INL/CON-23-72459-Revision-0

Modelling Nuclear Thermal Propulsion Reactor Expander Cycle Startup Transients

May 2023

Changing the World's Energy Future

Lise Cecile Madeleine Charlot, Vincent M Laboure, Mark D DeHart, Sebastian Schunert

Idaho National Laboratory

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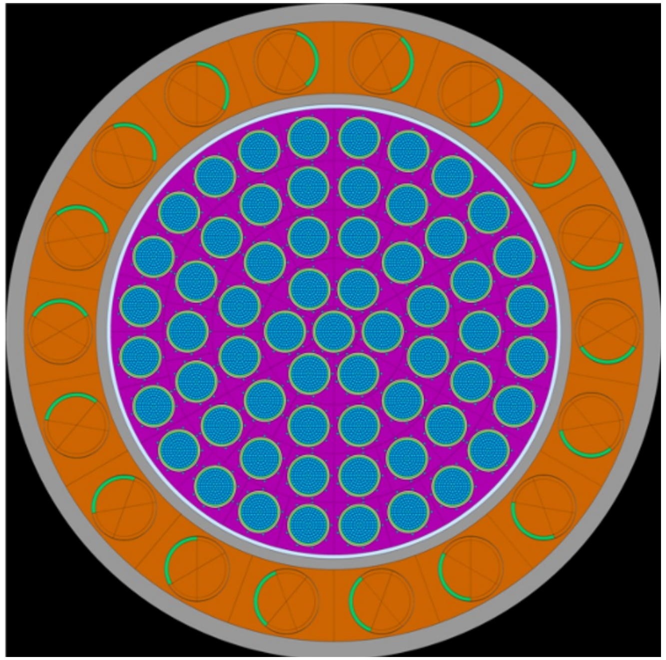
Overview

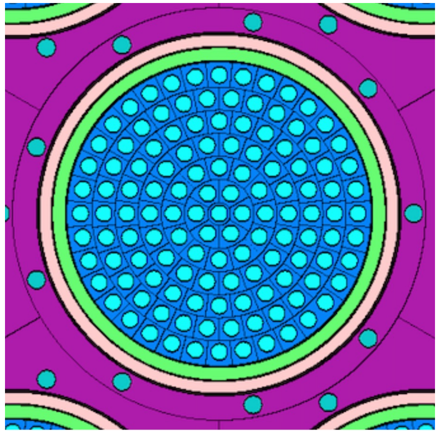
- System description
- Simulation tools: Griffin and RELAP-7/THM
- Modeling strategy
- Results

System description: Core Design

- Based on a BWXT/NASA Heat Transfer Working Group Nuclear Thermal Propulsion (NTP) concept
- 61 CERMET fuel assemblies arranged in circular rings
- Zirconium hydride (ZrH) monolith acting as a neutron moderator
- A radial reflector made of beryllium surrounds the core and includes 18 control drums
- Hydrogen cooling channels in the fuel matrix, moderator, and reflector



Radial cross-section of the core [1]

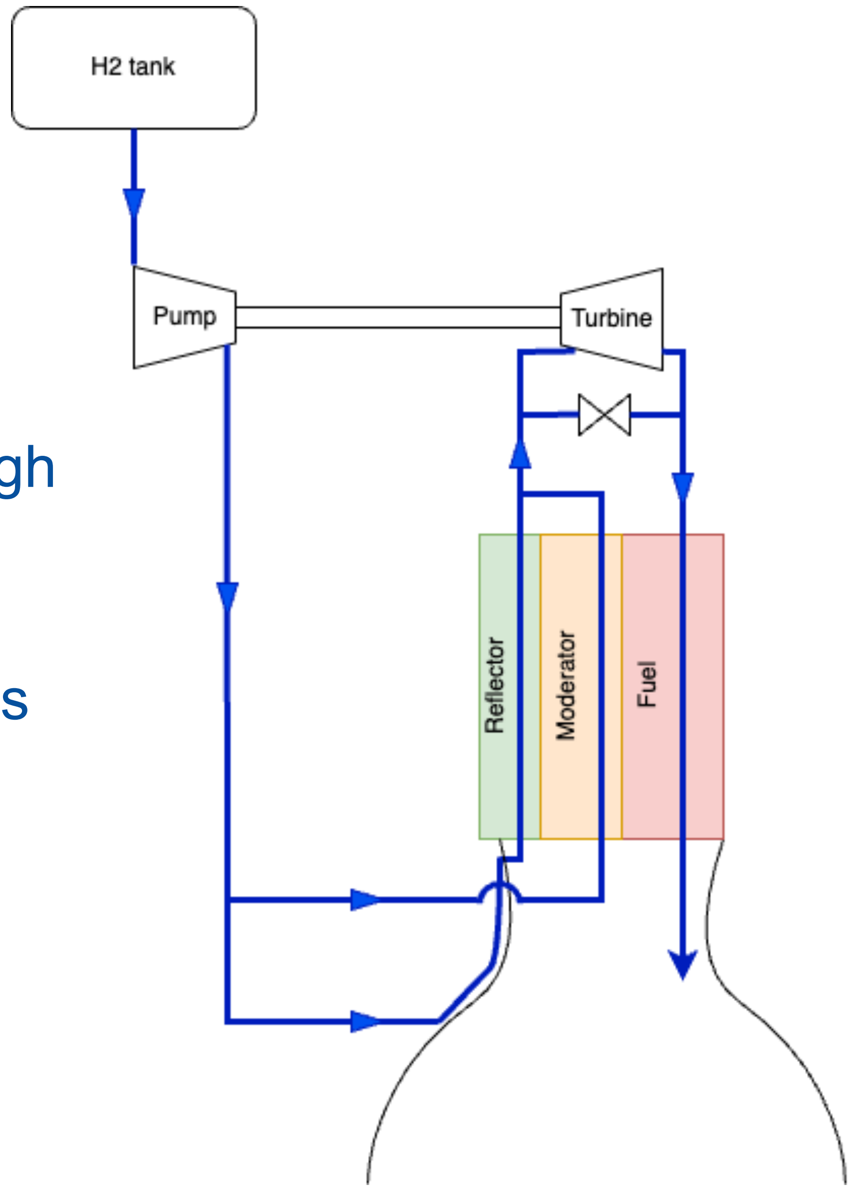


Assembly [1]

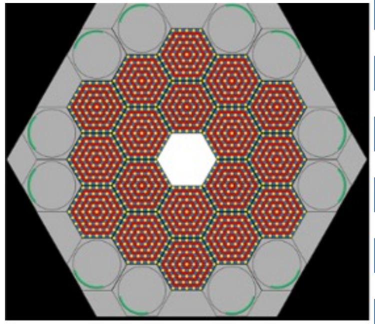
[1] Automated Power-following Control for Nuclear Thermal Propulsion Startup and Shutdown Using MOOSE-based Applications, Labouré et al., Progress in Nuclear Energy

Expander Cycle

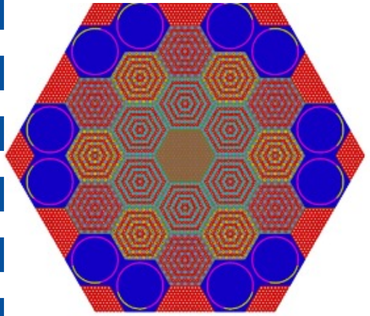
- Hydrogen is drawn from the tank by the pump
- Flow is split into two paths:
  - Regenerative cooling of the nozzle and through the reflector
  - Through the moderator
- Flow recombines to enter the turbine or its bypass
- Turbine and pump share the same shaft
- Fluid flows through the fuel cooling channels and exits through the nozzle to generate thrust



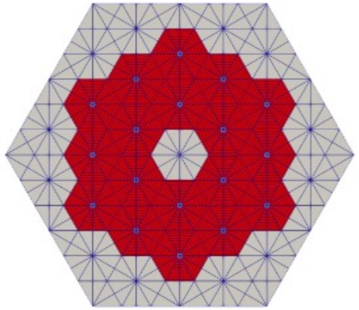
Griffin: Flexible, Extensible Reactor Physics



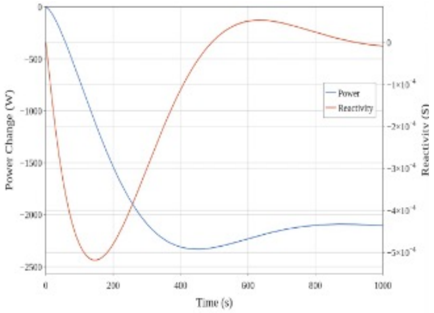
Monte Carlo



Heterogeneous



Homogenized



Point Kinetics

Higher fidelity

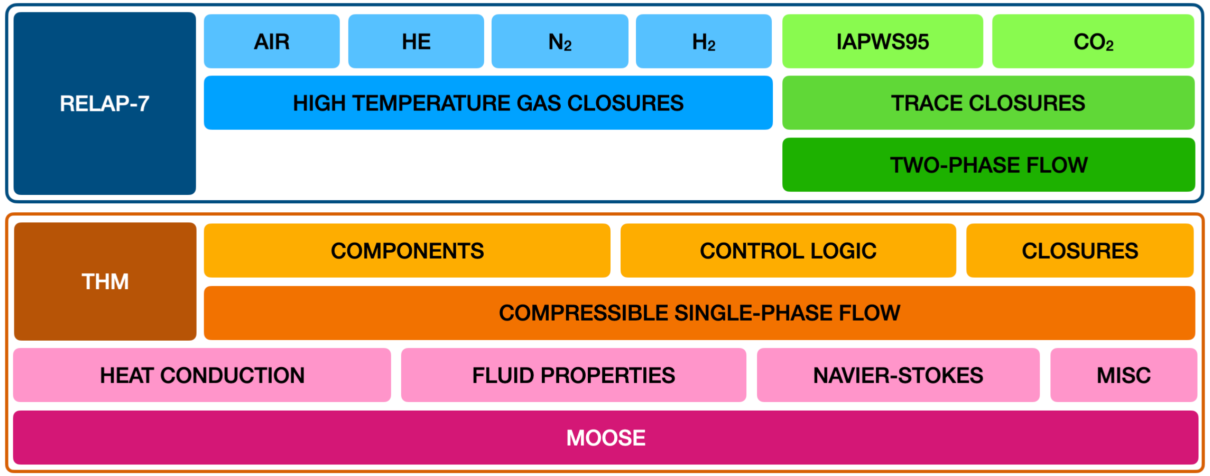
Faster turnaround

- Multiphysics Object-Oriented Simulation Environment (MOOSE) based
- Steady-state and transient simulation for neutrons, photons, thermal radiation, and phonons
- Different levels of fidelity
- Various discretization schemes
- Homogenization equivalence
- Microscopic and macroscopic depletion and decay heat calculations
- Multiphysics coupling

Thermal Hydraulics Modeling : RELAP-7 and Thermal Hydraulics Module

- MOOSE Thermal Hydraulics Module (THM):
  - Component-based approach to build thermal-hydraulic simulations
  - Solves for conservation of mass, momentum, and energy for single-phase, variable-area (1D), inviscid compressible flow
  - Two- and three- dimensional heat conduction
  - Open source within MOOSE

- RELAP-7:
  - Built on top of THM
  - Two-phase flow capabilities
  - Includes additional correlations and fluid properties
  - **Equivalent to THM for single-phase simulations**

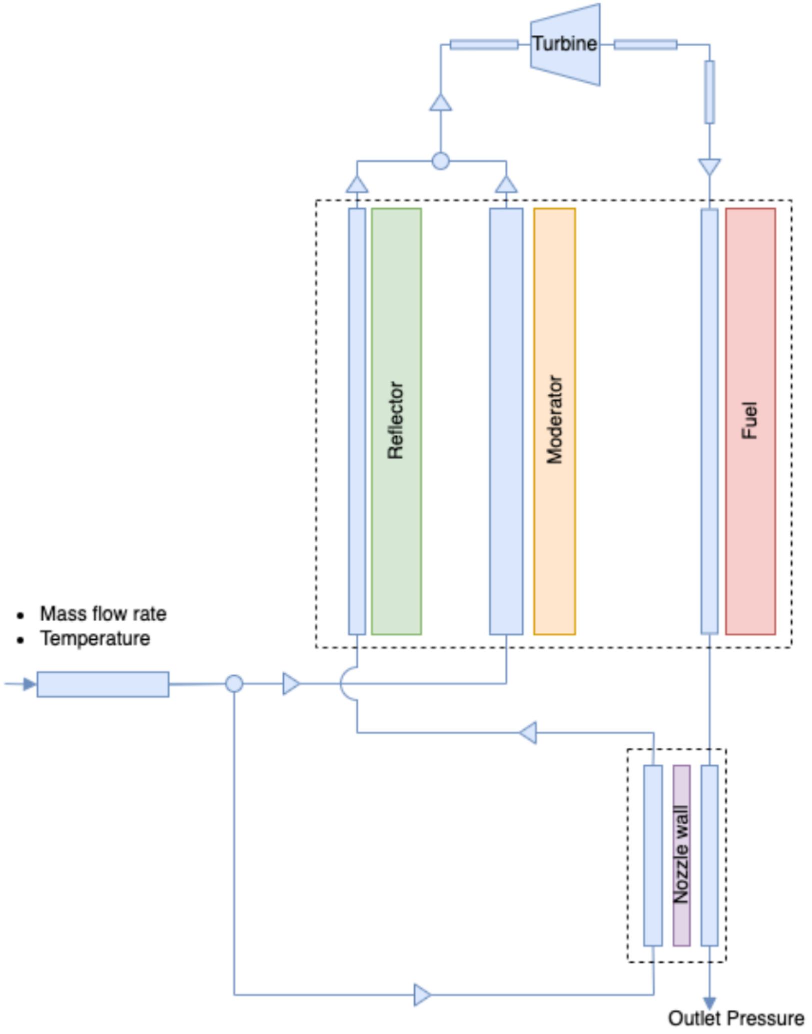


Modeling Strategy

- Reactor power obtained using the point kinetics equations (PKE) implemented in Griffin
- The reactivity model includes:
  - The reactivity insertion as a result of the control drums rotation
  - The Doppler feedback using the average fuel temperature
  - The hydrogen density feedback from the fuel channels
  - The hydrogen density feedback from the moderator channels
- Kinetics parameters obtained from a three-dimensional Serpent model developed at INL
- Power is uniformly deposited in the fuel, moderator, and reflector for thermal hydraulics (TH) calculations
- Fuel temperatures and hydrogen densities are provided by the TH model
- PKE and TH equations are strongly coupled

Modeling Strategy

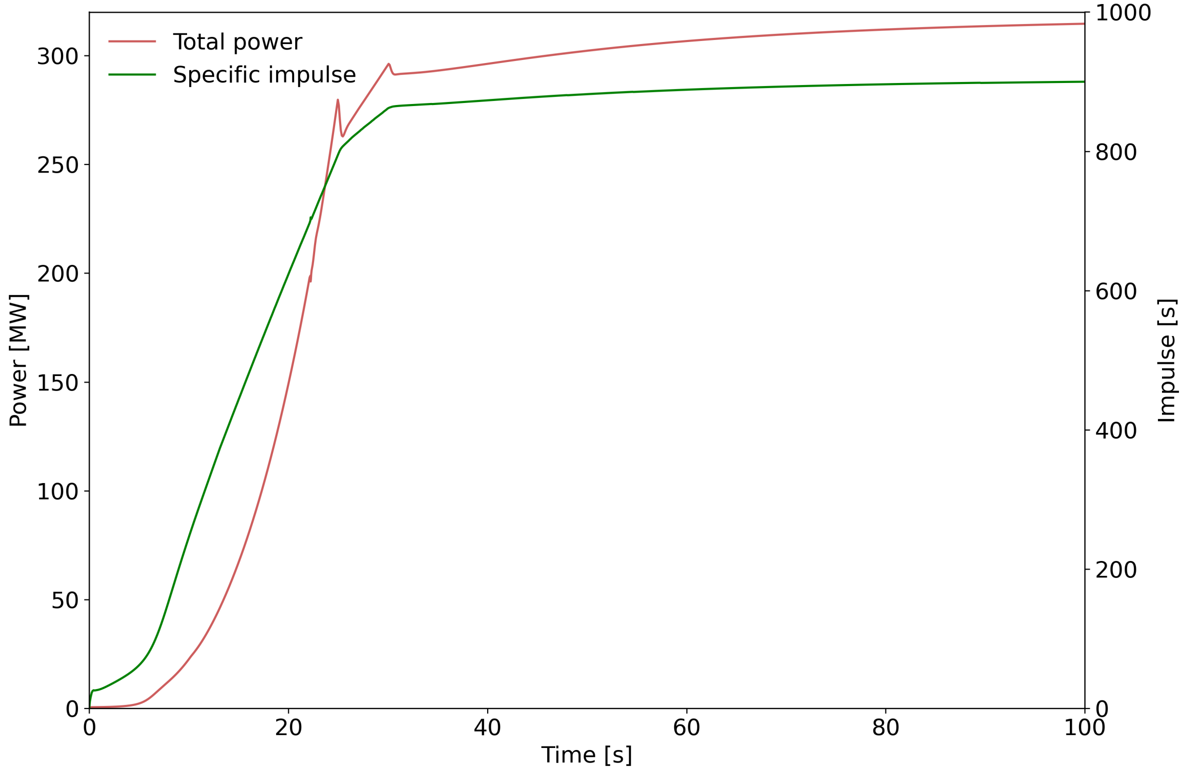
- Fuel, moderator, and reflector cooling channels are modeled with one flow channel in each region
- Representative heat structure for the fuel, moderator, and reflector
- Friction factor calculated using Churchill correlation
- Heat transfer coefficient calculated using Dittus-Boelter correlation
- Fluid properties for hydrogen from the RELAP-7 built-in package
- Power extracted from the turbine is controlled using a proportional integral derivative (PID) controller to obtain the target pressure ratio of 1.44
- Nozzle is modeled through a boundary condition



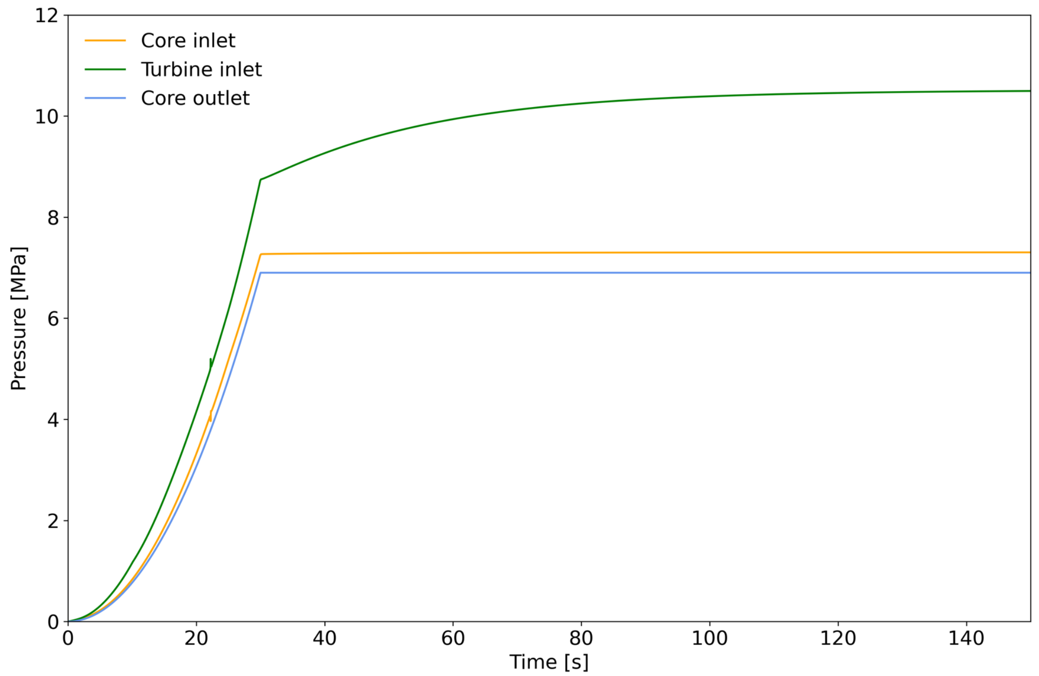
Startup Transient

- Initial conditions:
  - Small arbitrary power (<1 kW)
  - Uniform temperature of 50 K
  - Pressure of 500 Pa
- Reactivity insertion and mass flow rate ramp of 25 seconds
- Transient run over 300 seconds
- Steady state is obtained after about 150 seconds
- Steady-state operating conditions:

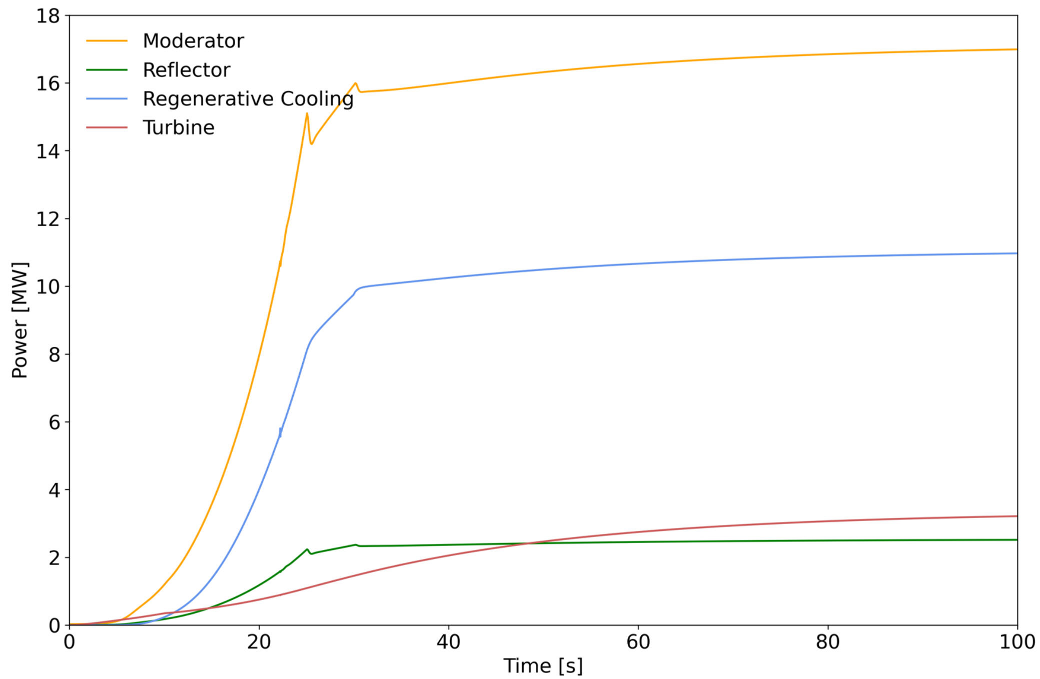
Total power	317 MW
Mass flow rate	7.51 kg/s
Chamber pressure	6.9 MPa
Inlet temperature	50 K



Results



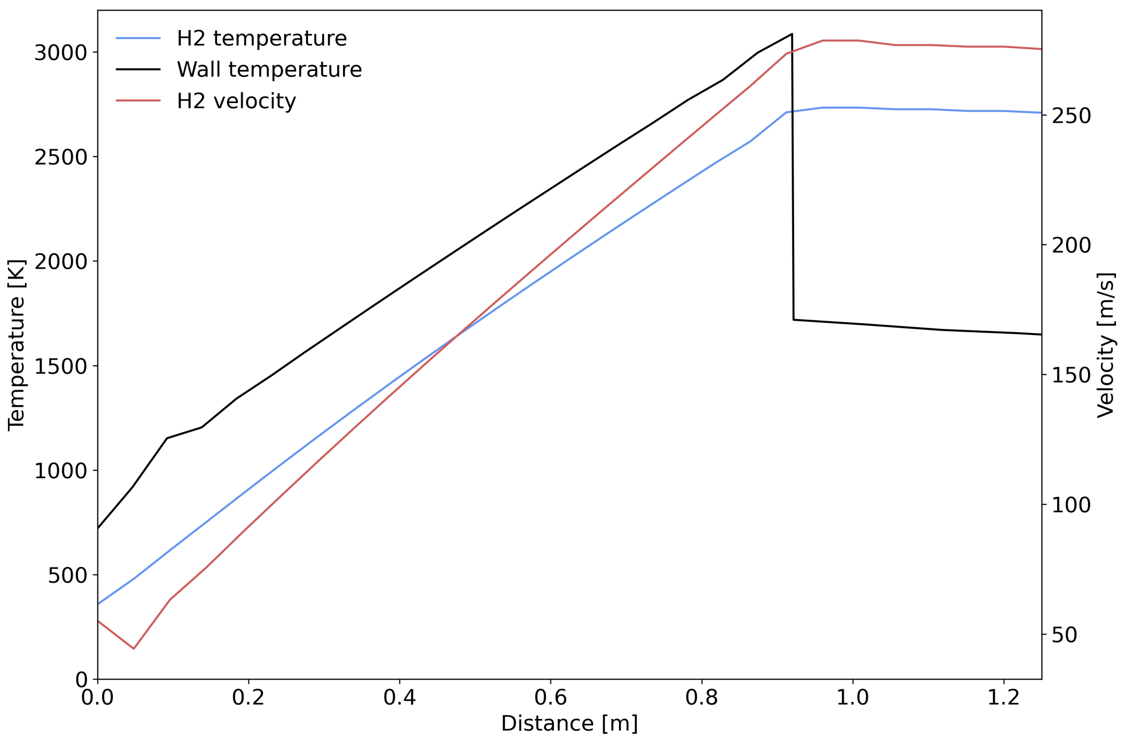
Pressure evolution



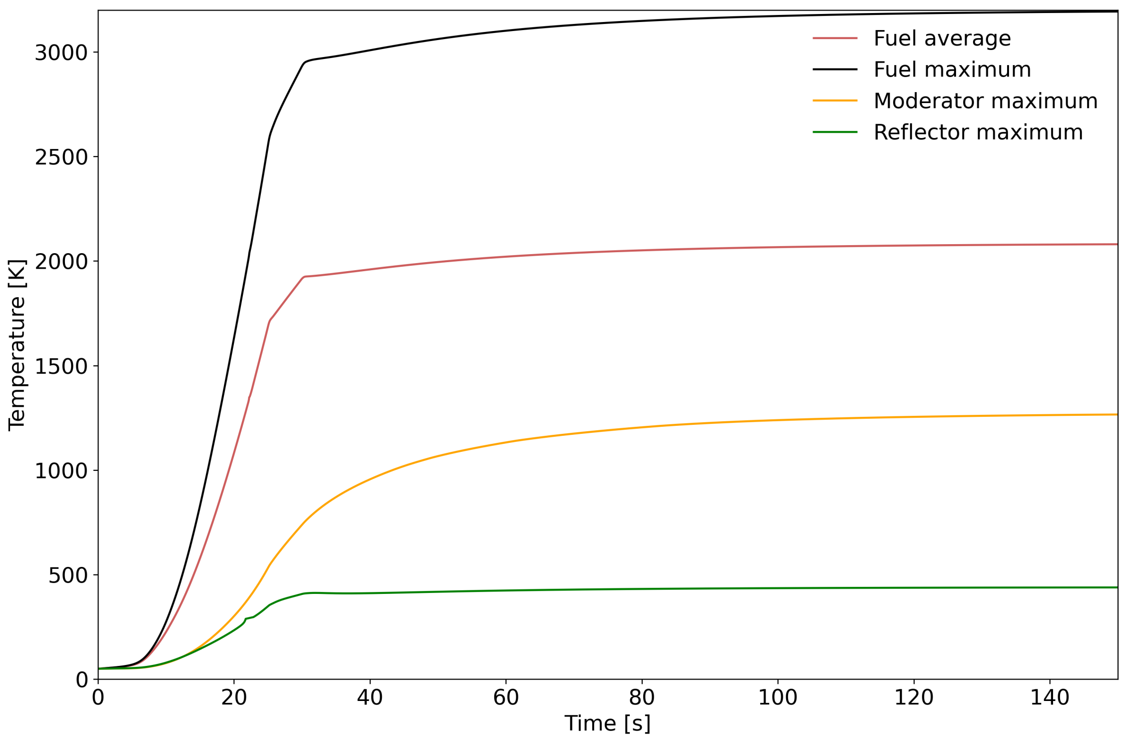
Power evolution

	Target	Calculated
Regenerative cooling (MW)	11.9	11.2
Turbine power (MW)	2.53	2.48
Flow fraction through moderator	0.62	0.64
Turbine pressure ratio	1.44	1.44

Results



Spatial distribution in the core of temperatures and coolant velocity



Temperature evolution

Conclusion

- Demonstrated the coupling of RELAP-7 (THM) and Griffin to model start-up transients
- Capability to run from low pressure and temperatures to nominal conditions
- Predicted the proper flow split between the regenerative cooling and reflector flow path and moderator flow path
- Predicted the correct pressure ratio across the turbine

- Future work:
  - Expand this model to explicitly model the nozzle and the turbo-pump with the shaft dynamics
  - Couple this model with a high-fidelity multiphysics core model

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