

REDUCTION OF RADIOLOGICAL CONSEQUENCES
OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

# Application of updated models to EPR LB-LOCA full core simulations

# EPR LB-LOCA simulations

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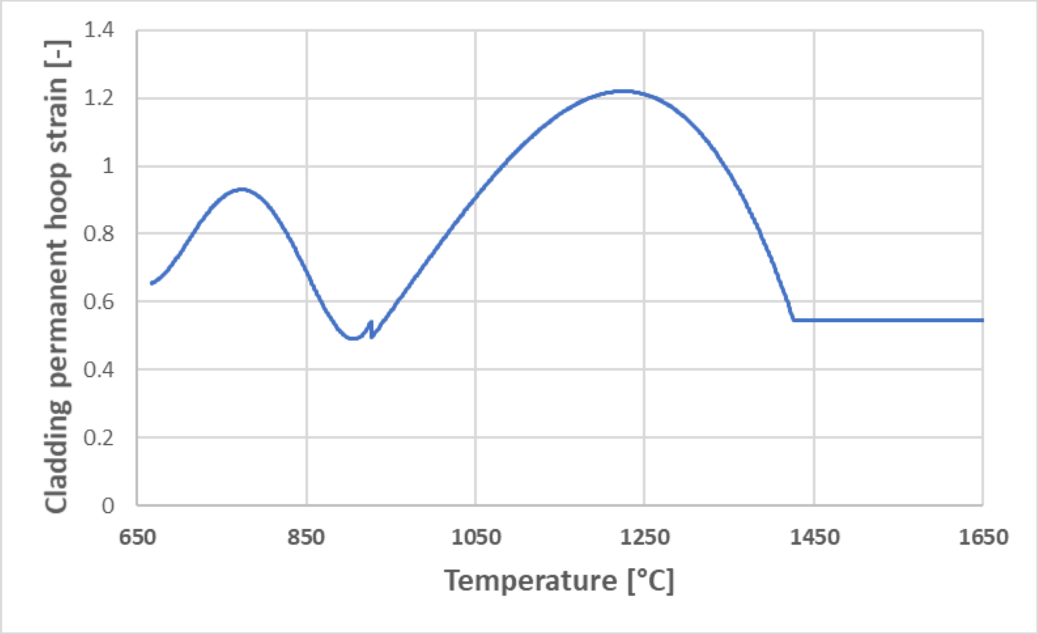
- EPR LB-LOCA analysis with the fuel performance code is performed to see the effect with various power histories and burnups.
- The original EPR LB-LOCA analysis used in the R2CA has not been done within this project. Analysis results are discussed in publications [1-3] (publication [3] contain some error corrections and is therefore the most up-to-date reference)
  - No other changes between initial calculations other than those mentioned earlier to FRAPTRAN, i.e., the same inputs and boundary conditions are used, and the same FRAPTRAN code version (V1.4)
- FRAPTRAN is coupled at VTT with VTT's in-house subchannel TH code GENFLO, and the original EPR simulations were done with that → new simulations also with FRAPTRAN-GENFLO

- ***Note!*** All the aforementioned modifications were done and tested with the as-received version of FRAPTRAN V1.4
- For the purpose of the EPR simulations, the developments were transferred into the coupled FRAPTRAN-GENFLO code

# Results



- After implementing the new phase transformation + Kaddour et al. creep model, no failures were detected with the IRSN BE criterion in 59 000 simulations (FRAPTRAN strain-based back-up failure criterion was disabled)
- After that, the scenario #1 was simulated with IRSN min. criterion (strain based criterion was disabled) → no cladding failures
- After that, strain based criterion was enabled and all the 59 scenarios simulated again → 1-2 failed rods per scenario
  - It thus appears that the failures are triggered by the secondary strain based criterion, not the stress based




*FRAPTRAN strain based cladding failure criterion*

*Note! There were also calculation errors as in previous EPR simulations, resulting from both FRAPTRAN and GENFLO. Max. error percentage was 6.6% of simulations (in global scenario #3)*

# Numbers of failing fuel rods in 59 global scenarios

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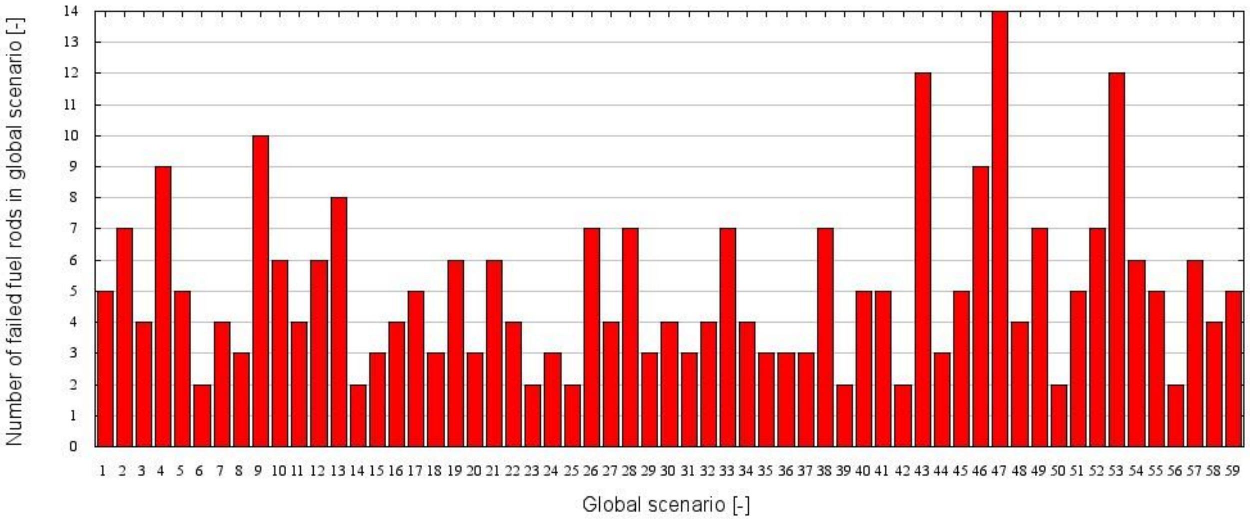
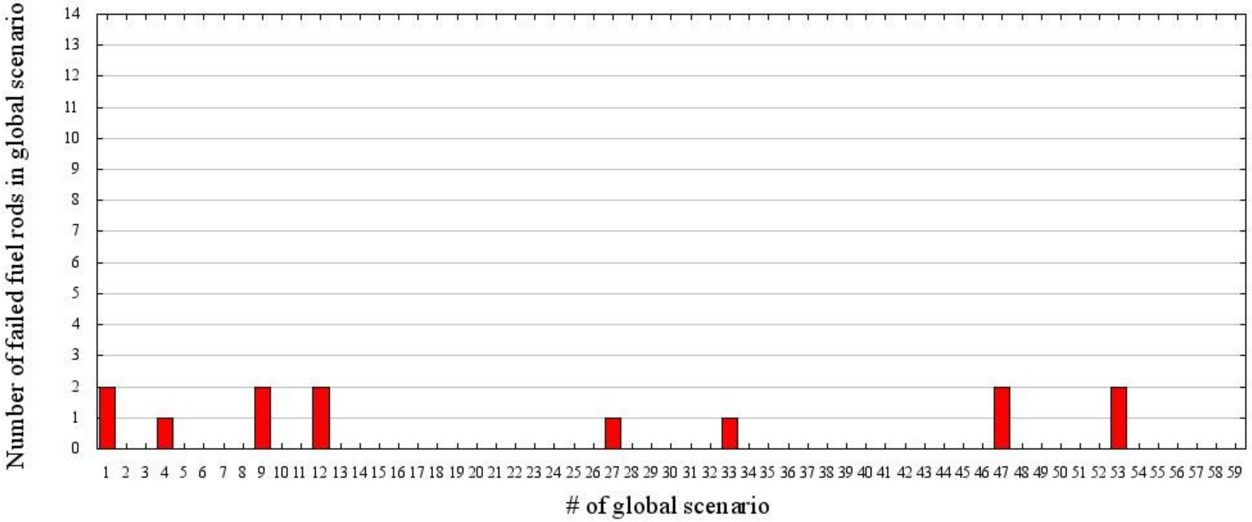
Original analysis results (with stress and strain based criteria)




Phase transformation + Kaddour et al. creep model + IRSN min failure criterion + orig. strain based criterion




1000 FRAPTRAN-GENFLO simulations per each global scenario, same rods were simulated in each scenario

# Summary and Conclusions



- Original FRAPTRAN mechanical model produces more conservative results than the new models
- New deformation models produce overall better predictions compared to the measured burst time and temperature.
- Bigger change in predictions is seen when moving from one mechanical model to another than when changing between various failure criteria
- EPR LB-LOCA full core simulations used Zy-4 deformation models, these will be updated to use specific M5 correlations.
- Further updates in the code will be applied only to BALON2 model in future. FRACAS-I model will be excluded from modifications.

# References

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS


[1] A.R. Massih (2009) , Transformation kinetics of zirconium alloys under non-isothermal conditions, Journal of Nuclear Materials 384 (2009) 330-335

[2] D. Kaddour, S. Frechinet, A.F. Gourgues, J.C. Brachet, L. Portier, A. Pineau, Experimental determination of creep properties of zirconium alloys together with phase transformation. Scr. Mater. 51 (2004) pp. 515–519.

[3] Rosinger, H.E., 1984. A Model to predict the failure of Zircaloy-4 fuel sheating during postulated LOCA conditions. Journal of Nuclear Materials 120, 41. https://doi.org/10.1016/0022-3115(84)90169-7

[4] R. O. Meyer and W. Wiesenack, “A critique of fuel behavior in LOCA safety analyses and a proposed alternative,” *Nuclear Engineering and Design*, vol. 394, Aug. 2022, doi: 10.1016/j.nucengdes.2022.111816.

[5] L. Olof Jernkvist and A. R. Massih, “Calibration of models for cladding tube high-temperature creep and rupture in the FRAPTRAN-QT-1.5 program 2021:04,” 2021. Available: www.ssm.se

[6] Arkoma, A., Hänninen, M., Rantamäki, K., Kurki, J., Hämäläinen, A., 2015. Statistical analysis of fuel failures in large break loss-of-coolant accident (LBLOCA) in EPR type nuclear power plant. Nuclear Engineering and Design, Vol. 285, pp. 1–14

[7] Arkoma, A., Ikonen, T., 2016. Sensitivity analysis of local uncertainties in large break loss-of-coolant accident (LB-LOCA) thermo-mechanical simulations. Nuclear Engineering and Design, Vol. 305, pp. 293-302

[8] Arkoma, A., Ikonen, T., 2016. Statistical and sensitivity analysis of failing rods in EPR LB-LOCA. In proceedings of: TopFuel 2016, Boise, Idaho, USA, September 11-15, 2016, Paper 17570

# Thank you!

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847656.

# Extra slides

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847656.

# Remark on FRAPTRAN vs. FRAPTRAN-GENFLO



- By using GENFLO thermal hydraulics with FRAPTRAN, the validation result presented in previous slides change
- FRAPTRAN-GENFLO results on the IFA-650 validation cases with the original FRAPTRAN V1.4 mechanical models and failure criteria can be found in: *Manngård, T., Stengård, J.-O., 2014. Evaluation of the Halden IFA-650 loss-of-coolant accident experiments 5, 6, and 7. Report number: 2014: 19 ISSN: 2000-0456*

Table 4: Comparison of calculated and measured results for the IFA-650 tests 5, 6 and 7.

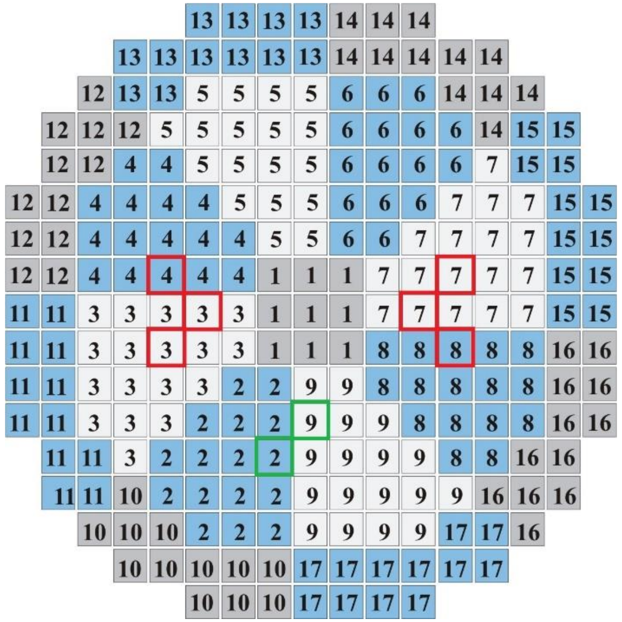
| Test/ Parameter | Calculation 1) | Calculation 2) | Measurement |
|---|---|---|---|
| IFA-650.5/ | | | |
| Time to cladding rupture, s | 198 | 157 | 178 |
| Rupture temperature, °C | 896 | 801 | 750 |
| Max. diametral cladding strain, % | 47♭ | 84♭ | 16 |
| Rod pressure at rupture, MPa | 4.6 | 5.9 | 7.2 |
| Outer surface oxide layer, μm (increase under LOCA) | 8 | 5 | 11 |
| IFA-650.6/ | | | |
| Time to cladding rupture, s | 530 | 455/518† | 525 |
| Rupture temperature, °C | 853 | 840/822† | 830 |
| Max. diametral cladding strain, % | 72♭ | 89♭/90♭† | 36 |
| Rod pressure at rupture, MPa | 4.2 | 4.1/4.2† | (6.4)‡ |
| Outer surface oxide layer, μm (increase under LOCA) | 1.5 | 3.5/2.5† | 2 |
| IFA-650.7/ | | | |
| Time to cladding rupture, s | 194 | 213 | 247 |
| Rupture temperature, °C | 1056 | 1092 | 1100 |
| Max. diametral cladding strain, % | 30♭ | 29♭ | 24 |
| Rod pressure at rupture, MPa | 0.89 | 0.86 | 1.05 |
| Outer surface oxide layer, μm (increase under LOCA) | 23 | 29 | 30 |

1) FRAPTRAN-GENFLO
2) FRAPTRAN-QT1.4c
♭ Value obtained from the calculated increase of cladding outer diameter relative to initial cladding diameter of test fuel rod.
† Results (after the / symbol) are obtained by applying a 3% reduction on the prescribed cladding outside surface temperatures (from heat-up until end of calculation).
‡ The level of absolute rod pressure could not be defined precisely in the IFA-650.6 test (Kekkonen 2007b).

# Previous EPR analysis with FRAPTRAN-GENFLO

*REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS*

- Analysis results are discussed in publications [1-3] (publication [3] contain some error corrections and is therefore the most up-to-date reference)
- Analysed accident sequence in EPR is chosen based on the regulatory requirements in Finland
  - As an initiating event, a double-ended break in a cold leg opens. Due to pressure decrease, reactor and turbine trips follow. Simultaneously with the turbine trip, the offsite power is lost and the main recirculating coolant pumps start to coast down. The core is uncovered. The content of the accumulators is injected to the primary loop when the accumulator pressure is reached. After a delay, the diesel generators are started and the medium head safety injections, and later on, the low head safety injections start operation, and the core is quenched. [1]

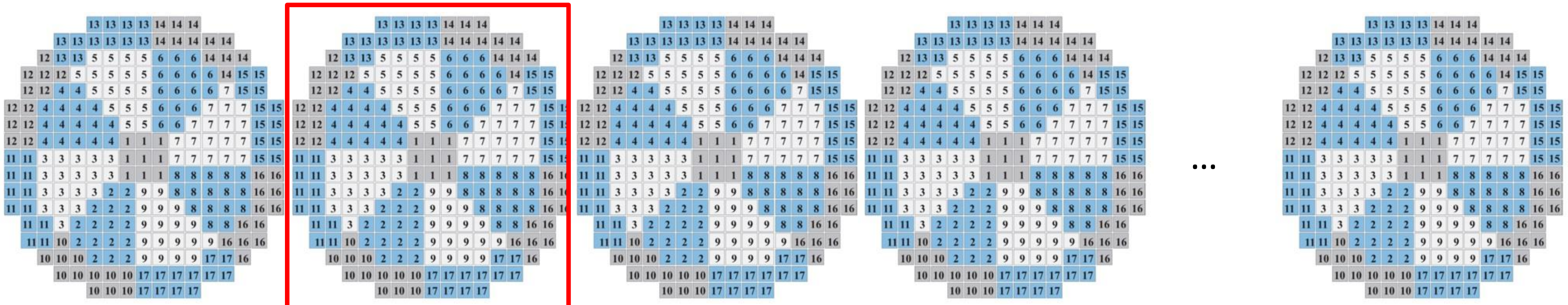



Core is divided into 17 coolant channels in Apros. Assemblies in which higher than 20% permanent cladding hoop strains were exhibited are marked with red. A few rods failed according to FRAPTRAN with less than 20% strain, and the related assemblies are marked with green. [1,3]


1. Arkoma, A., Hänninen, M., Rantamäki, K., Kurki, J., Hämäläinen, A., 2015. Statistical analysis of fuel failures in large break loss-of-coolant accident (LBLOCA) in EPR type nuclear power plant. Nuclear Engineering and Design, Vol. 285, pp. 1–14
2. Arkoma, A., Ikonen, T., 2016. Sensitivity analysis of local uncertainties in large break loss-of-coolant accident (LB-LOCA) thermo-mechanical simulations. Nuclear Engineering and Design, Vol. 305, pp. 293-302
3. Arkoma, A., Ikonen, T., 2016. Statistical and sensitivity analysis of failing rods in EPR LB-LOCA. In proceedings of: TopFuel 2016, Boise, Idaho, USA, September 11-15, 2016, Paper 17570

# For each global scenario (59 in total)

- A set of sampled model parameter values for fuel performance codes
- Thermal hydraulic and power history boundary conditions during accident from APROS (thus 59 APROS simulations)



1 2 3 4 … 59

## Local variation

- Fuel manufacturing parameter values are random sampled from their distributions
- Each rod has an own base irradiation history
- Local values remain unchanged when moving from one global scenario to another

**1000 randomly sampled rods were simulated in each global scenario**