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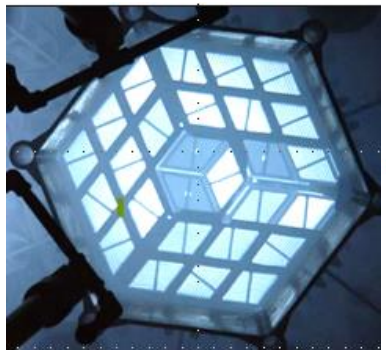
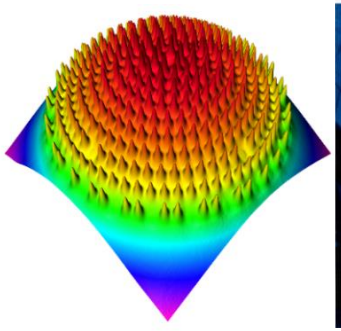
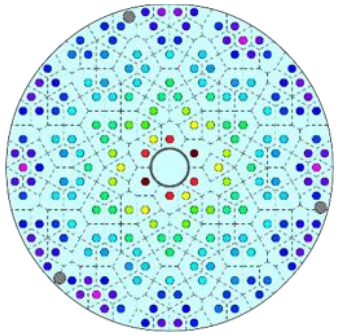
MATERIAL MANAGEMENT AND MINIMIZATION
CONVERT, REMOVE, DISPOSE

STAT7: Best Estimate Plus Uncertainty Approach to Predict Onset of Nucleate Boiling and Onset of Flow Instability Using Monte Carlo Method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National Nuclear Security Administration

U.S. DEPARTMENT OF ENERGY
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STAT7 Role in Technical Analyses Supporting Reactor Conversion

- Conversion analyses address
  - Neutron flux in experimental locations (often the prime mission)
  - Reaction rates, cycle length, fuel lifetime (economics)
  - Facility safety basis
- Analysis scope may include
  - Steady-state neutronics plus depletion & fuel shuffling
  - Steady-state thermal hydraulics safety analysis
  - Transient safety analysis
  - Structural mechanics & fluid-structure interactions
  - Materials & fuels performance

MIT reactor

- STAT7 statistical analysis methodology directly addresses important aspect of reactor licensing, e.g. measurement, fabrication, modeling uncertainties, and provides TH core performance parameters, LSSS and safety limits (SL). Currently RELAP5 (or other best estimate TH codes) do not have these capabilities without coupling to other codes.

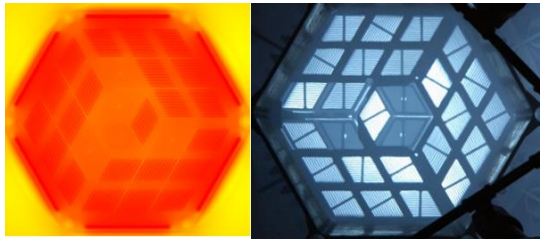
MATERIAL MANAGEMENT AND MINIMIZATION

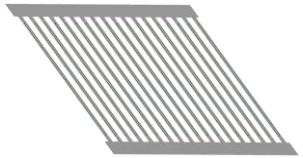
Computational Capabilities

Software for conversion, PRO-X analysis (blue = Argonne developed)

Neutronics & Depletion		Thermal Hydraulics & Safety Performance	
• MCNP5 • MCNP6.2 • SERPENT	• **ADDER** • **REBUS-PC** • VESTA • ORIGEN2.2	• **PLTEMP/ANL** • **STAT7 (in collaboration with MIT)**	• **PARET/ANL** • RELAP5-3D • RELAP5/Mod3.3
Fuel Performance		**Computational Structural Mechanics & Computational Fluid Dynamics (CSM & CFD)**	
• **DART** • LAMMPS • VASP		• COMSOL Multiphysics • FENICS • STAR-CCM+	

Statistical Approach for Uncertainties in the Steady-State Thermal Hydraulics Calculation: STAT7



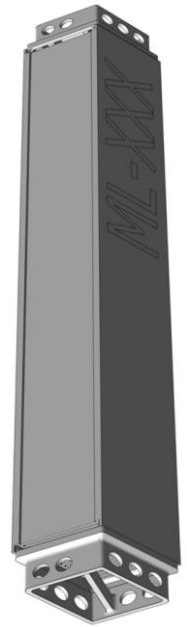


Summary:

- STAT7 is used to predict steady-state thermal-hydraulic performance and safety margins of research reactors (currently supporting MITR conversion project) with a statistical uncertainty propagation for key reactor parameters and fuel fabrication tolerances.

Key Information

- **Development history:** First official release of STAT7 v1.0 in 2017.
- **Current release:** STAT7 v1.1
- **Key capabilities:** Determine fuel plate temperatures (with or without fins), and coolant mass flow rate in parallel channels, including bypass channels, for steady-state flow; 1D heat transfer for fuel plates; single searches for power at which onset of nucleate boiling occurs at given probability (P_{ONB}); single searches for power at which onset of flow instability occurs at given probability (P_{OFI}).
- **Application:** Forced flow heat transfer uncertainty propagation; Ongoing LEU conversion support for MITR-II.
- **Advantages**: Efficiently determine core power TH margins such as ONB with statistical uncertainty propagation using Monte Carlo method.



MATERIAL MANAGEMENT AND MINIMIZATION

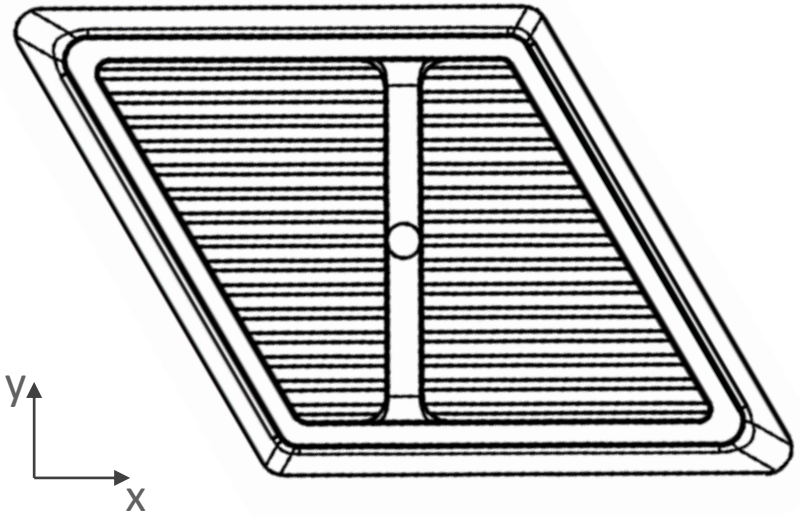
STAT7 Core Capabilities

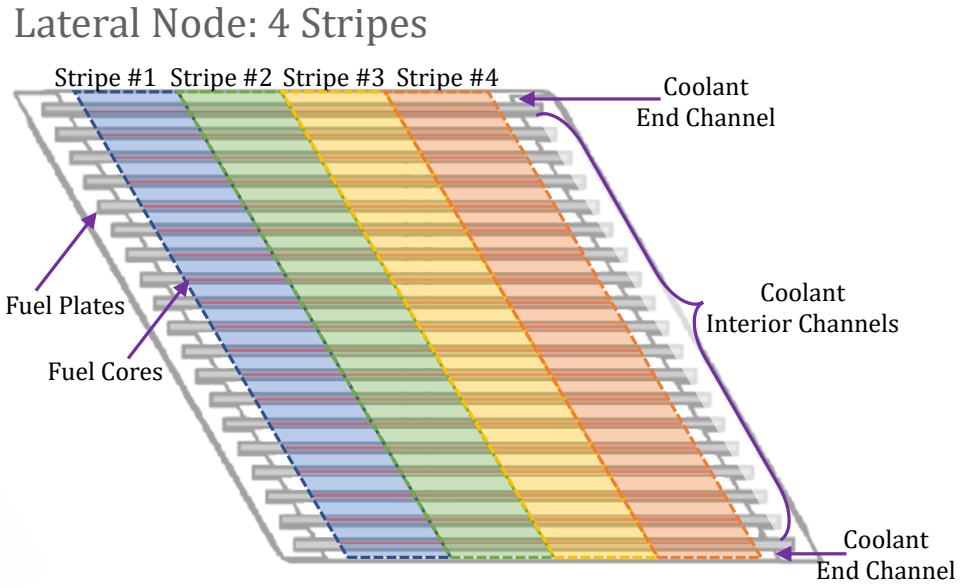
No.	Capabilities
1	Statistical Sampling
2	Water property
3A	Basic TH Calculation
3B	Bypass Option
3C	End-channel Treatment
3D	Fin option
3E	Viscosity effect
3F	Power split
3G	ONB Calculation
3H	OFI Calculation (Available in V1.1)

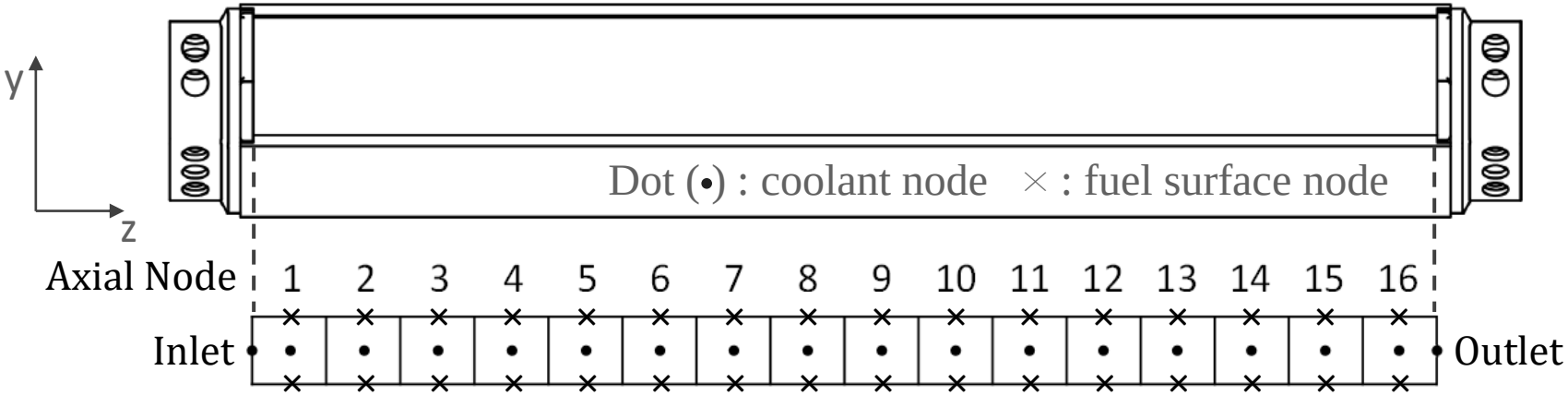
- STAT7 uses a Monte Carlo approach to address uncertainties from fabrication and other key reactor parameters.
- STAT7 accommodates flexibility in analyzing many realistic aspects of reactor fuel managements for the plate-type fuels with simple input settings.
- STAT7 automates multiple runs of the steady-state TH calculations with statistical prediction of safety limits such as onset of nucleate boiling (ONB) and onset of flow instability (OFI, in V1.1).
- STAT V1.1 update (from V1.0) provides one major bug fix (correction in bypass flow rate calculation for finned fuel assembly) and one major new calculation capability (No. 7 – OFI Calculation).

- Verification and Validation methods for capabilities no. 1 and 2 (random number generator and water properties fit functions) have been updated to test the capabilities directly from the implementation by employing of the Fortran to Python interface generator, “F2Py”, which is a utility provided by the “NumPy” Python library.

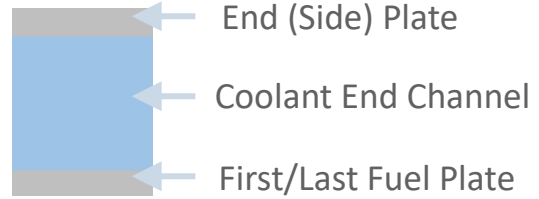
STAT7: MITR Fuel Element Modeling



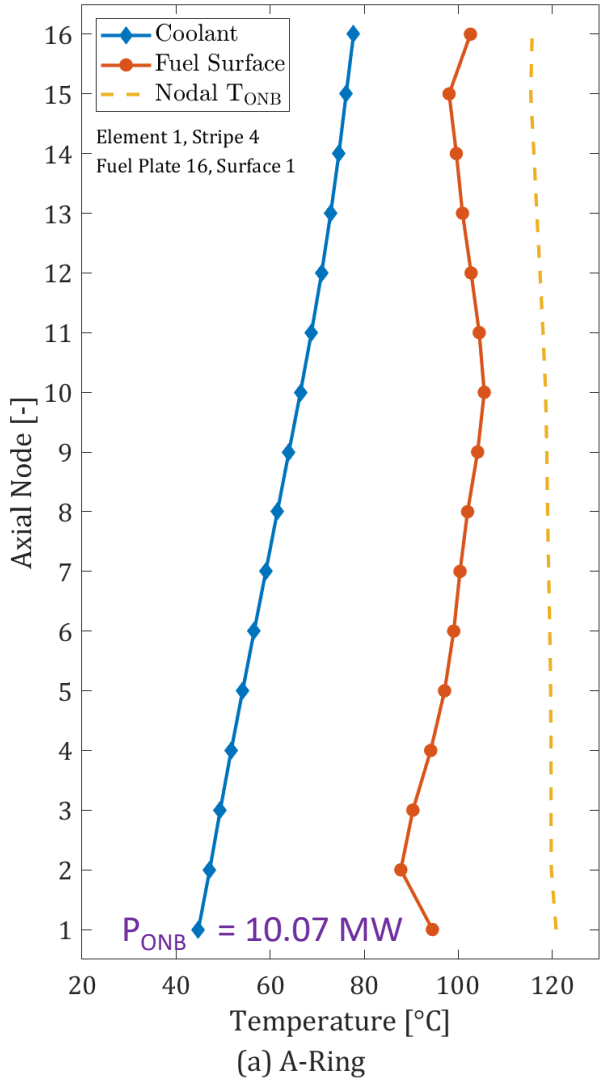




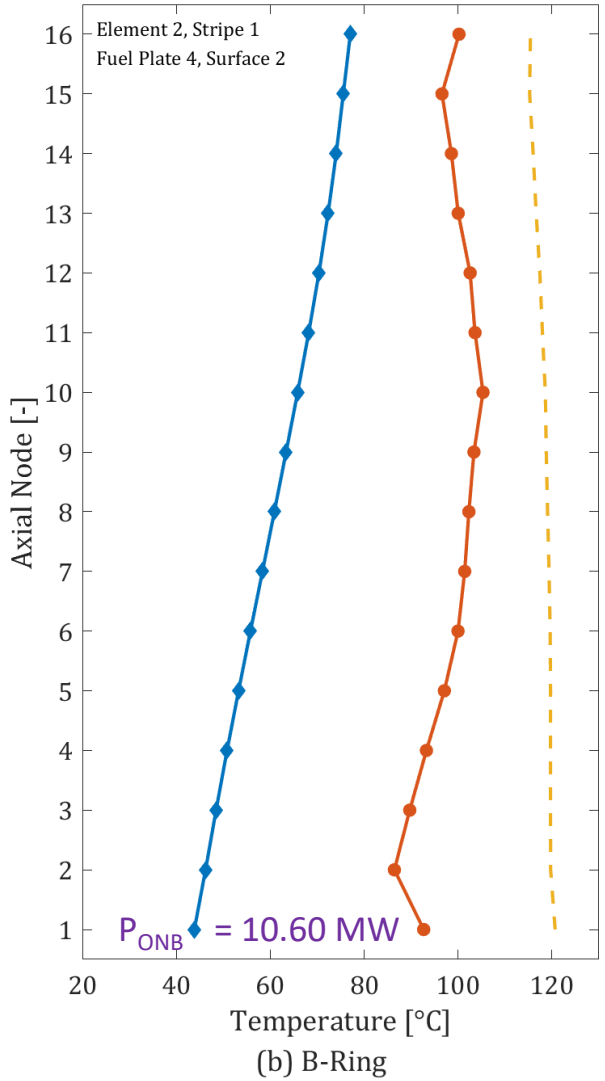
- The current nodalization scheme of MITR fuel element (LEU and HEU) in STAT7 employs 4 lateral nodes (stripes) and 16 axial nodes.
  - Axial heat conduction is not solved.
  - In addition to 16 axial nodes defined at the cell center for both coolant and fuel surface nodes, coolant inlet and outlet nodes are defined at the cell face.
- Boundary condition for the coolant end channel can be:
  - No slip walls + one-sided heating.
  - Slip wall (one-side) + one-sided heating.
  - No slip walls + two-side heating. (Not in use for the MITR analysis).



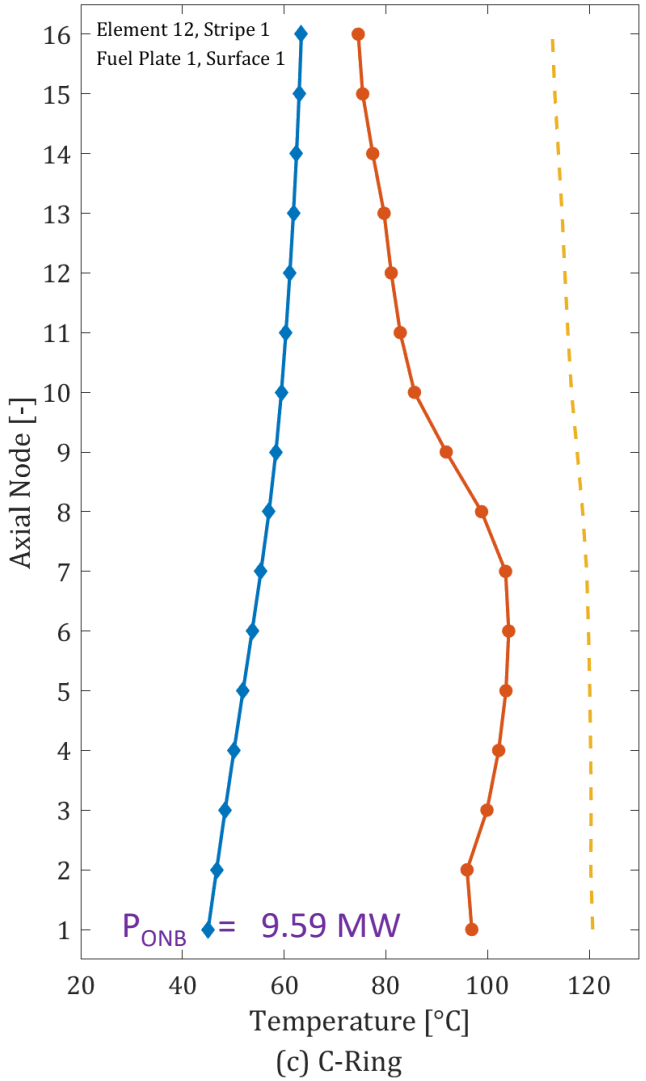
STAT7: Typical Temperature Distribution of MITR LEU element



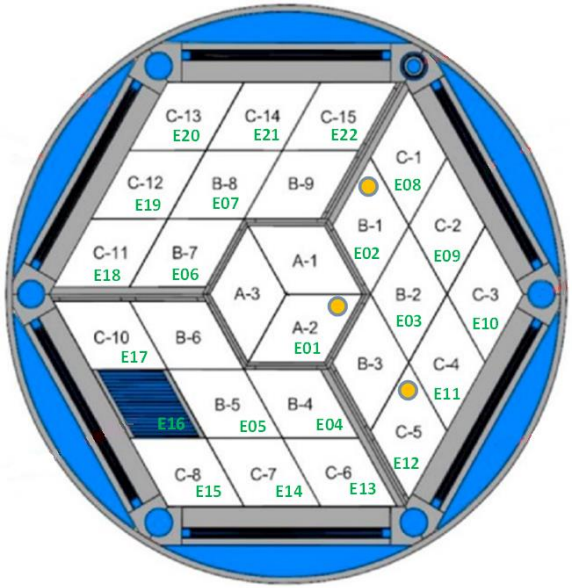
(a) A-Ring



(b) B-Ring



(c) C-Ring



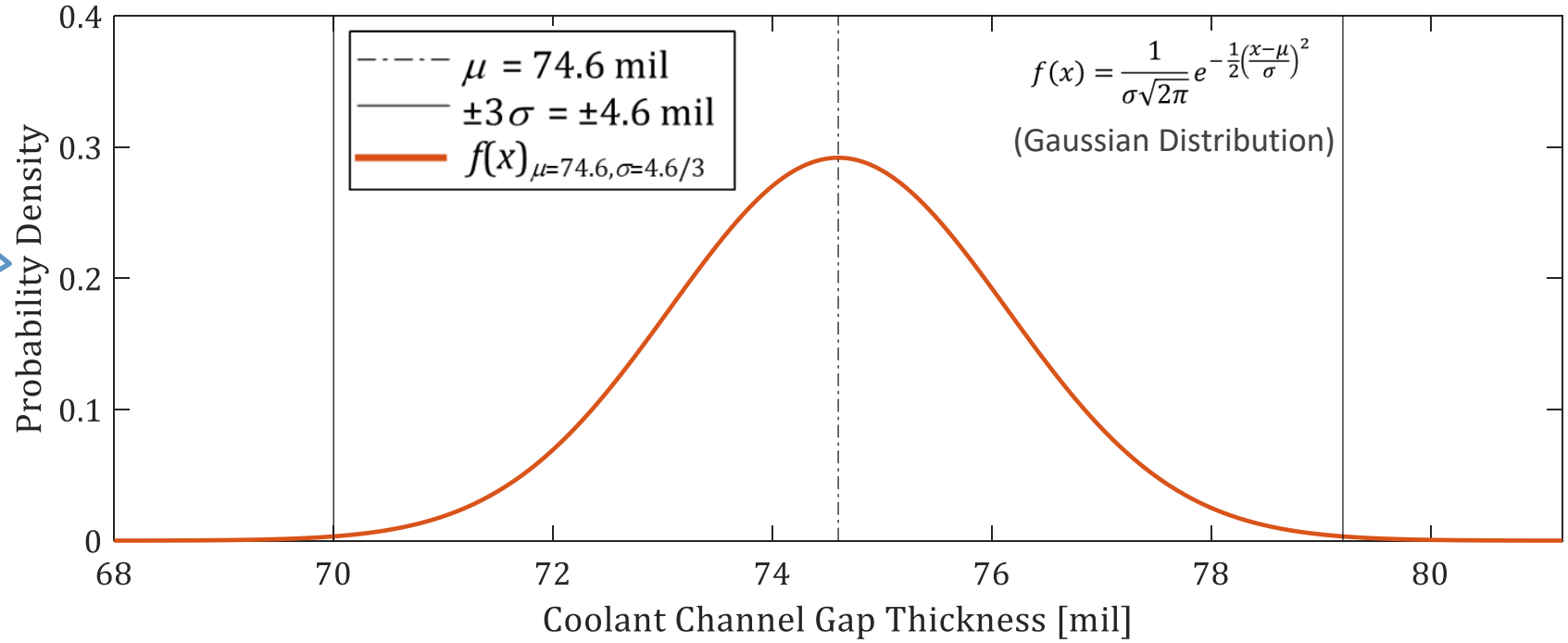
P_{LSSS} = 8.68 MW

Temperature Profiles from Various Reactor Locations at corresponding P_{ONB}

MATERIAL MANAGEMENT AND MINIMIZATION

Typical Uncertainties Imposed in STAT7 Calculation for MITR Analysis

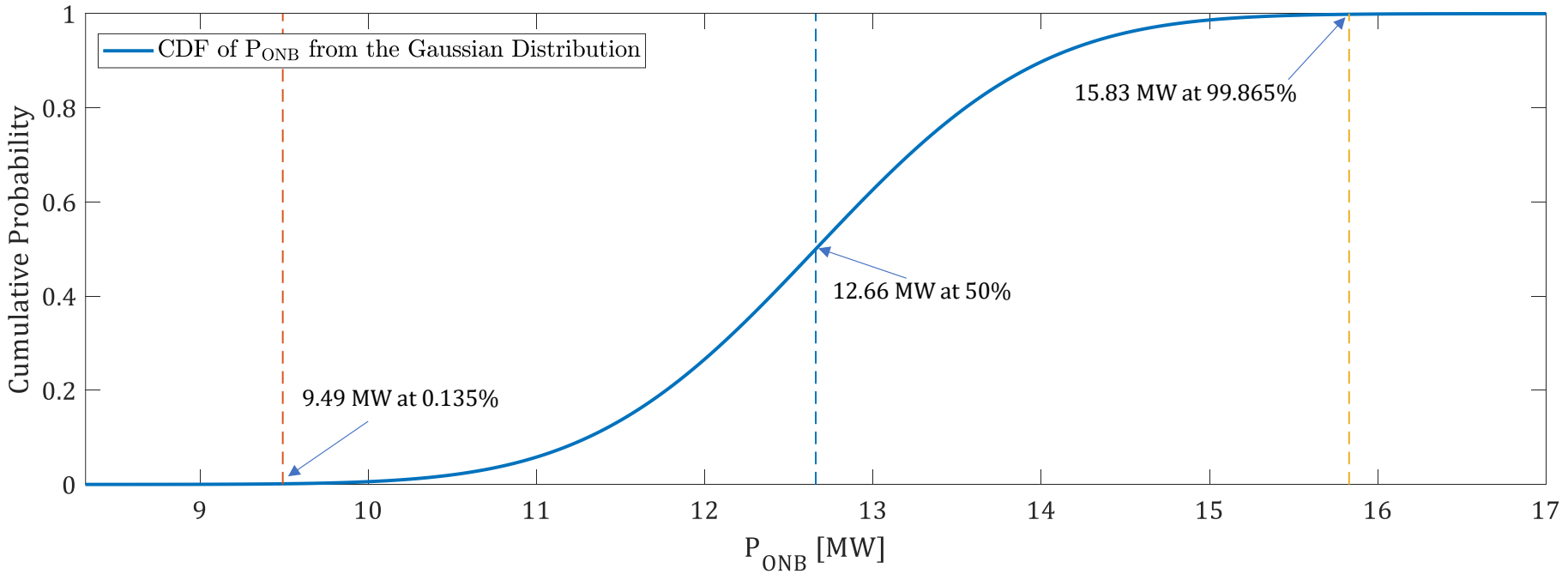
Uncertainty Parameters	3σ uncertainty (%)
Reactor Power Measurement	5.00
Primary Flow Measurement	5.00
Film Heat Transfer Coefficient	20.0
Local Power	14.1
Coolant Channel Gap Thickness	6.17



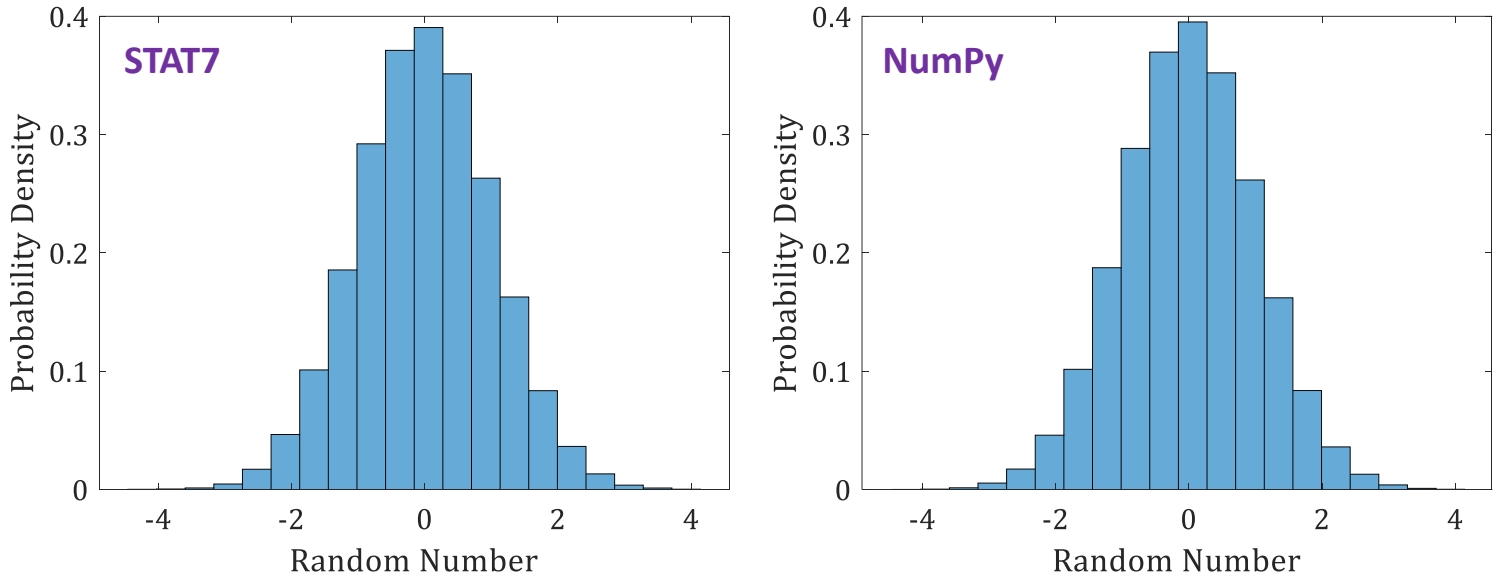
- The Uncertainty parameters are statistically sampled with corresponding 3σ uncertainty and nominal input values. The sampled quantities are employed in the TH calculations with many histories (typically 100,000 histories) for uncertainty propagation.

Thermal Hydraulics Safety Limits - ONB & OFI

- NUREG-1537, Part II, *Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors*, the acceptance criteria for the TH design in research and test reactor with a forced-convection cooling system include avoiding departure from nucleate boiling (DNB) or critical heat flux (CHF) and avoiding flow instability in any fuel channel.
- In some reactor analyses, including MITR-II, limits – such as limiting safety system settings (LSSS) – are based on avoiding onset of nucleate boiling (ONB) to provide additional margin because ONB will occur before either onset of flow instability (OFI) or CHF. STAT7 can predict the operational safety margins to ONB (using Bergles-Rohsenow Correlation) or OFI (using Whittle and Forgan Correlation) with statistical uncertainty propagation.



STAT7: Statistical Sampling using the Random Number Generator



Normalized standard normal distribution generated by STAT7 (left) and NumPy Python library (right)

- The generated set of numbers passed the χ^2 goodness-of-fit test; thus, the distribution follows the standard normal distribution with a 95% level of confidence.

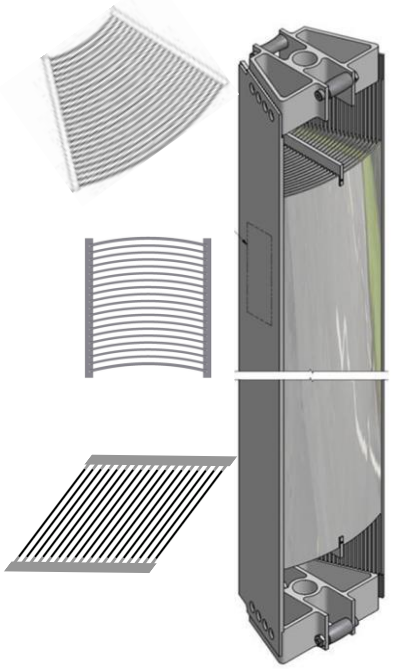
- The generated set of numbers passed the runs test for randomness; thus, the numbers are generated randomly with a 95% level of confidence.

STAT7: Code-to-code Verification of General TH & ONB Calculation Capabilities Against PLTEMP/ANL Code

- **Test problem specifications**

  - A hypothetical fuel element with 4 fuel plates with different power factors (0.4, 0.8, 1.2, and 1.6)
  - STAT7 and PLTEMP/ANL simulations are carefully aligned to ensure consistent initial and boundary conditions.
  - Fuel plates have fins to increase surface area of heat transfer

PLTEMP/ANL



Summary:

- PLTEMP/ANL is used to predict steady-state thermal-hydraulic performance and safety margins of research reactors.

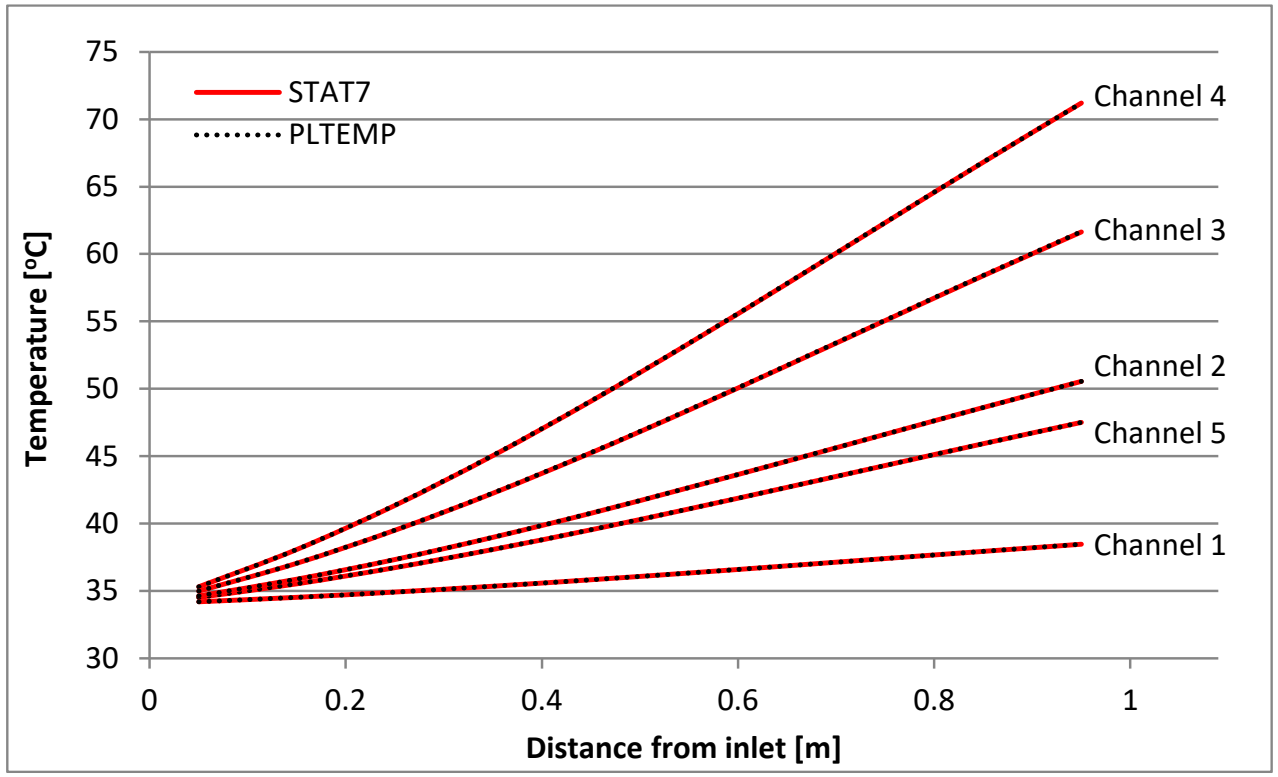
Key Information

- **Development history:** First release of PLTEMP/ANL in 1985. Continually updated to address reactor conversion needs (including appropriate correlations).
- **Current release:** PLTEMP/ANL v4.3.
- **Key capabilities:** Determine fuel plate (flat or curved, with stripes) or pin temperatures, and coolant mass flux in parallel channels, including bypass channels, for steady-state flow; 2D heat transfer for fuel plates; single/double searches for many output parameters.
- **Application:** Many conversions completed worldwide and used in licensing, covering natural convection and forced flow.
- **Advantages**: Efficiently determine margins to ONB, DNB, and OFI, with and without hot channel factors, including extension to whole core modeling and coupling to graphics.
- **Coming soon**: 3D heat conduction and Turbulence mixing in PLTEMP/ANL v4.4.

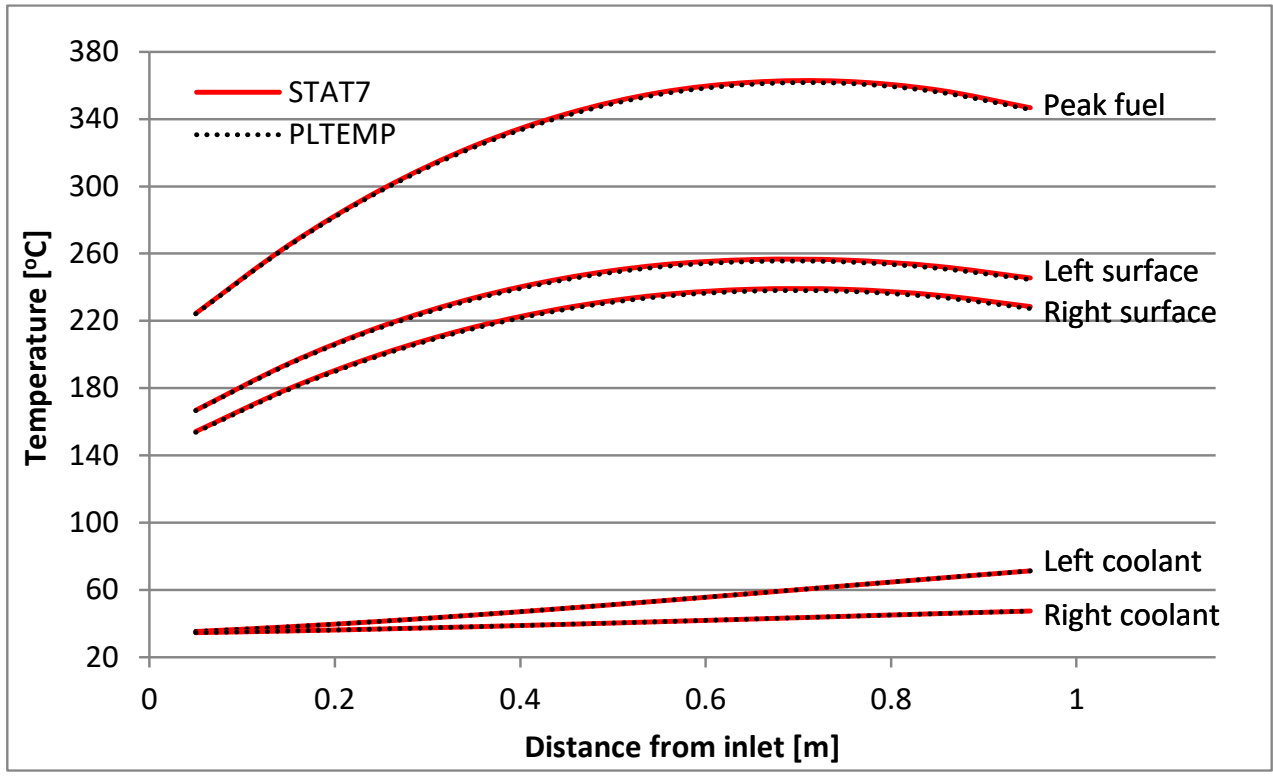
MATERIAL MANAGEMENT AND MINIMIZATION

STAT7 vs PLTEMP/ANL: General TH & ONB Verification Results

- **Verification results**



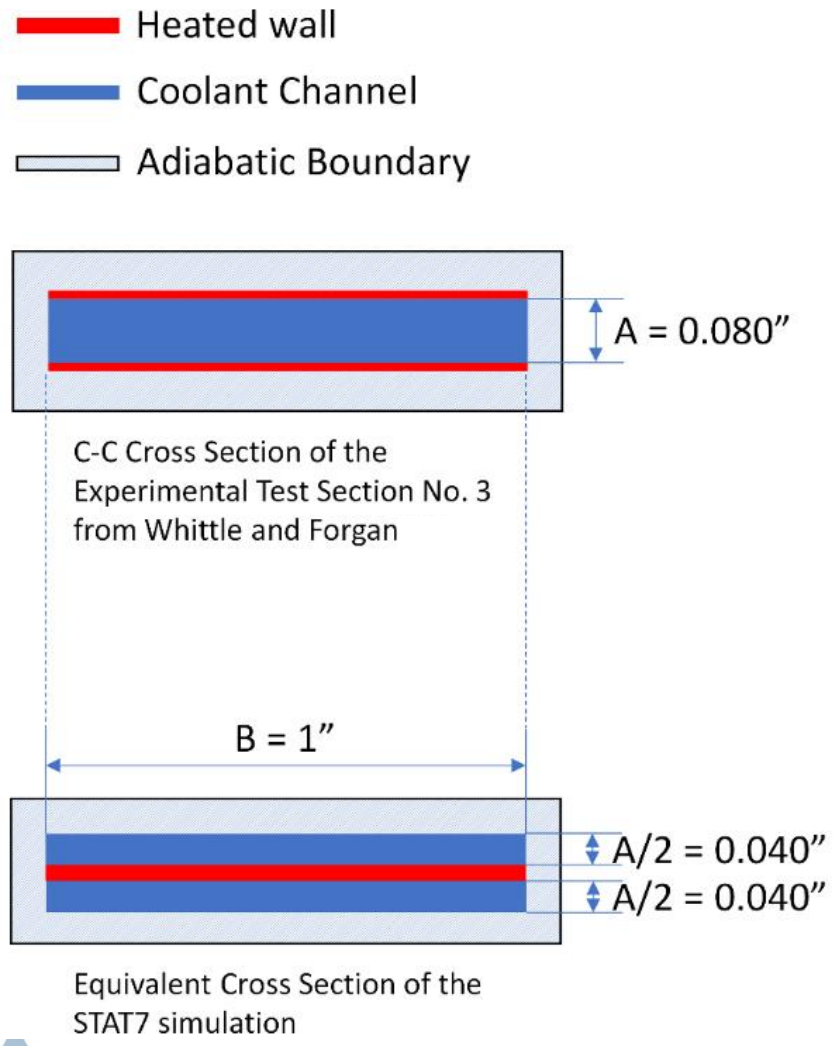
Coolant temperature profiles for all channels



Fuel Plate #4 temperature profiles

STAT7: Code-to-code Verification of OFI Calculation Capabilities Against PLTEMP/ANL Code

- **Test problem specifications**



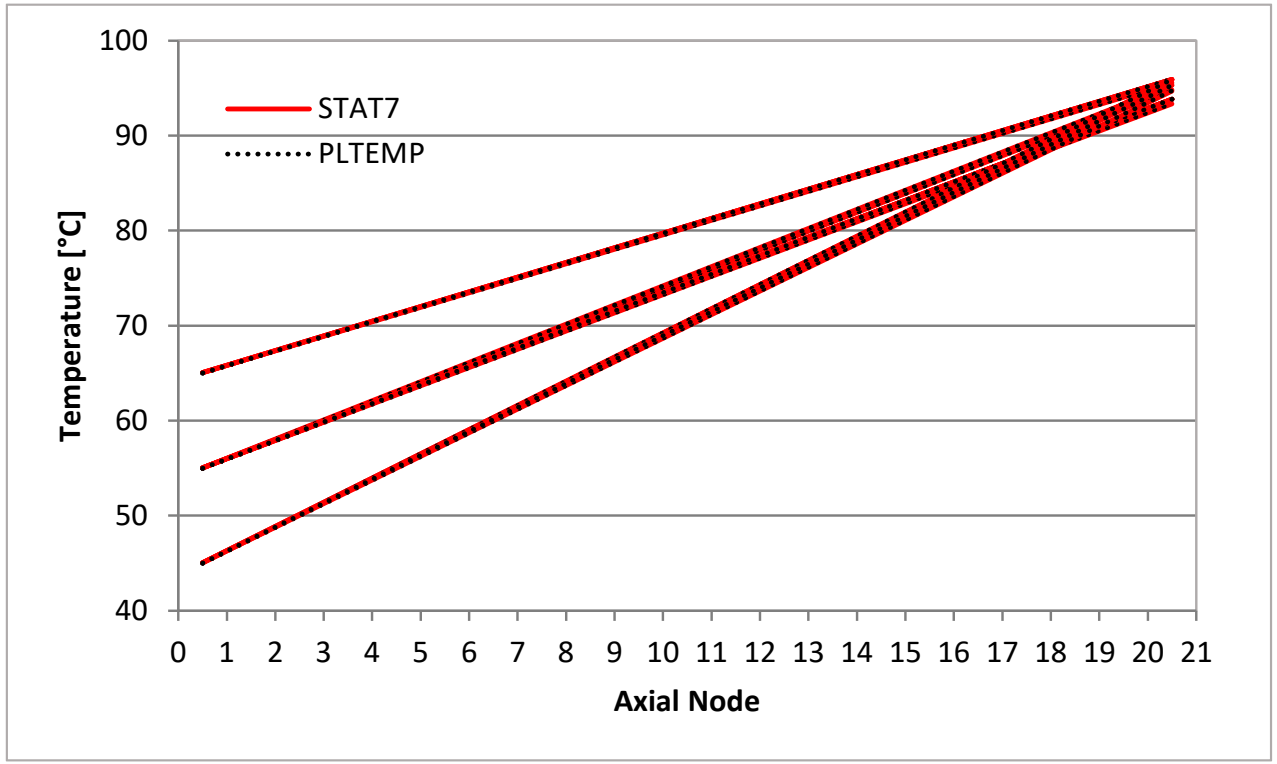
No.	Coolant gap thickness	Fuel width	L_H	Length between pressure taps	L_H/D_H	P_H/P_W
1	0.127	1.0	24	24.5	94.5	0.890
2	0.096	1.0	16	19.0	83.0	0.910
3	0.080	1.0	16	19.0	100.0	0.925
4	0.055	1.0	21	21.5	191.0	0.950

- 16 different test cases with 4 different test sections are established to simulate the experiment from Whittle and Forgan (1967).
- To accurately replicate the experimental conditions, the simulations utilize a model where a single rectangular channel with heated side walls is represented as two rectangular half channels. This modeling approach preserves all geometric parameters in the experiment.

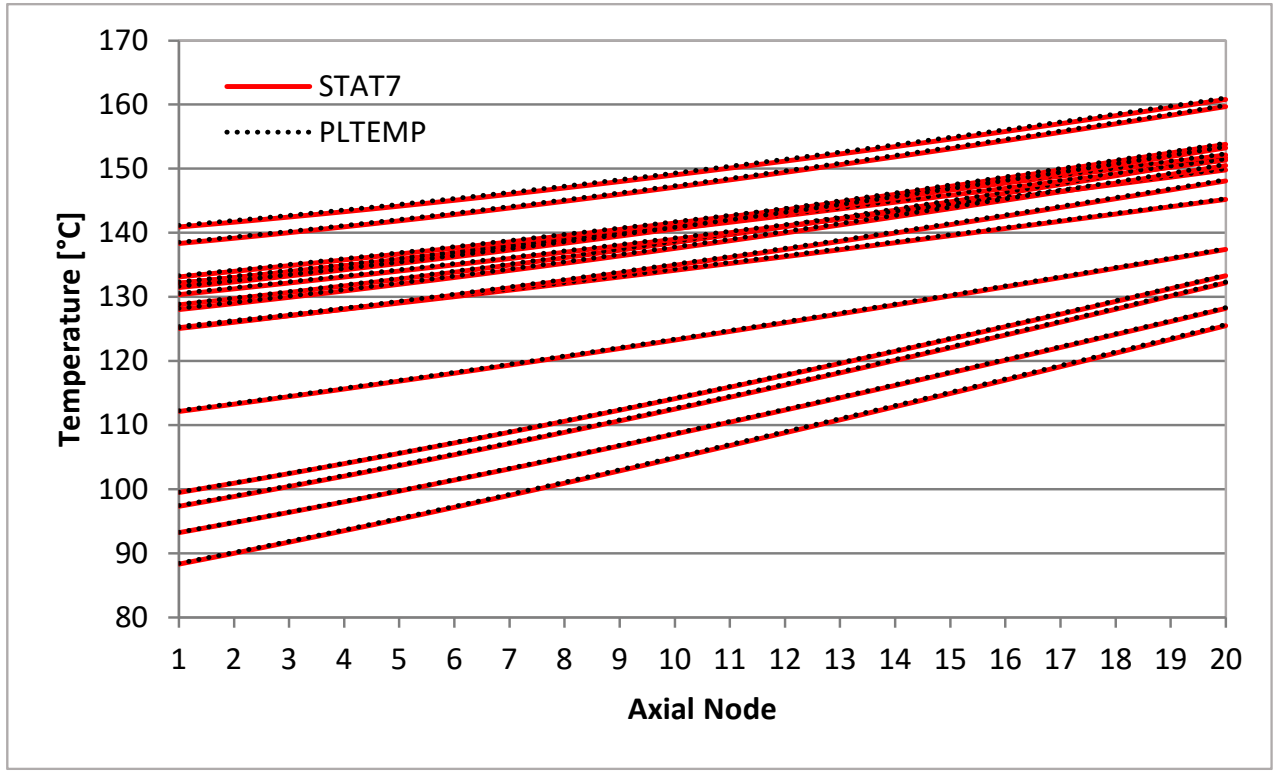
MATERIAL MANAGEMENT AND MINIMIZATION

STAT7 vs PLTEMP/ANL : OFI Temperature Verification Results

- **Verification results**



Coolant temperature profiles



Fuel Plate temperature profiles

STAT7 vs PLTEMP/ANL : OFI Power Search Verification Results

- **Verification results**

	Experiment			STAT7		PLTEMP/ANL		Code-to-code
Test Section	$q''_{OFI,EXP}$ [W/cm^2]	$P_{OFI,EXP}$ [MW]	η	P_{OFI} [MW]	|1-C/M[a]|	P_{OFI} [MW]	|1-C/M[a]|	Relative difference
No. 1	104	0.0322	22.1	0.0322	0.0%	0.0323	0.3%	0.29%
	145	0.0449	25.2	0.0448	0.2%	0.0450	0.2%	0.39%
	184	0.0570	20.8	0.0568	0.3%	0.0571	0.2%	0.49%
	250	0.0774	25.2	0.0772	0.3%	0.0775	0.2%	0.44%
No. 2	123	0.0254	22.1	0.0254	0.0%	0.0255	0.4%	0.36%
	177	0.0365	22.1	0.0365	0.1%	0.0367	0.3%	0.44%
	203	0.0419	22.1	0.0418	0.3%	0.0421	0.3%	0.59%
	218	0.0450	23.4	0.0449	0.2%	0.0452	0.3%	0.57%
No. 3	66	0.0136	28.2	0.0136	0.2%	0.0137	0.2%	0.43%
	177	0.0365	26.6	0.0365	0.1%	0.0366	0.2%	0.32%
	218	0.0450	26.6	0.0449	0.2%	0.0451	0.2%	0.44%
	276	0.0570	26.6	0.0569	0.1%	0.0571	0.2%	0.34%
No. 4	67	0.0182	31.1	0.0182	0.2%	0.0182	0.1%	0.12%
	127	0.0344	36.3	0.0344	0.0%	0.0345	0.2%	0.21%
	176	0.0477	31.1	0.0476	0.2%	0.0478	0.1%	0.33%
	226	0.0612	33.8	0.0611	0.2%	0.0613	0.1%	0.33%

Conclusion

- The general statistical approach and thermal hydraulics calculation capabilities of STAT7 are described.
- Key capabilities of the STAT7 software including the random number generator, onset of nucleate boiling and onset of flow instability calculations have been verified and validated.
- The random number generator has been verified and validated using the F2Py interface. The generated random number sequence passed the χ^2 goodness-of-fit test and run test for randomness with 95% confidence level.
- The hydraulics, heat transfer, onset of nucleate boiling, and onset of flow instability prediction capabilities are verified and validated using code-to-code comparison against another Argonne-developed thermal hydraulics software, the PLTEMP/ANL v4.3 code.
- In addition, the onset of flow instability power search capability is validated against the Whittle and Forgan experimental data.
- The code-to-code comparison results showed good agreements between PLTEMP/ANL and STAT7 results with the maximum relative difference of 0.60%. The validation results against the experimental data also showed good agreements as well (≤0.3%).

Acknowledgement

- The authors express their gratitude to the staff of the MIT Nuclear Reactor Laboratory with whom this code was conceived. In particular, the Master's degree work of Keng-Yen Chiang provided the initial methodology to begin this effort which was continued in a collaboration between MIT and Argonne staff. Floyd Dunn, who originally authored this software, Son Pham who originally completed the STAT7 V&V referred to in this work, and Joshua Rudolph who developed the F2Py interface for STAT7 are gratefully acknowledged.
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Thank You!
Any Questions?