KNS Autumn 2022

# An application of data assimilation to improve the prediction of the reflood tests

**Nguyen Huu Tiep** [a], Hae-Yong Jeong [a], Kyung-Doo Kim [b]

[a]*Department of Quantum and Nuclear Engineering, Sejong University, Seoul, Republic of Korea*

[b]*Korea Atomic Energy Research Institute, Daejeon, Republic of Korea*

*Corresponding email: tiepngh@sejong.ac.kr*

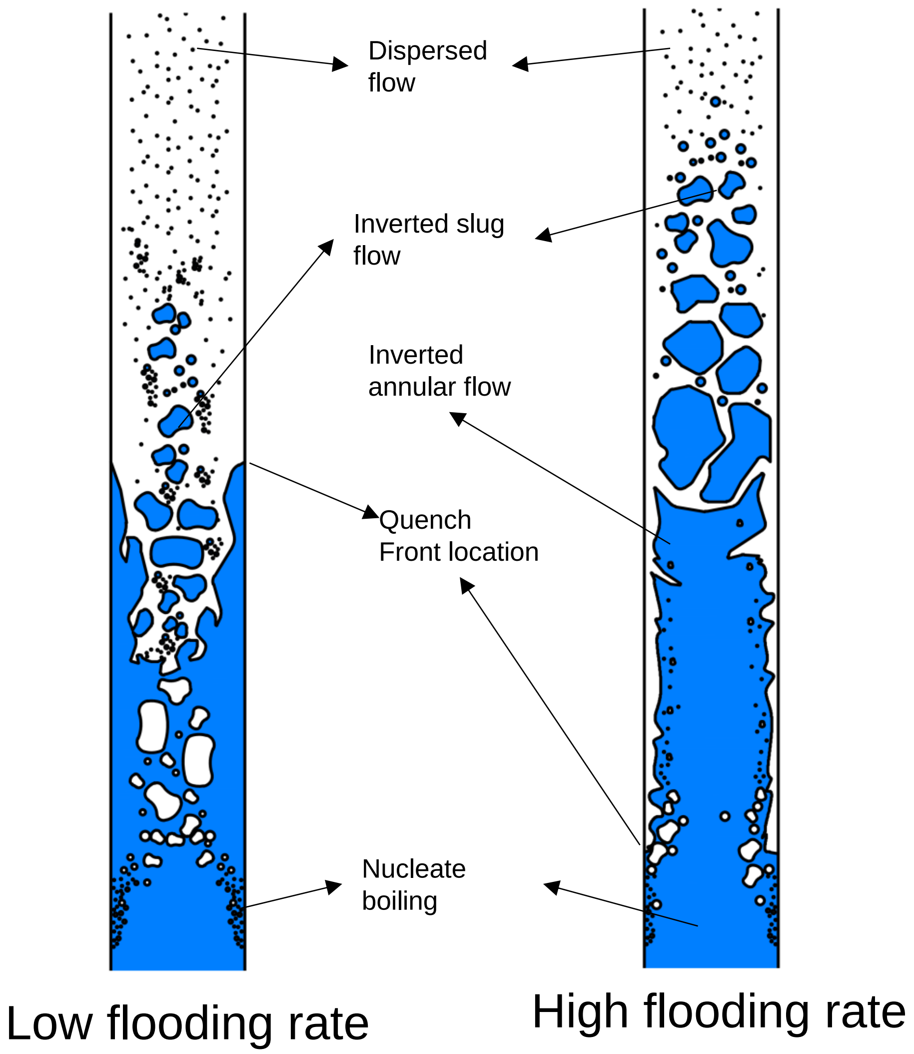
Changwon, Oct 21st, 2022

# Contents

# 1. Introduction (1/3)

- All heat transfer modes can be observed (nucleate boiling, film boiling, inverted annular flow, inverted slug flow, dispersed flow…)

- Reflood experiments: FLECHT SEASET, RBHT 2012, FEBA, RBHT open test data 2019 (OECD/NEA).



# 1. Introduction (2/3)

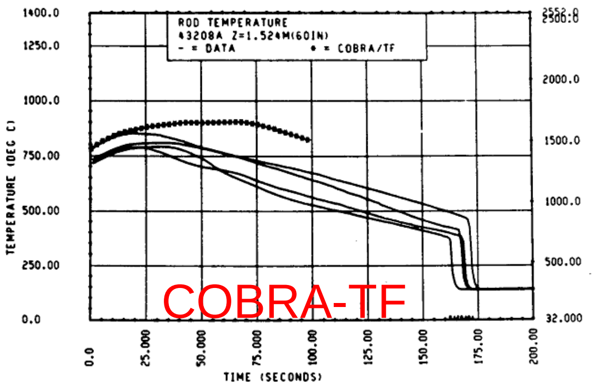
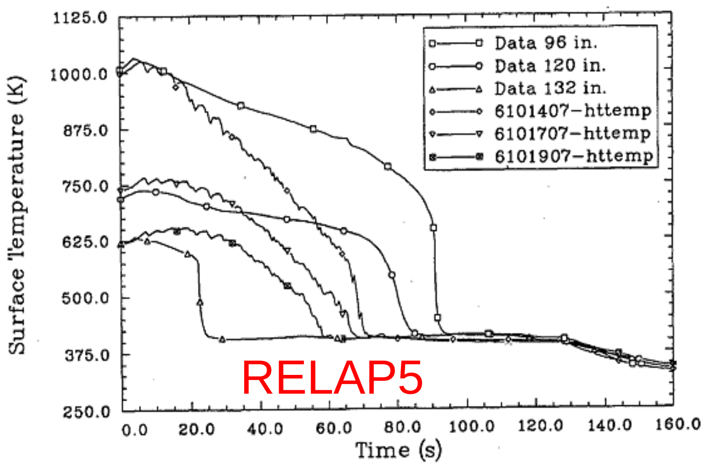
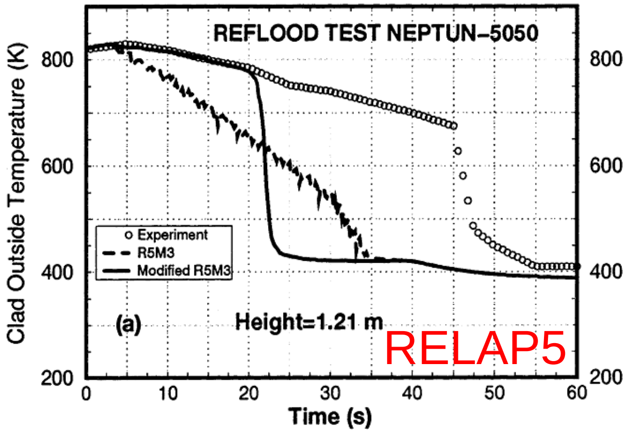



Figure 3-95. Comparison of COBRA-TF-Calculated Heater Rod Temperature Versus Time With FLECHT SEASET 21-Rod Data, Test 43208A, 1.52 m (60 in.) Elevation

Paik et al., 1985




Carlson et al., 1990




Elias et al., 1998

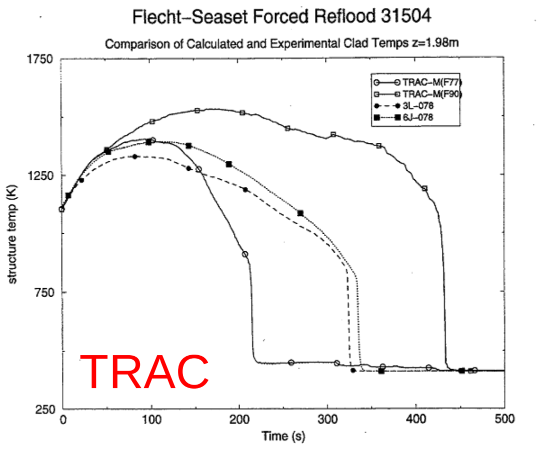
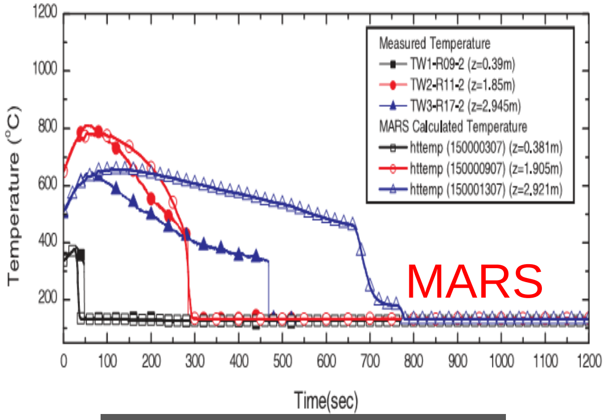



Figure 4.9 Comparison of Calculated and Experimental Clad Temps. @z=1.98m

Odar et al., 2001




Choi et al., 2010

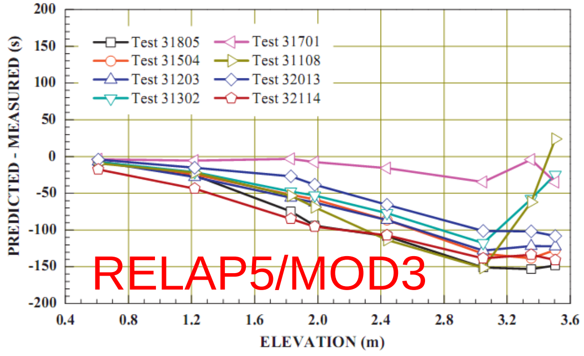
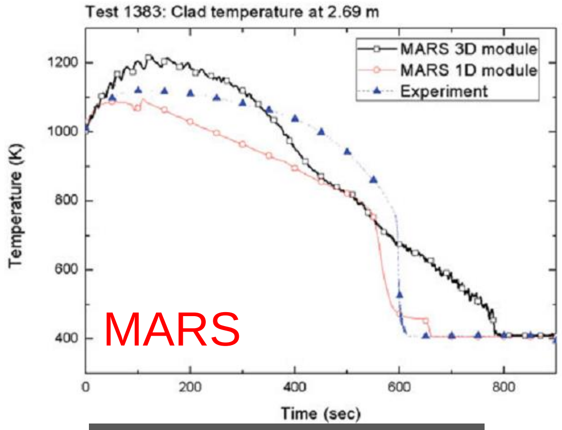
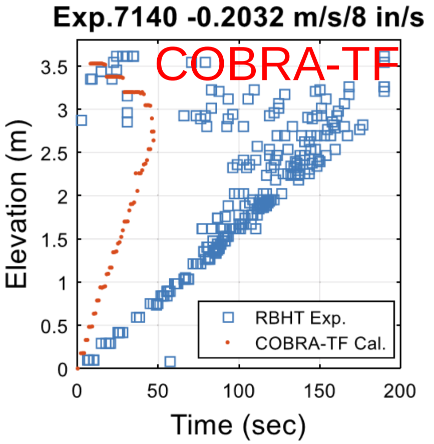



**Fig. 6.** Deviations of quench times (FLECHT-SEASET tests, original model).

Choi and No, 2012




Seo et al., 2015




Jin et al., 2015

# 1. Introduction (3/3)

- □ To introduce the application of STARU data assimilation framework

  - ✓ Improving the prediction results
  - ✓ Identifying the most sensitive uncertainty source in the simulation

# 2. Data assimilation (1/2)

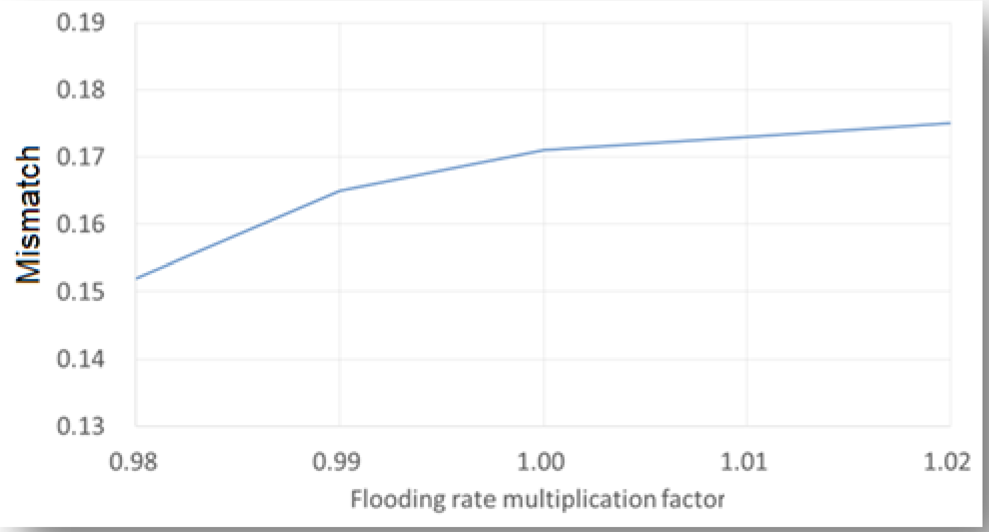
□ Data assimilation (to adjust the input parameters within their uncertainty ranges to improve the predictions)

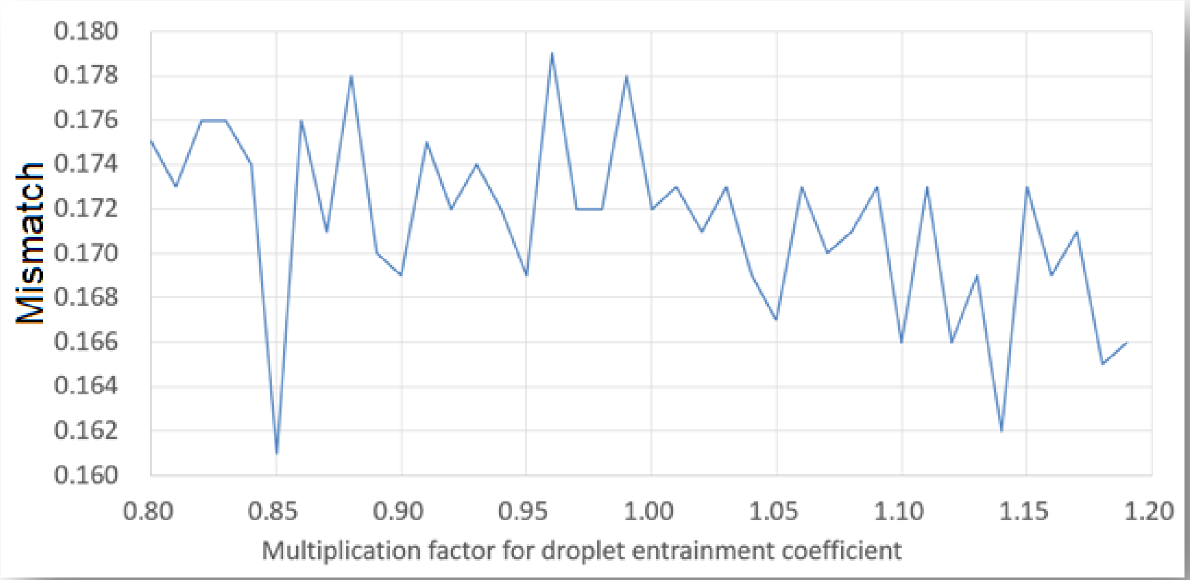
✓ Set of the prepared input parameters for **simulation**

- Initial and boundary conditions – low uncertainty band
- Physical models – high uncertainty band

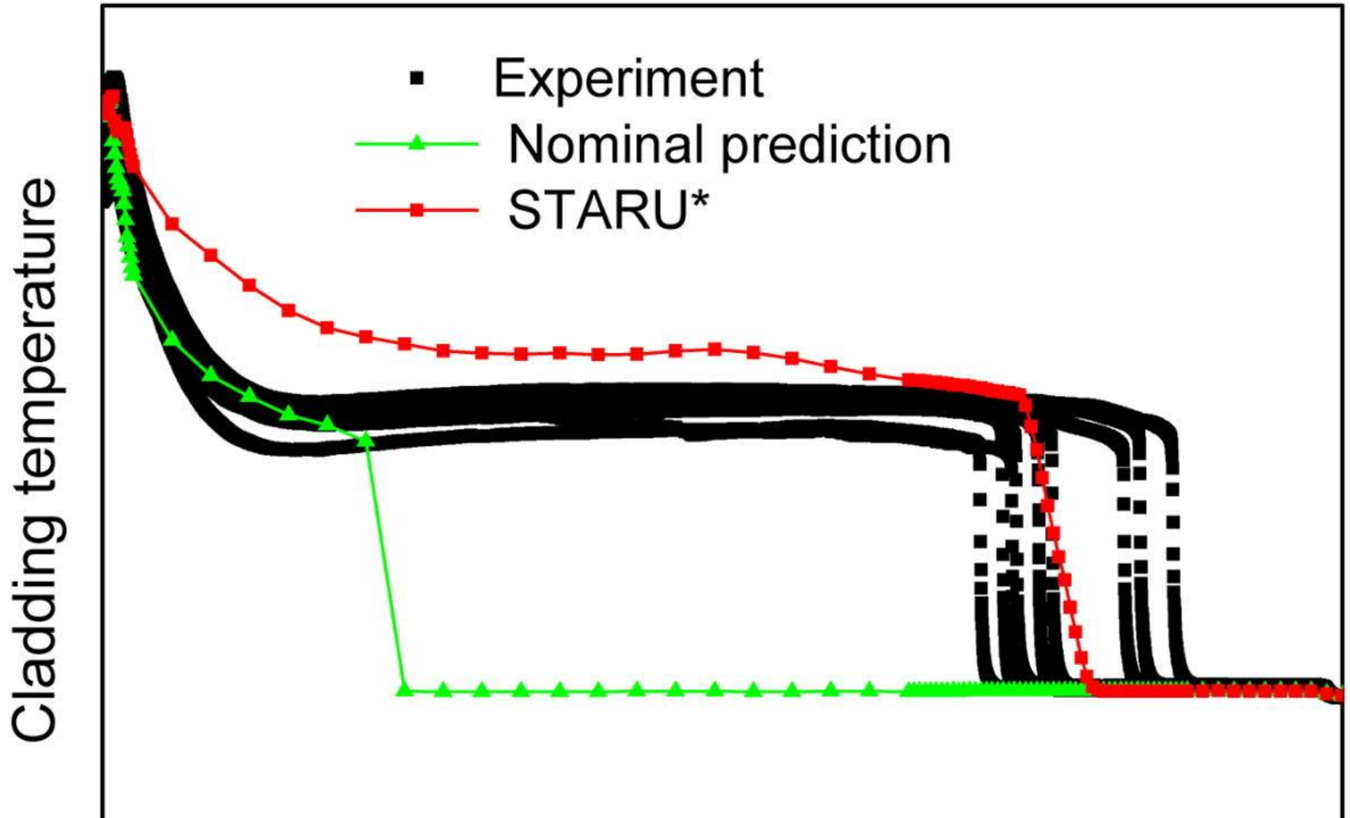
✓ Set of **experimental data** to evaluate our prediction

✓ Mismatch = | **Predicted – Measured |**



- Data assimilation (DA)
  - ✓ Parameters adjustment for improving the predicted values.
- DA consisted
  - ✓ Sensitivity analysis
  - ✓ Uncertainty quantification
  - ✓ Accuracy evaluation method
  - ✓ Sampling method
- Object
  - ✓ SPACE code (Ha et al., 2011)
  - ✓ STARU data assimilation framework
  - ✓ FLECHT SEASET reflood tests




*The best predictions obtained by a newly proposed data assimilation framework (STARU) in which the parameters were justifiably adjusted within their uncertainty range using sampling approach.


Ha, S. J., Park, C. E., Kim, K. D., and Ban, C. H., 2011. Development of the SPACE code for nuclear power plants. Nuclear Engineering and Technology, 43(1), 45-62.

Tiep, N.H., Kim, K.D., Heo, J., Choi, C.W. and Jeong, H.Y. A newly proposed data assimilation framework to enhance predictions for reflood tests. Nuclear Engineering and Design, 390, p.111724, 2022.

Loftus, M. J., Hochreiter, L. E., Conway, C. E., Dodge, C. E., Tong, A., Rosal, E. R., ... and Wong, S., 1981. PWR FLECHT SEASET unblocked bundle, forced and gravity reflood task data report. Volume 1 (No. EPRI-NP-1459-Vol. 1; NUREG/CR-1532-Vol. 1; WCAP-9699-Vol. 1). Westinghouse Electric Corp., Pittsburgh, PA (USA). Nuclear Energy Systems Div.

# 3. Materials and tools (1/4)

## The FLECHT SEASET reflood tests and responses

- ✓ Number of F-S test: 9
- ✓ Harmonization the experiment and I/O data (number of data points and time steps for both experiment and responses)
- ✓ Number of responses: 5

| The reflood tests | | Flooding rate (mm/s) | Power (kW/m) | Maximum initial clad temperature (K) | Pressure (MPa) | Inlet temperature (K) |
|---|---|---|---|---|---|---|
| F-S | F1-31021 | 38.60 | 1.30 | 1153.00 | 0.28 | 325 |
| | F2-31302 | 76.50 | 2.30 | 1142.00 | 0.28 | 325 |
| | F3-31504 | 24.00 | 2.30 | 1136.00 | 0.28 | 324 |
| | F4-33849 | 25.90 | 1.90 | 1018.00 | 0.28 | 331 |
| | F5-34103 | 38.10 | 2.40 | 1158.00 | 0.28 | 324 |
| | F6-34316 | 25.00 | 2.40 | 1162.00 | 0.28 | 324-392 |
| | F7-34420 | 38.90 | 2.40 | 1392.00 | 0.27 | 324 |
| | F8-34711 | 17.00 | 1.40 | 1161.00 | 0.13 | 306 |
| | F9-35050 | 25.90 | 1.60 | 1031.00 | 0.14 | 316 |

Loftus, M. J., Hochreiter, L. E., Conway, C. E., Dodge, C. E., Tong, A., Rosal, E. R., ... and Wong, S., 1981. PWR FLECHT SEASET unblocked bundle, forced and gravity reflood task data report. Volume 1 (No. EPRI-NP-1459-Vol. 1; NUREG/CR-1532-Vol. 1; WCAP-9699-Vol. 1). Westinghouse Electric Corp., Pittsburgh, PA (USA). Nuclear Energy Systems Div.

(cladding temperatures at two different elevations, the steam temperature, the pressure drop, and the quenching time).

# 3. Materials and tools (2/4)

The selection of the parameters - 42 multipliers (Tiep et al., 2022).

- ✓ Form loss coefficients (forward and reverse flow)
- ✓ Interfacial Friction Factors (liquid-vapor IFF factors)
- ✓ Droplet Entrainment, De-entrainment
- ✓ Convective Heat Transfers coefficients
- ✓ Interphase Heat Transfer coefficients

Tiep, N.H., Kim, K.D., Heo, J., Choi, C.W. and Jeong, H.Y. A newly proposed data assimilation framework to enhance predictions for reflood tests. Nuclear Engineering and Design, 390, p.111724, 2022.

# 3. Materials and tools (3/4)

## The Absolute Relative Difference method (Tiep et al., 2022)

$$R = \sum_{j=1}^{m} \sum_{i=1}^{n} \left| \frac{V_{C_i}^j}{V_C^j + V_E^j} - \frac{V_{E_i}^j}{V_C^j + V_E^j} \right| * k^j$$

$$V_C^j = \sum_{i=1}^{n} V_{C_i}^j \qquad V_E^j = \sum_{i=1}^{n} V_{E_i}^j$$

$V_C$: the calculation value

$V_E$: the experimental values

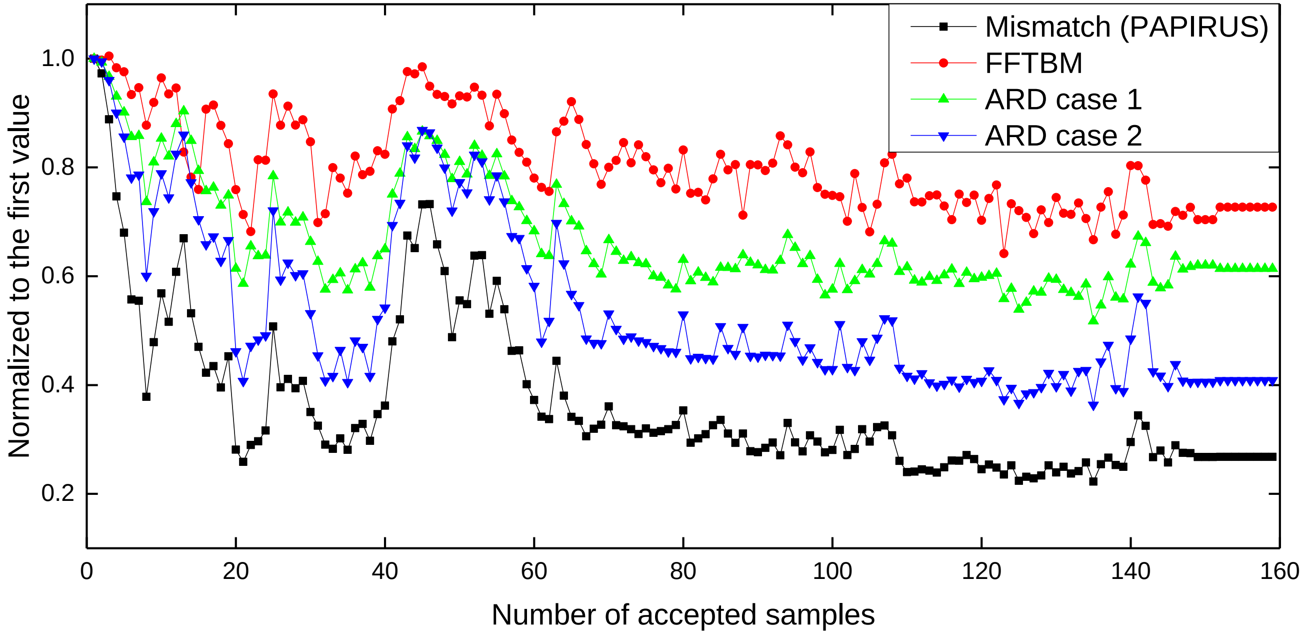
*j* : the responses

*k* : the weighting factor for each response

*n* : the total number of data points

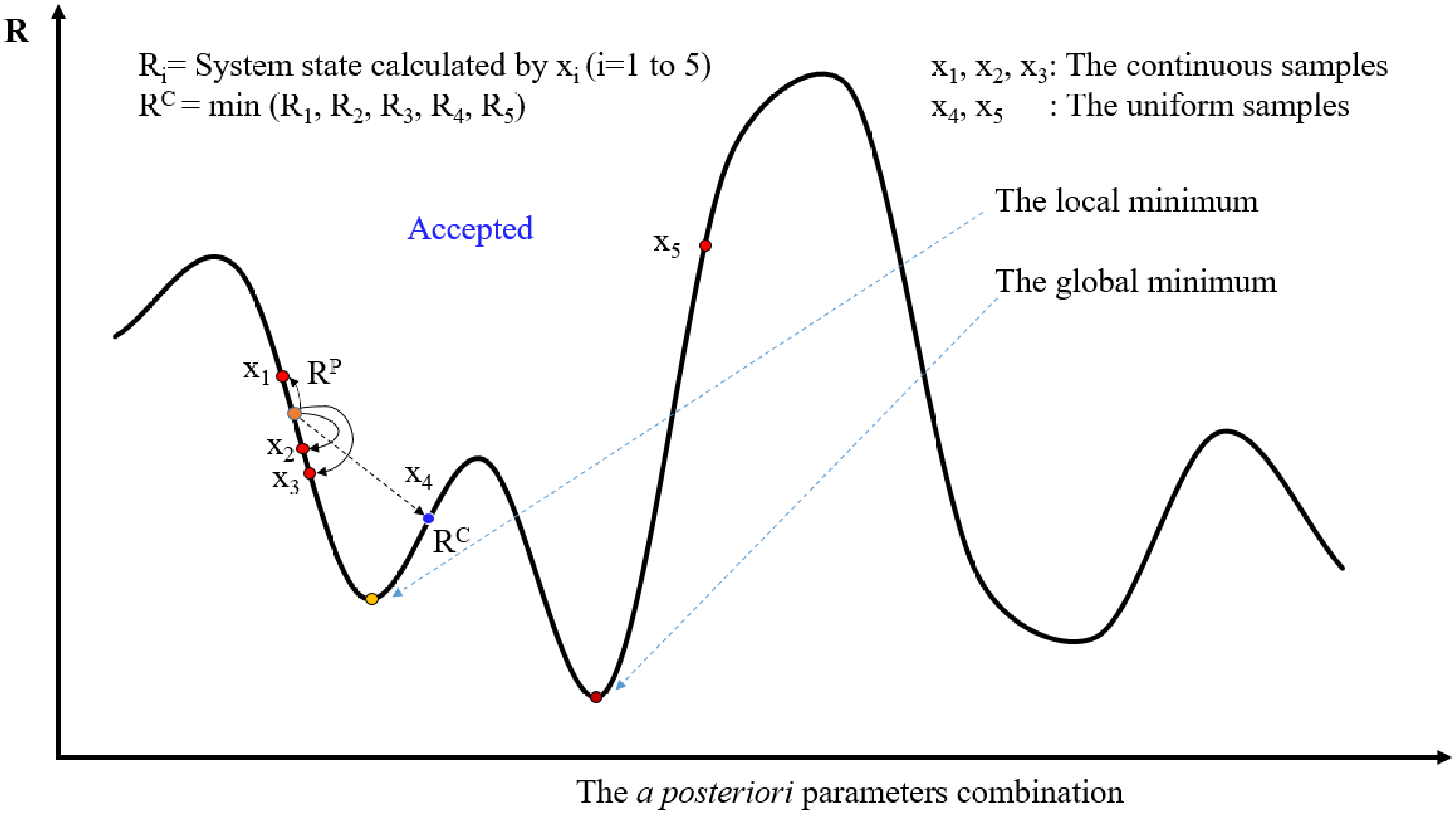
*m* : the total number of responses

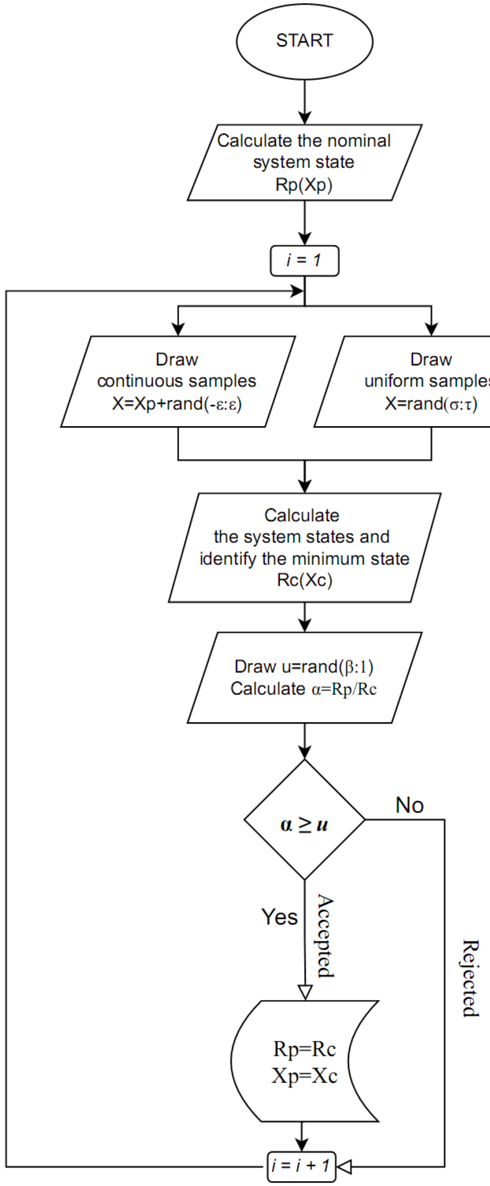
| N | k1 | k2 | k3 | k4 | k5 |
|---|---|---|---|---|---|
| Case 1 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Case 2 | 1.0 | 1.0 | 0.25 | 0.25 | 1.0 |



# 3. Materials and tools (4/4)

## The sampling technique (Tiep et al., 2022)



# 4. Results (1/5)

## The overall enhancements

ARD evaluations for STARU DA results

| No | Test case | ARD method | | Improvement (%) |
|---|---|---|---|---|
| | | Before DA | After DA | |
| 1 | F1-31021 | 0.192 | 0.110 | 42.9 |
| 2 | F2-31302 | 0.293 | 0.187 | 36.2 |
| 3 | F3-31504 | 0.240 | 0.156 | 35.3 |
| 4 | F4-33849 | 0.208 | 0.119 | 42.6 |
| 5 | F5-34103 | 0.216 | 0.105 | 51.3 |
| 6 | F6-34316 | 0.212 | 0.181 | 14.7 |
| 7 | F7-34420 | 0.200 | 0.116 | 42.1 |
| 8 | F8-34711 | 0.320 | 0.170 | 46.8 |
| 9 | F9-35050 | 0.302 | 0.129 | 57.2 |

FFTBM evaluations for PAPIRUS DA results

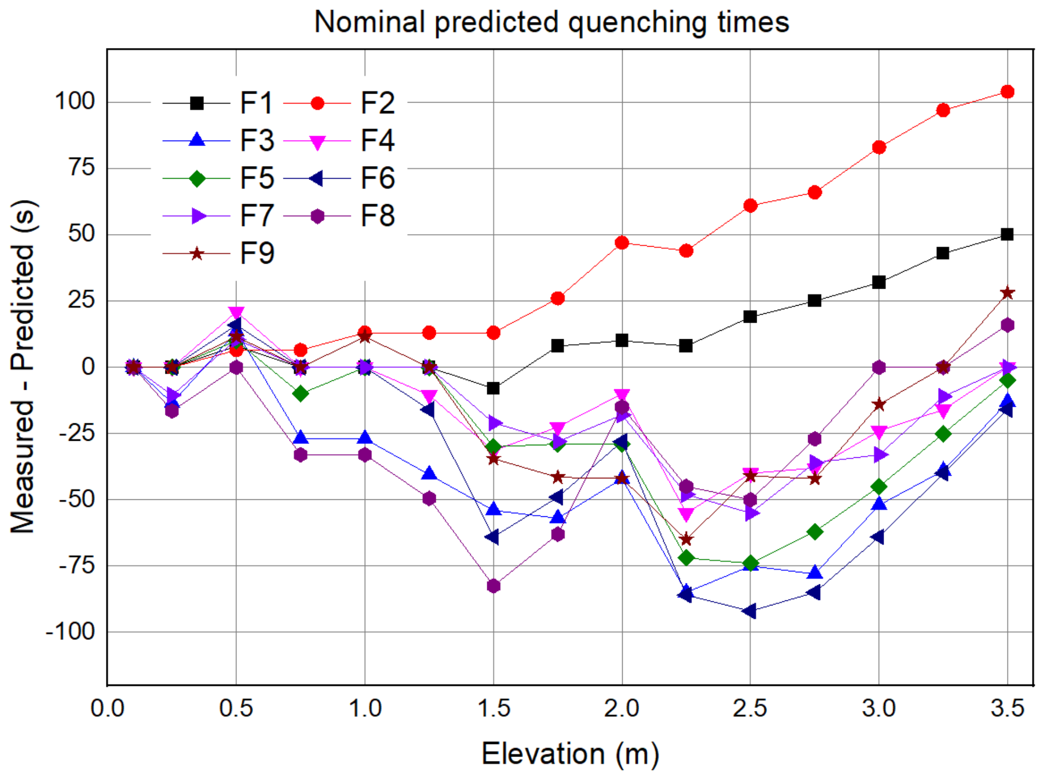
**Table 6**
The $AA_{total}$ values for sampling approach.

| No. | Run | $AA_{total}$ | | $\frac{(1)-(2)}{(1)}$, (%) |
|---|---|---|---|---|
| | | Nominal value (1) | The *a posteriori* value (2) | |
| 1 | 31021 | 0.205 | 0.193 | 6.0 |
| 2 | 31302 | 0.264 | 0.250 | 5.4 |
| 3 | 31504 | 0.231 | 0.177 | 23.6 |
| 4 | 33849 | 0.258 | 0.251 | 2.6 |
| 5 | 34103 | 0.286 | 0.266 | 6.9 |
| 6 | 34316 | 0.299 | 0.243 | 18.7 |
| 7 | 34420 | 0.239 | 0.217 | 9.4 |
| 8 | 34711 | 0.307 | 0.261 | 15.1 |
| 9 | 35050 | 0.294 | 0.254 | 13.7 |

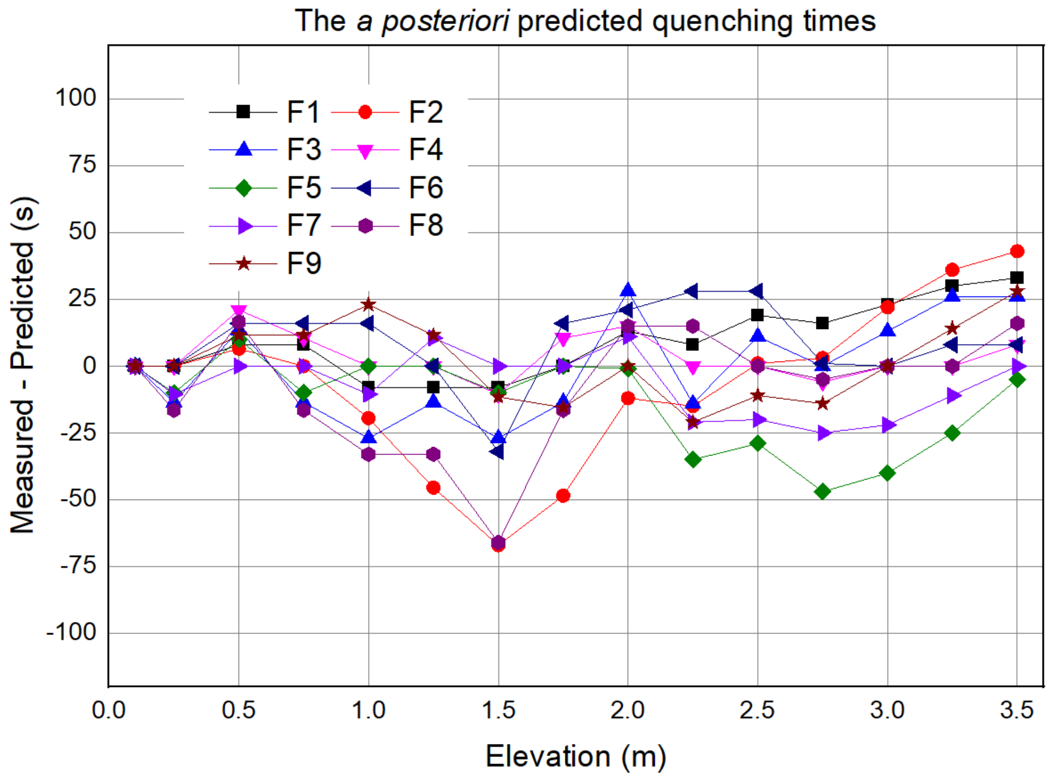
Tiep, N. H., Kim, K. D., J. Heo, 2021. Improvement in the accuracy of SPACE prediction for the unblocked FLECHT SEASET reflood tests by data assimilation. Annals of Nuclear Energy,

# 4. Results (2/5)

## All quenching time enhancements



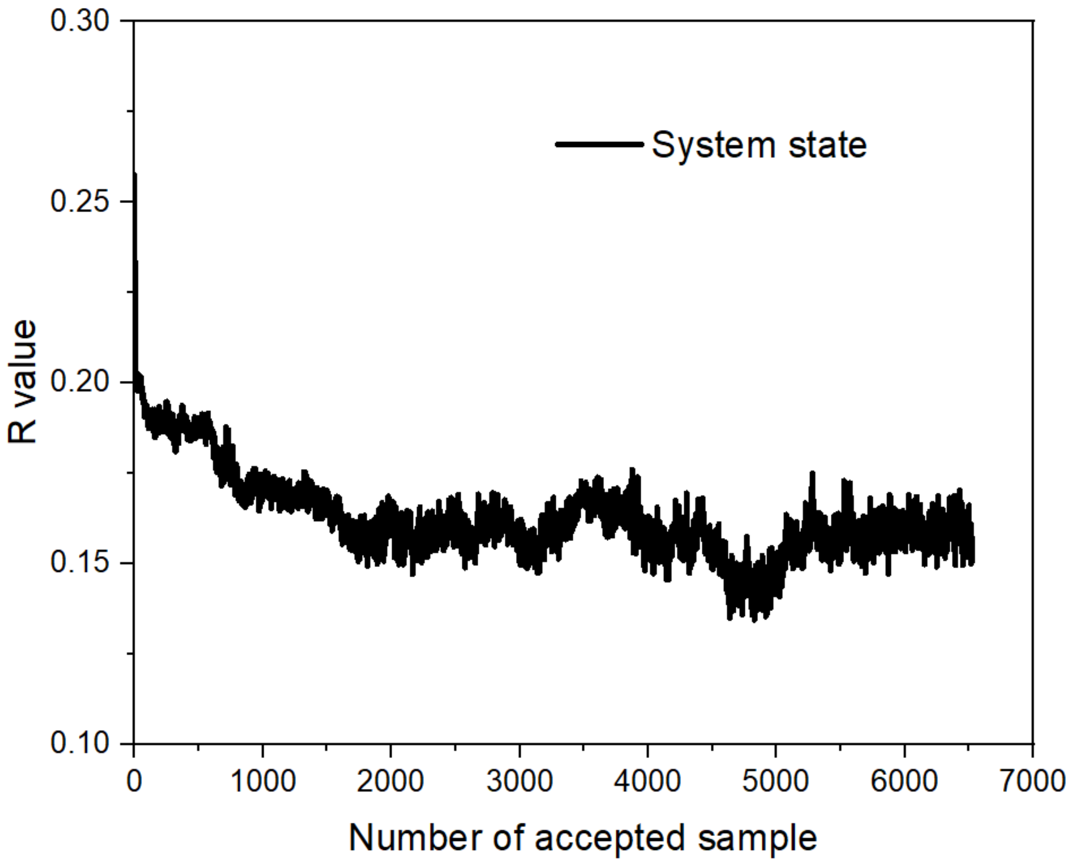

Before data assimilation




After data assimilation

# 4. Results (3/5)

## The system state



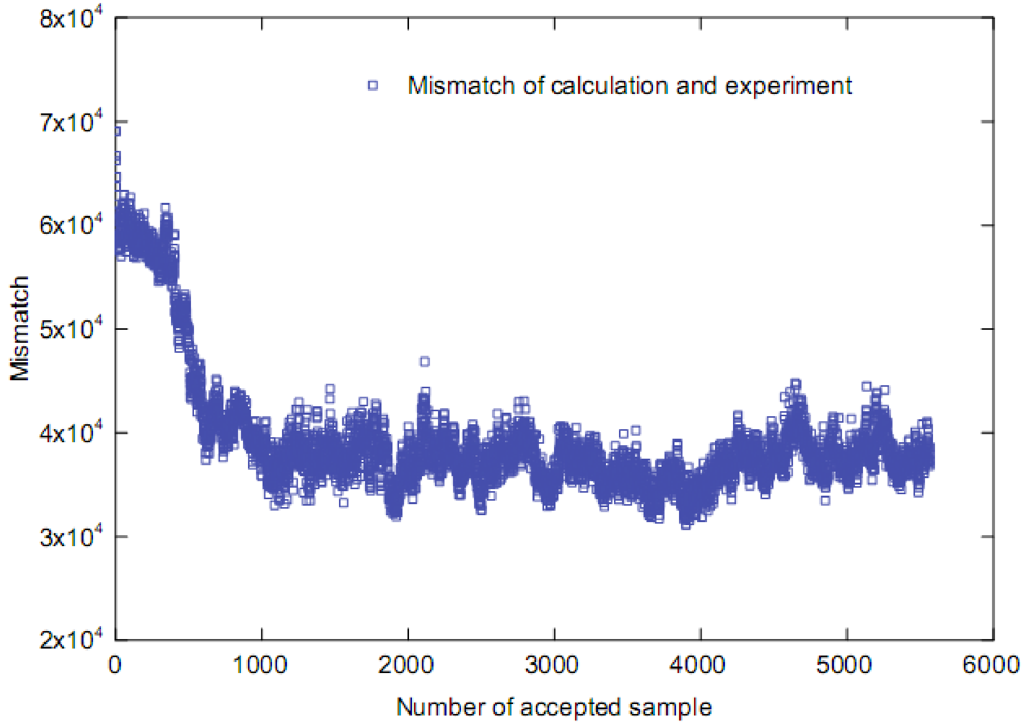
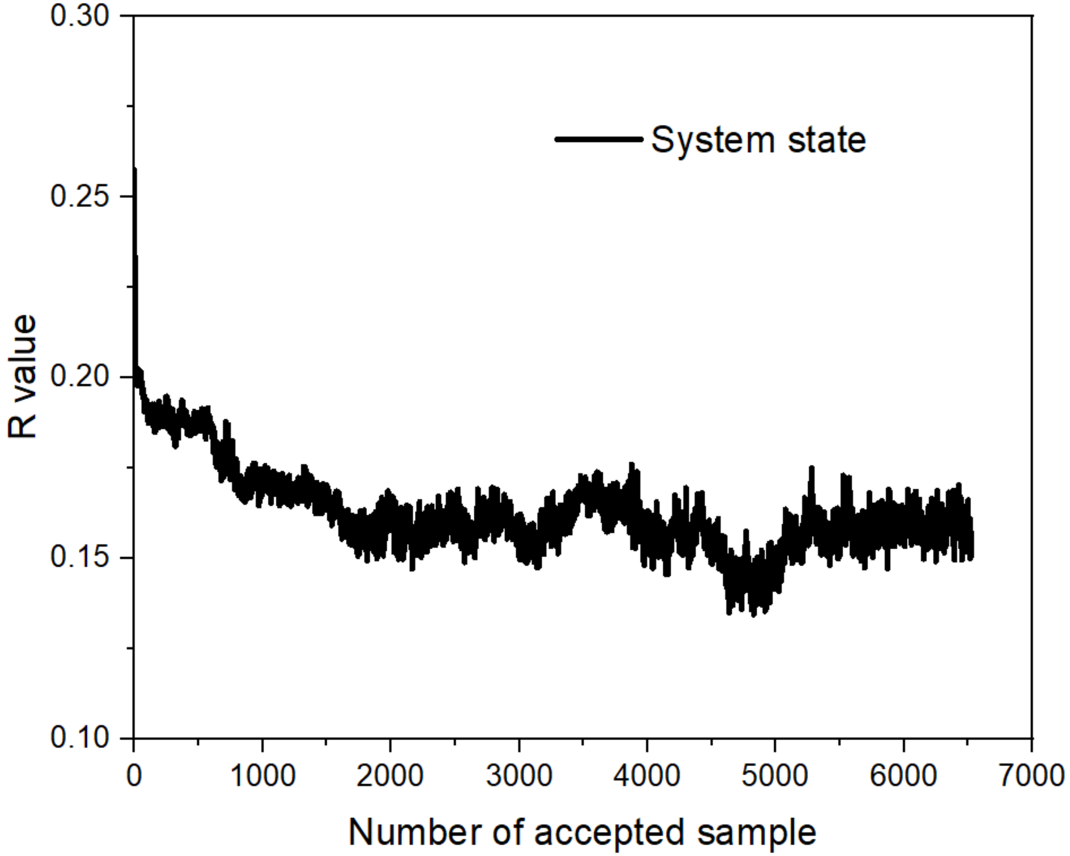



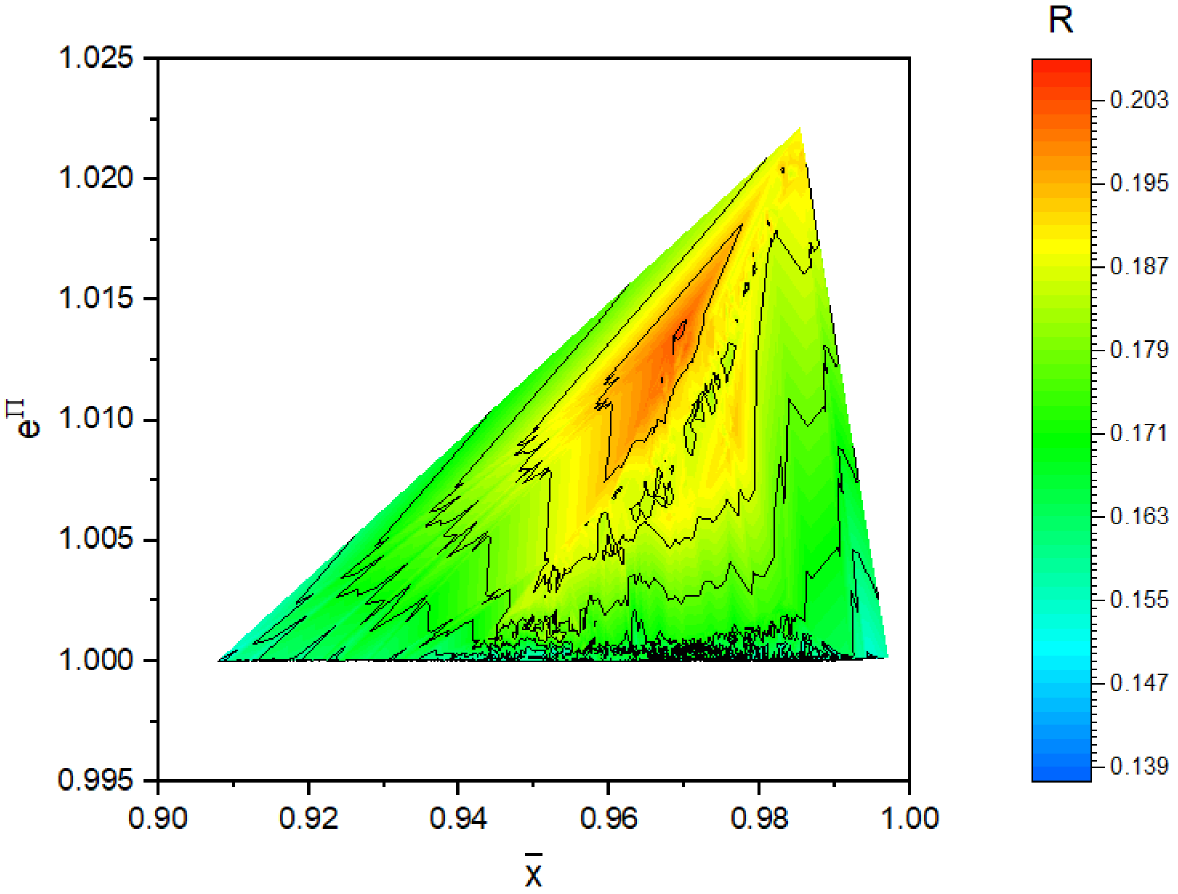

**Fig. 7.** The total mismatch distributions.

Tiep, N. H., Kim, K. D., J. Heo, 2021. Improvement in the accuracy of SPACE prediction for the unblocked FLECHT SEASET reflood tests by data assimilation. Annals of Nuclear Energy,

# 4. Results (3/5)

## The system state

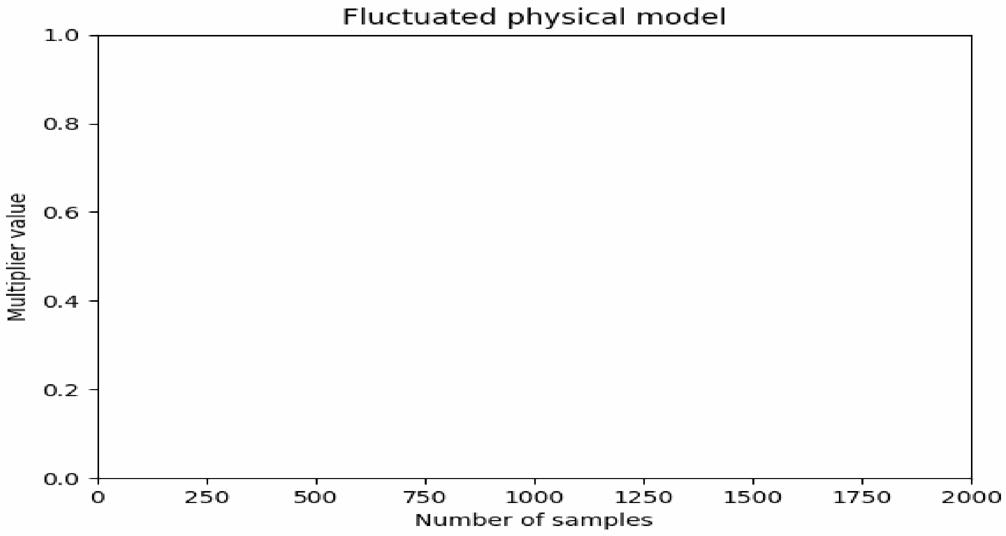


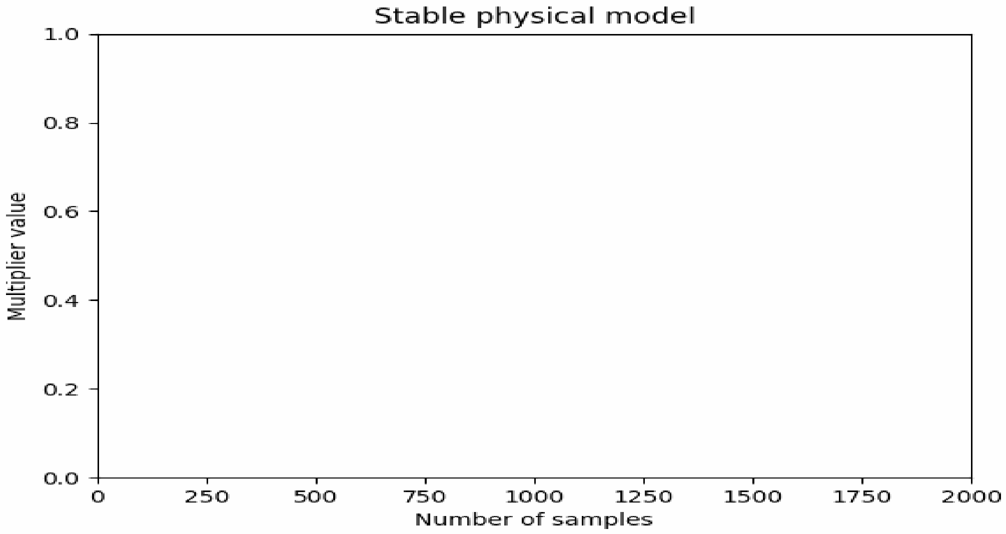



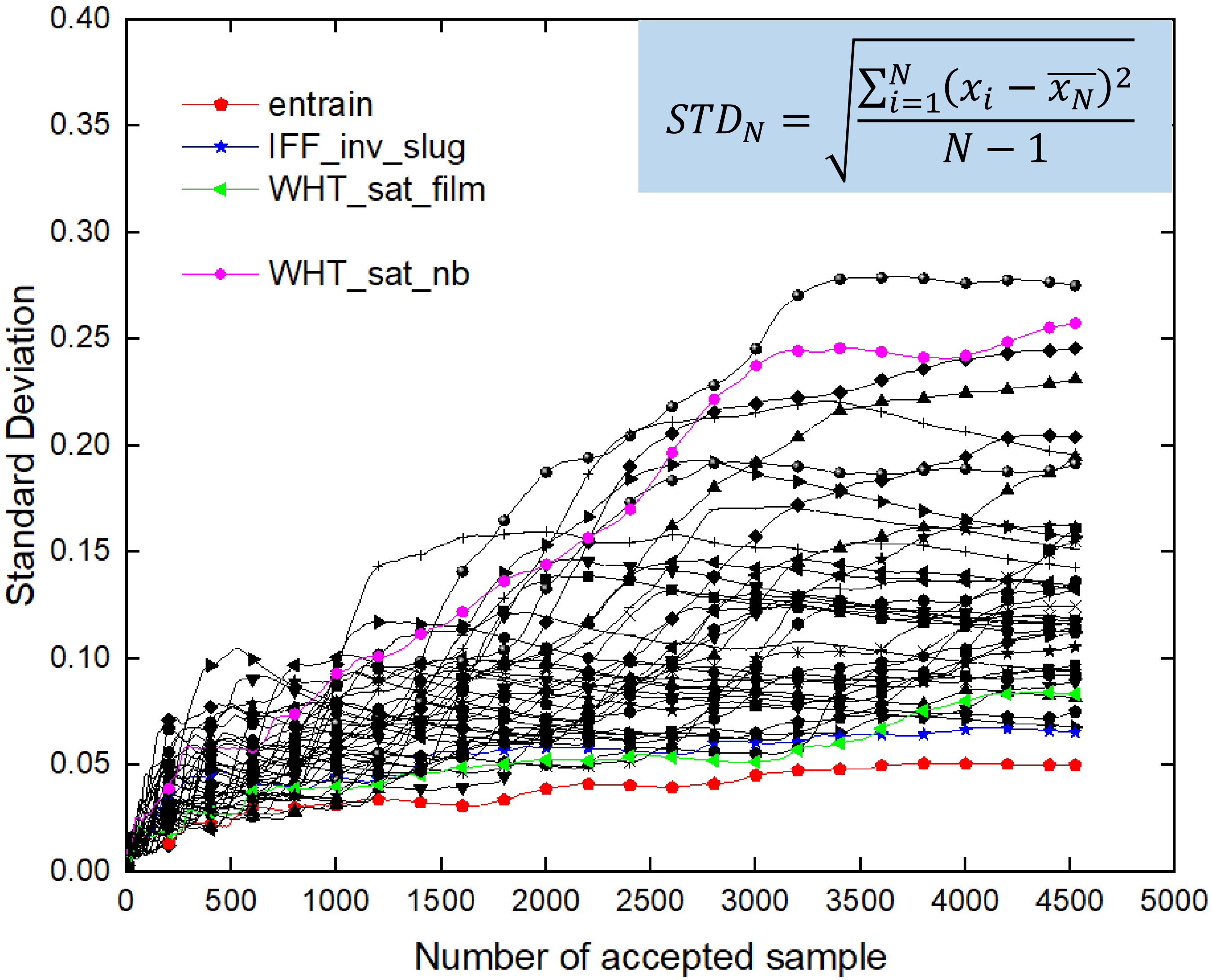

$$e^{\Pi} = exp\left(\prod_{i=1}^{i=n} x_i\right) \quad ; \bar{x} = \frac{1}{n}\left(\sum_{i=1}^{i=n} x_i\right)$$

# 4. Results (4/5)

## The Standard Deviation (STD) result



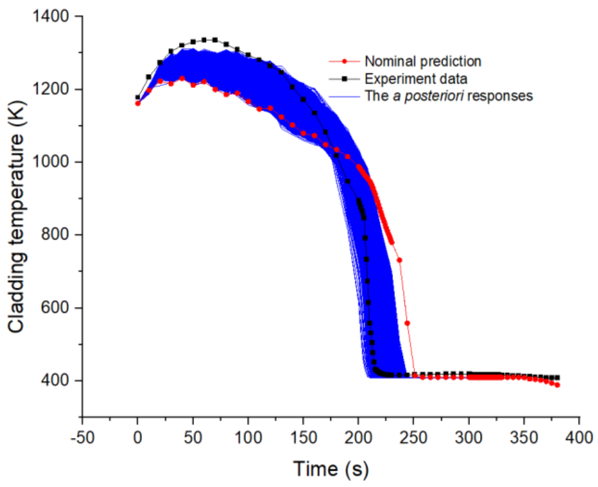



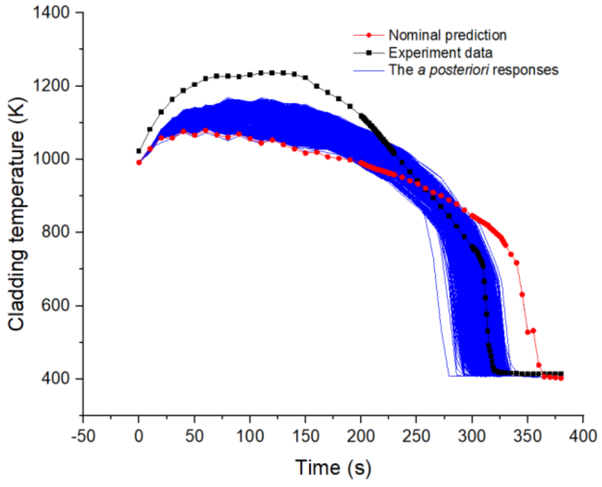

$$STD_N = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \overline{x_N})^2}{N-1}}$$

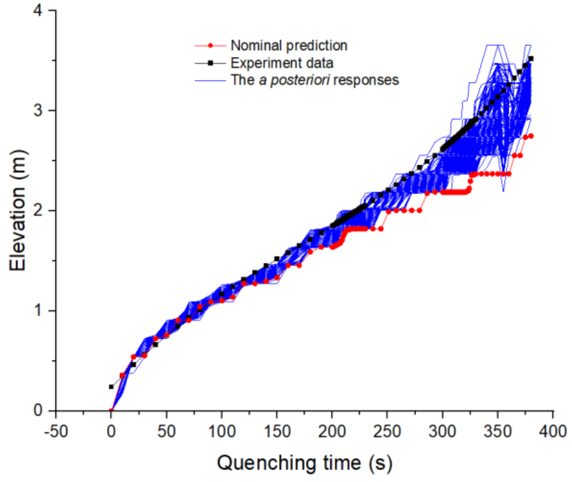
# 4. Results (5/5)

## Cladding temperatures and quenching time improvements

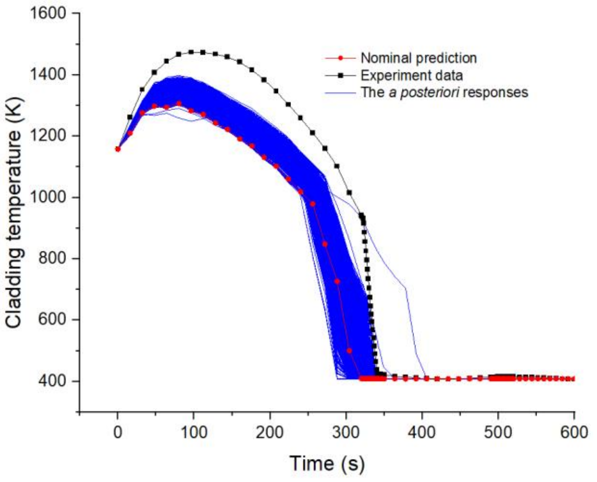
F5-34103 test case

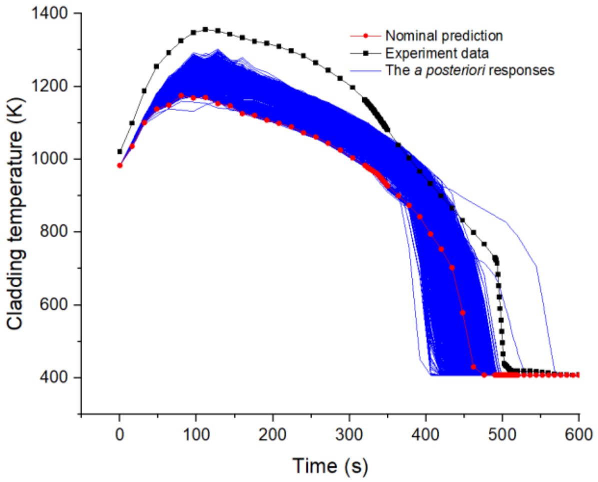


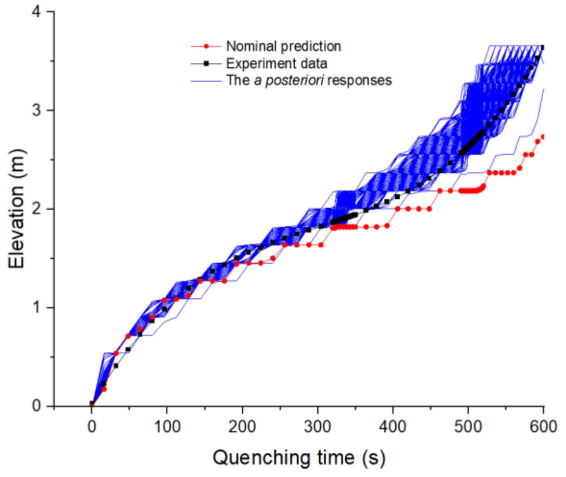




F6-34316 test case



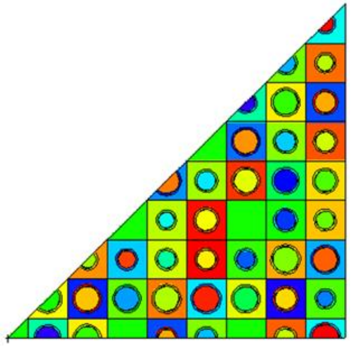
# 5. Conclusion and Future work

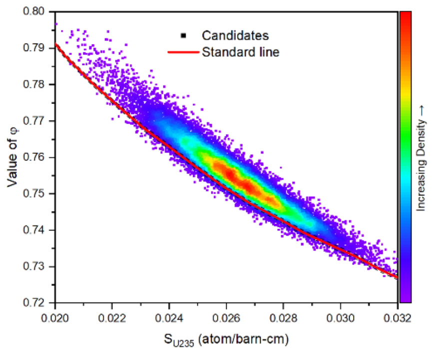
## Concluding remarks for STARU application

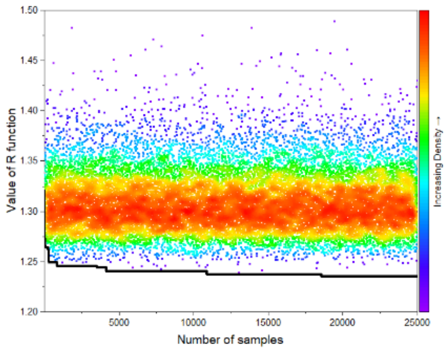
- ✓ The prediction for the F-S reflood tests were enhanced.
- ✓ The most sensitive uncertainty source were identified.

## Future work

- ➢ STARU may be amenable to implementation for the other computer codes to search the best values of the parameters (MARS-KS, RELAP5, MELCOR, CUPID…)
- ➢ STARU can be implemented to find the optimized fuel enrichment configuration (NuScale reactor).





Thank you very much for your attention!

# References


1. Cacuci, D. G., and Ionescu-Bujor, M. 2010. Best-estimate model calibration and prediction through experimental data assimilation-I: Mathematical framework. Nuclear science and engineering, 165(1), 18-44.
2. Candini, A., and Petilli, M. 1973. AMARA: a code using the Lagrange's multipliers method for nuclear data adjustment (No. CNEN-RT/FI--73-39). Comitato Nazionale perl'Energia Nucleare.
3. Carlson, K. E., Riemke, R. A., Rouhani, S. Z., Shumway, R. W., and Weaver, W. L., 1990. RELAP5/MOD3 Code Manual Volume III: Developmental Assessment Problems. NUREG0CR-5535, EGG-2596~ Draft.
4. Choi, T. S., and No, H. C., 2012. An improved RELAP5/MOD3. 3 reflood model considering the effect of spacer grids. Nuclear engineering and design, 250, 613-625.
5. Choi, Ki-Yong, Seok Cho, Hyoung-Kyu Cho, and Chul-Hwa Song, 2010. Parametric sensitivity study on the reflooding models of the MARS code based on 6x6 rod bundle test results. Nuclear technology 170, no. 1: 54-67.
6. E.R. Rosal, T.F. Lin, I.S. McClellan, R.C. Brewer, Rod Bundle Heat Transfer Facility Description Report, NUREG/CR-6976, 2010.
7. Flaspoehler, T. and Petrovic, B., 2016. Radiation damage assessment in the reactor pressure vessel of the integral inherently safe light water reactor (I2S-LWR). EPJ Web of Conferences 106, 03004 (2016).
8. Fukuya, K., 2013. Current understanding of radiation-induced degradation in light water reactor structural materials. Journal of Nuclear Science and Technology, 2013, Vol. 50, No. 3, 213-254.
9. Gandini, A. 1988. Uncertainty analysis and experimental data transposition methods based on perturbation theory. Uncertainty Analysis, 217-258.
10. Ha, K. S., Jeong, J. J., and Sim, S. K., 1998. Improvement of liquid droplet entrainment model in the COBRA-TF code. Nuclear Engineering and Technology, 30(3), 181-193.
11. Ha, S. J., Park, C. E., Kim, K. D., and Ban, C. H., 2011. Development of the SPACE code for nuclear power plants. Nuclear Engineering and Technology, 43(1), 45-62.
12. Heo, J., and Kim, K. D., 2015. PAPIRUS, a parallel computing framework for sensitivity analysis, uncertainty propagation, and estimation of parameter distribution. Nuclear Engineering and Design, 292, 237-247.
13. Heo, J., Kim, K. D., and Lee, S. W., 2018. Validation and uncertainty quantification for FEBA, FLECHT-SEASET, and PERICLES tests incorporating multi-scaling effects. Annals of Nuclear Energy, 111, 499-508.
14. Heo, J., Lee, S. W., and Kim, K. D., 2014. Implementation of data assimilation methodology for physical model uncertainty evaluation using post-CHF experimental data. Nuclear Engineering and Technology, 46(5), 619-632.
15. Heo, J., Turinsky, P. J., and Doster, J. M., 2013. Optimization of Thermal-Hydraulic Reactor System for SMRs via Data Assimilation and Uncertainty Quantification. Nuclear Science and Engineering, 173(3), 293-311.
16. Hochreiter, L. E., F. Cheung, T. F. Lin, A. Baratta, and C. Frepoli, 2000. Dispersed Flow Heat Transfer Under Reflood Conditions in a 49-Rod Bundle: Test Plan and Design-Results from Tasks 1-10. PSU ME/NE-NRC-04-98-041.
17. Hochreiter, L. E., Fan-Bill Cheung, T. F. Lin, S.Ergun, A. Sridharan, A. Ireland, and E. R. Rosal., 2012. RBHT reflood heat transfer experiments data and analysis. Tech. Rep.
18. Ihle, P., and K. Rust., 1984. FEBA: Flooding Experiments with Blocked Arrays: Data Report. Test Series I though IV. Kernforschungszentrum.
19. Jin, Y., Cheung, F. B., Bajorek, S. M., Tien, K., and Hoxie, C. L., 2019. Development of a two-phase flow mass quality correlation in the post-dryout DFFB regime during reflood transients. International Journal of Heat and Mass Transfer, 137, 1076-1087.
20. Jin, Yue, Fan-Bill Cheung, Koroush Shirvan, Stephen M. Bajorek, Kirk Tien, and Chris L. Hoxie, 2020. Numerical investigation of rod bundle thermal-hydraulic behavior during reflood transients using COBRA-TF. Annals of Nuclear Energy 148: 107708.
21. Jeong, J. J., H. Y. Yoon, I. K. Park, and H. K. Cho, 2010. The CUPID code development and assessment strategy. Nuclear Engineering and Technology 42, no. 6: 636-655.
22. Kennedy, M. C., and O'Hagan, A. 2001. Bayesian calibration of computer models. Journal of the Royal Statistical Society: Series B (Statistical Methodology), 63(3), 425-464.
23. Kovtonyuk, A., Lutsanych, S., Moretti, F., and D'Auria, F. 2017. Development and assessment of a method for evaluating uncertainty of input parameters. Nuclear Engineering and Design, 321, 219-229.
24. Lee, N., 1982. PWR FLECHT SEASET unblocked bundle, forced and gravity reflood task data evaluation and analysis report (No. 10). The Commission.
25. Lee, Y. J., BD, C., Park, C. J., and TS, H., 1994. Improvements to the RELAP5/MOD3 Reflood Model and Assessment. Nuclear Engineering and Technology, 26(2), 265-276.
26. Loftus, M. J., Hochreiter, L. E., Conway, C. E., Dodge, C. E., Tong, A., Rosal, E. R., ... and Wong, S., 1981. PWR FLECHT SEASET unblocked bundle, forced and gravity reflood task data report. Volume 1 (No. EPRI-NP-1459-Vol. 1; NUREG/CR-1532-Vol. 1; WCAP-9699-Vol. 1). Westinghouse Electric Corp., Pittsburgh, PA (USA). Nuclear Energy Systems Div.
27. Mascitti, J.A. and Madariaga, M., 2011. Method for the calculation of DPA in the reactor pressure vessel of Atucha II. Science and Technology of Nuclear Installations, Volume 2011, Article ID 534689.
28. Mendizabal, R., de Alfonso, E., Freixa, J., and Reventos, F., 2016. OECD/NEA PREMIUM Benchmark Final Report. NEA/CSNI/R (2016) 18.
29. Murao, Y., and Sugimoto, J., 1981. Correlation of heat transfer coefficient for saturated film boiling during reflood phase prior to quenching. Journal of Nuclear Science and Technology, 18(4), 275-284.
30. NRC, 10CFR.50.46. The acceptance criteria for emergency core cooling system for light water nuclear power reactors (last updated on March 24, 2021).
31. Oberkampf, W. L., Trucano, T. G., and Hirsch, C. 2004. Verification, validation, and predictive capability in computational engineering and physics. Appl. Mech. Rev., 57(5), 345-384.
32. Odar, F., 2001. Assessment of the TRAC-M codes using Flecht-Seaset reflood and steam cooling data. Division of Systems Analysis and Regulatory Effectiveness, Office of Nuclear Regulatory Research, US Nuclear Regulatory Commission.
33. Paik, C. Y., Hochreiter, L. E., Kelly, J. M., and Kohrt, R. J., 1985. Analysis of FLECHT-SEASET 163-rod blocked bundle data using COBRA-TF (No. NUREG/CR--4166). Westinghouse Electric Corp.
34. Petra, N., Martin, J., Stadler, G., and Ghattas, O. 2014. A computational framework for infinite-dimensional Bayesian inverse problems, Part II: Stochastic Newton MCMC with application to ice sheet flow inverse problems. SIAM Journal on Scientific Computing, 36(4), A1525-A1555.
35. Petruzzi, A., and D'Auria, F. 2014. Uncertainties in predictions by system thermal-hydraulic codes: the CASUALIDAD method. In 2014 22nd International Conference on Nuclear Engineering. American Society of Mechanical Engineers Digital Collection.
36. Prošek, A., D'Auria, F., and Mavko, B., 2002. Review of quantitative accuracy assessments with fast Fourier transform based method (FFTBM). Nuclear Engineering and Design, 217(1-2), 179-206.
37. Rosal, E.R., Lin, T.F., McClellan, I.S., Hochreiter, L.E., Cheung, F.B., Rhee, G., Kelly, J.M., and Bajorek, S.M., "The Pennsylvania State University and U.S. Nuclear Regulatory Commission Rod Bundle Heat Transfer Facility," Proc. of the 6th ASME-JSME Thermal Engineering Joint Conference, March 16-20, 2003.
38. Rulko, R.P. (Editor), 1997. Computing radiation dose to reactor pressure vessel and internals. OECD-NEA, NEA/NSC/DOC (96) 5.
39. Seo, Gwang Hyeok, Hong Hyun Son, and Sung Joong Kim, 2015. Numerical analysis of RBHT reflood experiments using MARS 1D and 3D modules. Journal of Nuclear Science and Technology, 52, no. 1: 70-84.
40. Taguchi, G., and Konishi, S., 1987. Taguchi methods: orthogonal arrays and linear graphs-tools for quality engineering. American Supplier Institute. Center for Taguchi Methods.
41. Tarantola, A. 2005. Inverse problem theory and methods for model parameter estimation. Society for Industrial and Applied Mathematics.
42. The RELAP5-3D Code Development Team, Code Manual Volume IV: Models and Correlations", INEEL-EXT-98-00834-V4, Revision 2.4, June 2005.
43. The TRACE V5.0 United States Nuclear Regulatory Commission, Theory Manual: Field Equations, Solution Methods, and Physical Models, DC 20555-0001.
44. Tiep, N. H., Hoang, S. M. T., Hartanto, D., Kim, K. D., Kim, J. K., Tuan, N. M., & Ha, P. N. V., 2020. Investigation of the VVER-1000 reactor pressure vessel neutron fluence and displacement per atom using MCNP6. Radiation Physics and Chemistry, 177, 109141.
45. Tiep, N. H., Kim, K. D., J. Heo, 2021. Improvement in the accuracy of SPACE prediction for the unblocked FLECHT SEASET reflood tests by data assimilation. Annals of Nuclear Energy, 161, 108462.
46. Tiep, N.H., Kim, K.D., Heo, J., Choi, C.W. and Jeong, H.Y. A newly proposed data assimilation framework to enhance predictions for reflood tests. Nuclear Engineering and Design, 390, p.111724, 2022.
47. Williams, B., Higdon, D., Gattiker, J., Moore, L., McKay, M., and Keller-McNulty, S. 2006. Combining experimental data and computer simulations, with an application to Flyer plate experiments. Bayesian Analysis, 1(4), 765-792.
48. Yadigaroglu, G., Nelson, R. A., Teschendorff, V., Murao, Y., Kelly, J., and Bestion, D., 1993. Modeling of reflooding. Nuclear engineering and design, 145(1-2), 1-35.
49. Yang, Bao-Wen, Stephen M. Bajorek, Yue Jin, and Fan-Bill Cheung, 2021. Progress in reflood thermal hydraulics studies in the past 40 years. Nuclear Engineering and Design 376: 111073.
50. Yoon, Han Young, Jae Ryong Lee, Hyungrae Kim, Ik Kyu Park, Chul-Hwa Song, Hyoung Kyu Cho, and Jae Jun Jeong, 2014. Recent improvements in the CUPID code for a multi-dimensional two-phase flow analysis of nuclear reactor components. Nuclear Engineering and Technology 46, no. 5: 655-666.
51. Yoo, Jee Min, Yun Je Cho, Han Young Yoon, and Jae Jun Jeong, 2019. Analysis of the effect of liquid droplet models on the reflood heat transfer using the CUPID code. Nuclear Engineering and Design 354: 110148.
52. Yoon, S. H., Kim, K. D., Heo, J., You, B. H., and Ha, K., 2020. Effects of newly developed entrainment model for a thermal hydraulic system code (SPACE) based on breakup of large droplets in reflood. Annals of Nuclear Energy, 144, 107582.