HENRI System in TREAT

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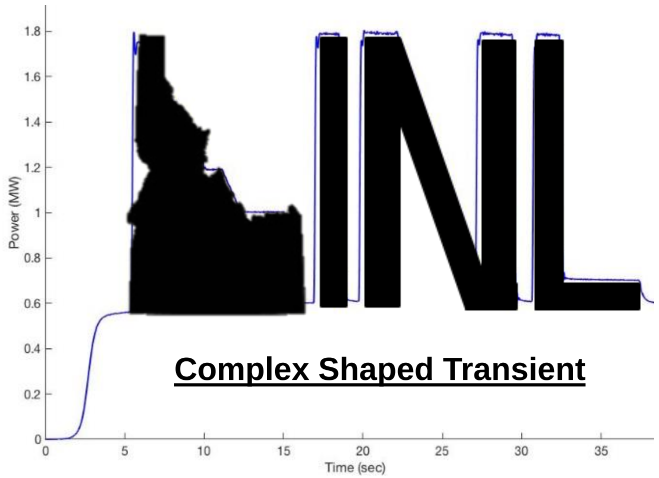
Overview

- Motivation for TREAT HENRI
- Description of the RELAP5-3D model
- Transient calculations
- Conclusions

Motivation for TREAT HENRI

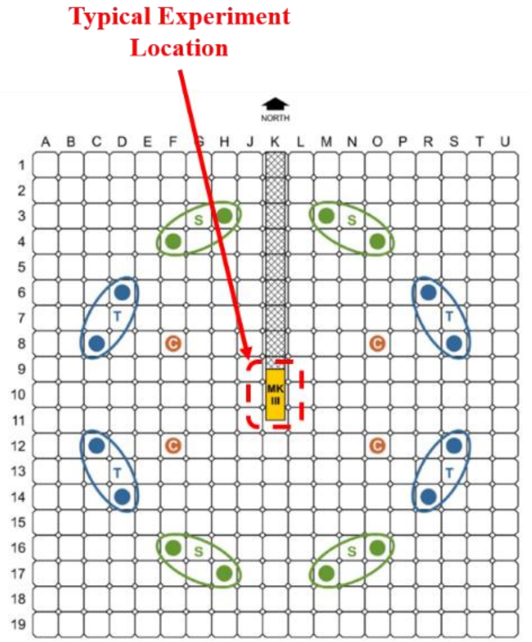
TREAT – Overview

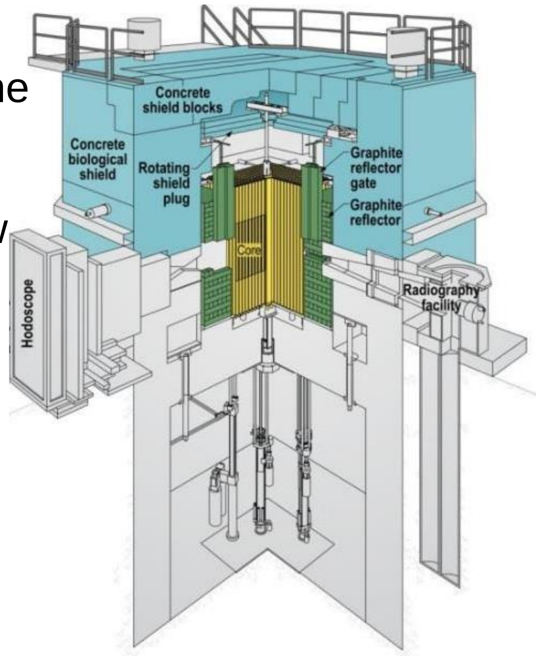
- **The Transient Reactor Test (TREAT) facility resumed operations in order to support fuel safety testing and other areas of transient science.**
- **TREAT: Core comprised of air-blower-cooled, Zircaloy-clad graphite/fuel blocks.**
  - 120 kW steady state, ~20 GW peak in pulse mode
  - Virtually any power history possible within 2500 MJ max core transient energy
  - No reactor pressure vessel/containment; facilitates access for in-core instrumentation



Complex Shaped Transient

- **Experiment design**
  - The reactor provides neutrons, and the experiment vehicle does the rest
  - The tests displace a few driver fuel assemblies, handled in a cask outside the core
  - Recoverable historic designs do not include water-environment vehicles; new designs are needed
- **Four slots for viewing the core center**
  - Two are in use for the fast-neutron hodoscope, neutron radiography
- **Collocated with related facilities at INL**
  - ATR and HFEF
  - Fuel fabrication and characterization

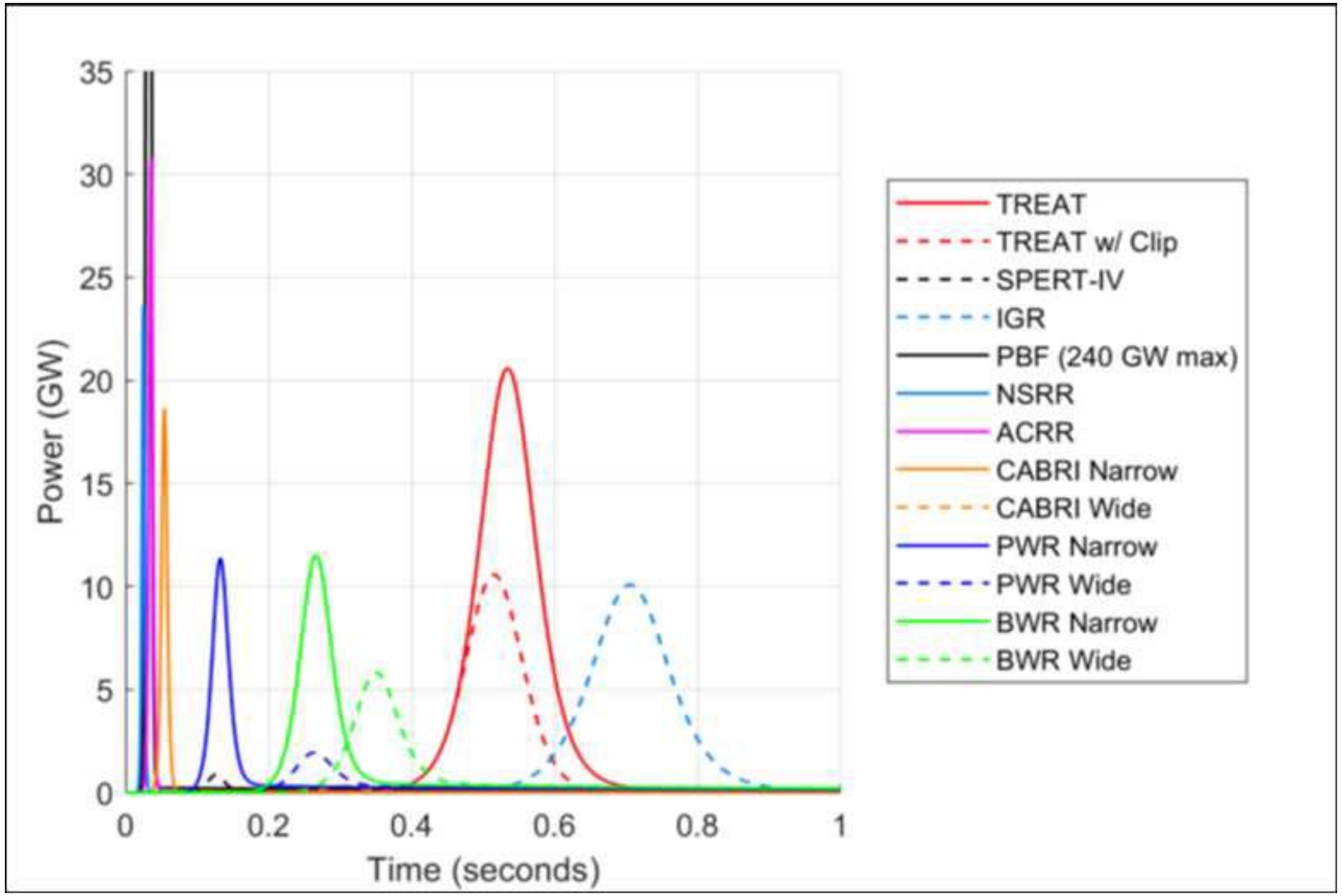




Advanced RIA testing at TREAT

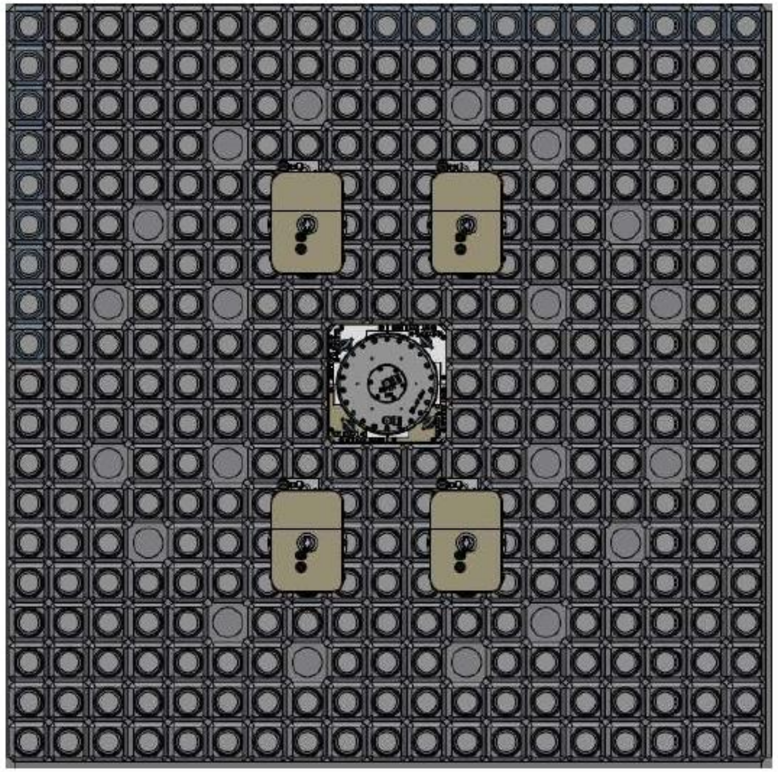
RIA testing for advanced nuclear fuel testing is desired, the problem being that no reactors are currently able to produce a sufficient “prototypic” pulse width for achieving the type of testing being modeled.

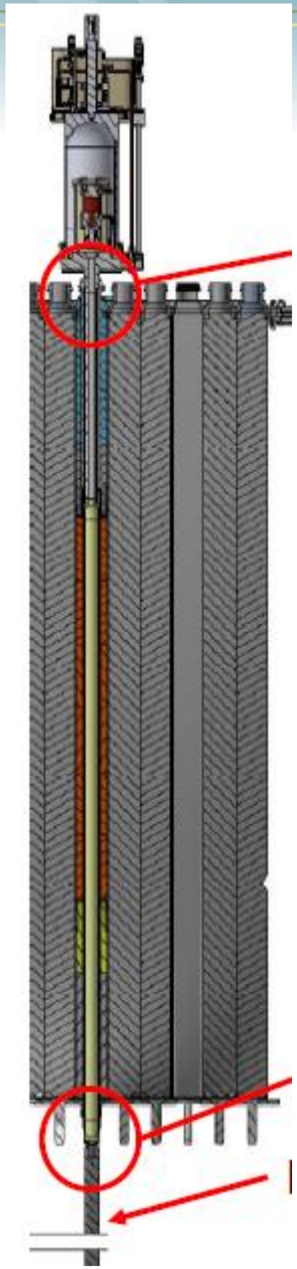
- Too wide or narrow pulse can lead to a non-prototypic reaction in the fuel.



HENRI

He^3 Negative Reactivity Injection





Thermal-hydraulic design and safety considerations

- There is an optimum He^3 loading balancing:
  - Negative reactivity insertion
  - Helium heating

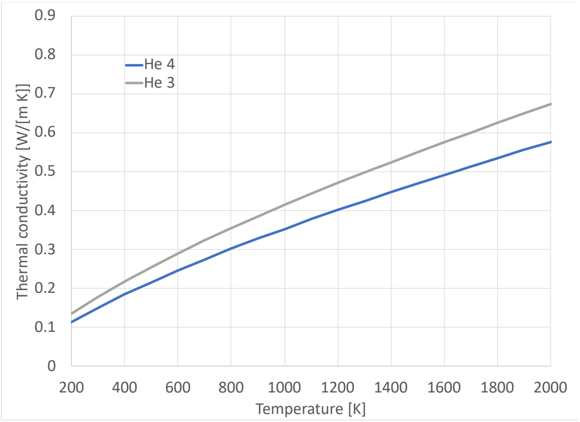
- **Problem**: Find the worst-case scenario for the safety analysis
  - 4.5% dk/k step insertion. 1 HENRI already filled with He^3. Can we get the reactor to start? This may be the case in which the most energy is deposited in the He^3.
  - 4.5% dk/k step insertion. 1 HENRI fires at the pulse peak; the transient and other rods do not actuate until later.
  - 4.5% dk/k step insertion. HENRI does not fire until later, once the fuel assembly heat has led to the peak temperature.

HENRI TH model

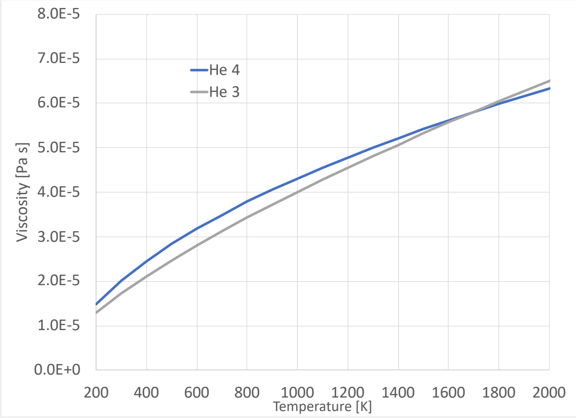
He^3

He^3 vs. He^4 properties

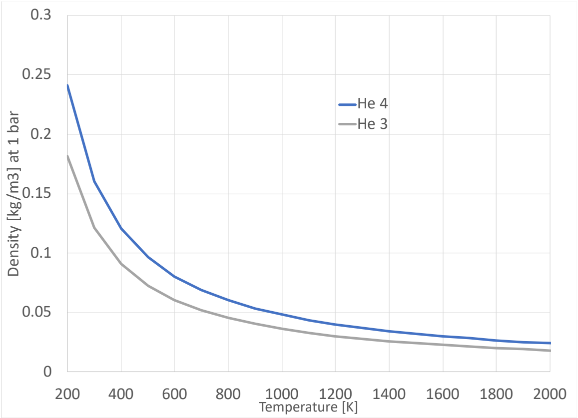
- The properties of He^3 significantly differ from those of He^4.
  - To properly capture helium heating (density) and pressure wave propagation (friction => viscosity), He^3 properties were implemented in RELAP5-3D (as a new non-condensable option).



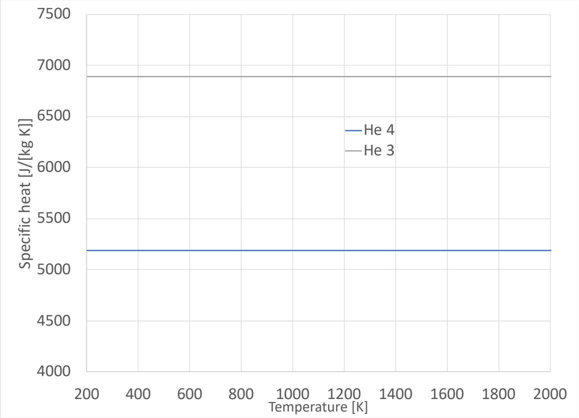
Thermal conductivity



Viscosity



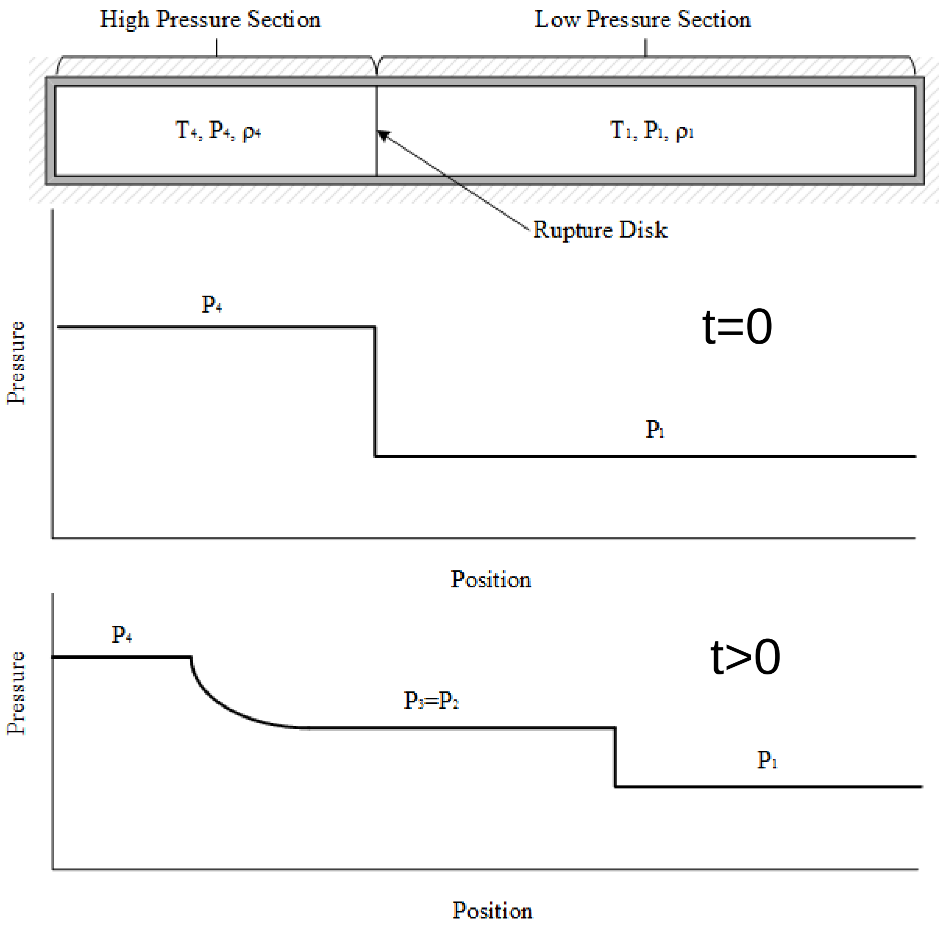
Density



Specific heat

Verification of the He³ implementation in RELAP5-3D

- Shock tube analysis



Analytic solution

Pressure

$$\frac{P_4}{P_1} = \frac{P_2}{P_1}\left[1 - \frac{(\gamma - 1)\left(\frac{P_2}{P_1} - 1\right)}{\sqrt{2\gamma\left[2\gamma + (\gamma + 1)\left(\frac{P_2}{P_1} - 1\right)\right]}}\right]^{\frac{-2\gamma}{\gamma - 1}}$$

Temperature

$$\frac{T_2}{T_1} = \frac{P_2}{P_1}\left(\frac{\frac{\gamma+1}{\gamma-1} + \frac{P_2}{P_1}}{1 + \frac{(\gamma+1)P_2}{(\gamma-1)P_1}}\right)$$

Density

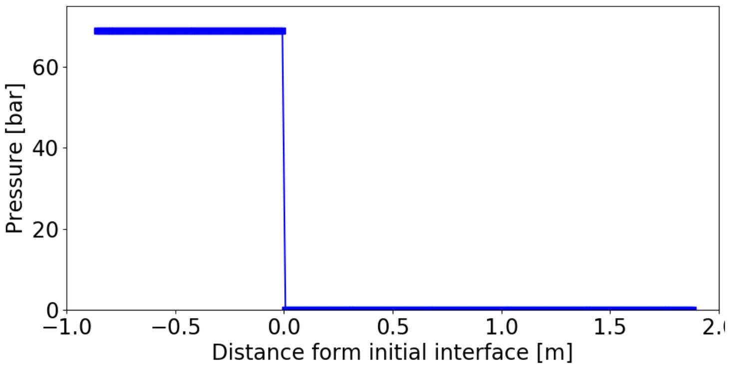
$$\frac{\rho_2}{\rho_1} = \frac{1 + \frac{(\gamma+1)P_2}{(\gamma-1)P_1}}{\frac{\gamma+1}{\gamma-1} + \frac{P_2}{P_1}}$$

Shock wave velocity

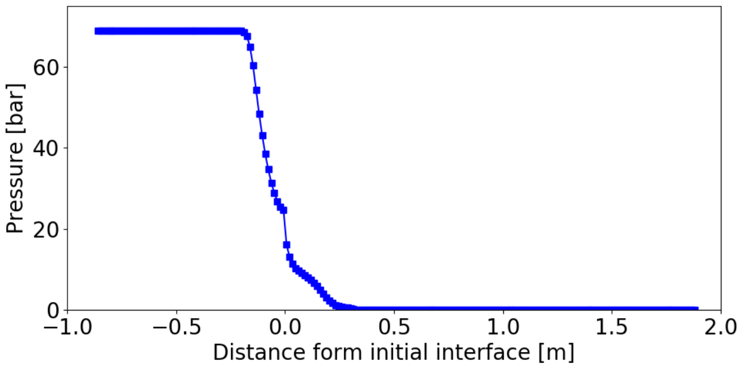
$$w = a\sqrt{\frac{\gamma + 1}{2\gamma}\left(\frac{P_2}{P_1} - 1\right) + 1}$$

RELAP5-3D results

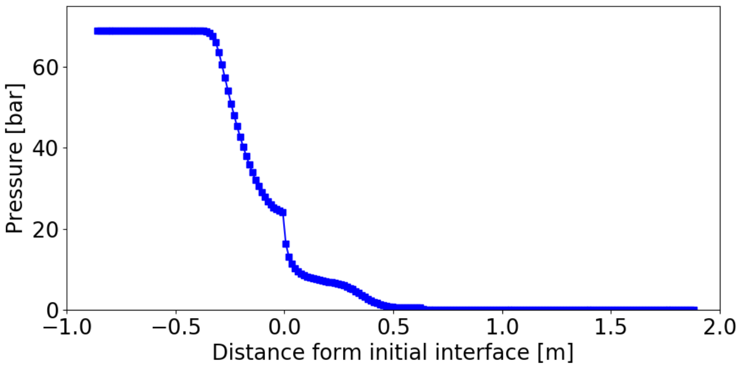
RELAP5-3D results for example pressure wave propagation in He3-filled shock tubes



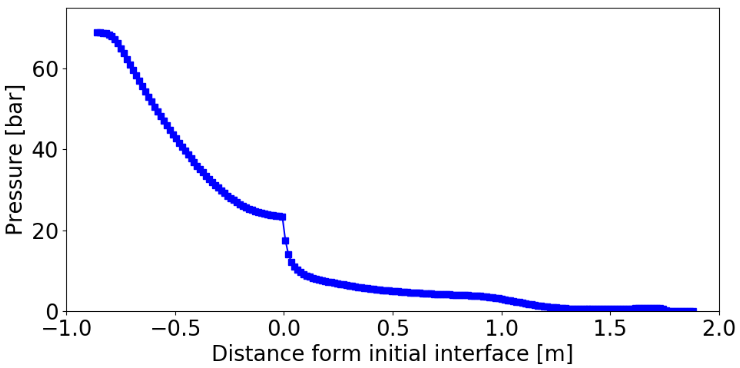
t = 0.00 ms



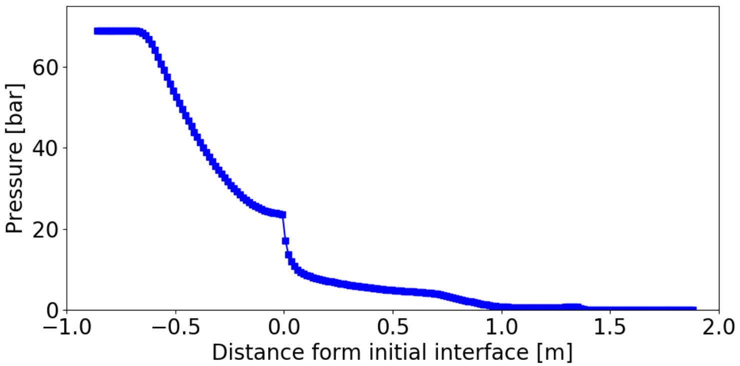
t = 0.10 ms



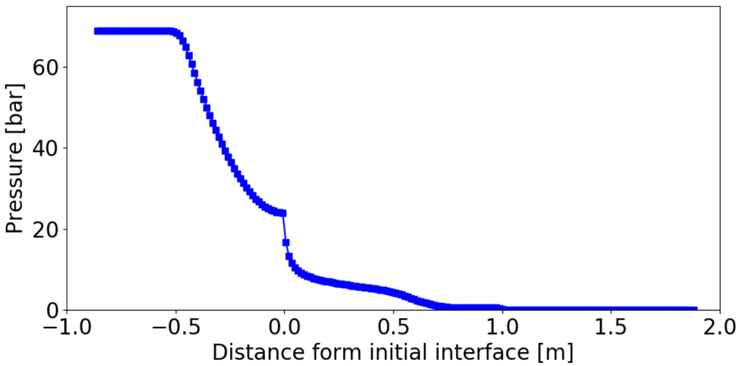
t = 0.25 ms



t = 0.40 ms



t = 0.50 ms



t = 0.65 ms

RELAP5-3D results vs. analytic solution

	RELAP5-3D		P4	P1	P2/P1			T2/T1			ρ2/ρ1			v [m/s]		
	Mesh size	Timestep	[bar] (psi)	[bar] (pis)	RELAP5	Theory	%	RELAP5	Theory	%	RELAP5	Theory	%	RELAP5	Theory	%
Mesh and timestep size	~1cm	1e-10 s	68.95 (1000)	0.0689 (1.0)	9.27	9.44	**-1.74**	2.96	3.27	**-9.51**	3.13	2.88	**8.62**	2687	2785	**-3.52**
	~1cm	1e-8 s	"	"	9.37	"	**-0.71**	2.98	"	**-8.86**	3.14	"	**8.96**	2697	"	**-3.14**
	~3cm	1e-8 s	"	"	8.40	"	**-10.95**	2.75	"	**-15.74**	3.04	"	**5.71**	2583	"	**-7.25**
	~6cm	1e-8 s	"	"	16.54	"	**75.16**	0.88	"	**-73.09**	18.77	"	**550.86**	238	"	**-91.45**
P4/P1 ratio	~1cm	1e-8 s	34.47 (500)	0.0689 (1.0)	8.13	8.32	**-2.24**	2.58	2.99	**-13.54**	3.14	2.78	**13.04**	2706	2619	**3.33**
	"	"	34.47 (500)	0.0344 (0.5)	8.48	9.44	**-10.18**	2.58	3.27	**-20.96**	3.27	2.88	**13.62**	2717	2785	**-2.44**
	"	"	34.47 (500)	0.0068 (0.1)	10.40	11.95	**-12.89**	2.07	3.90	**-46.85**	5.01	3.05	**63.89**	2710	3124	**-13.25**

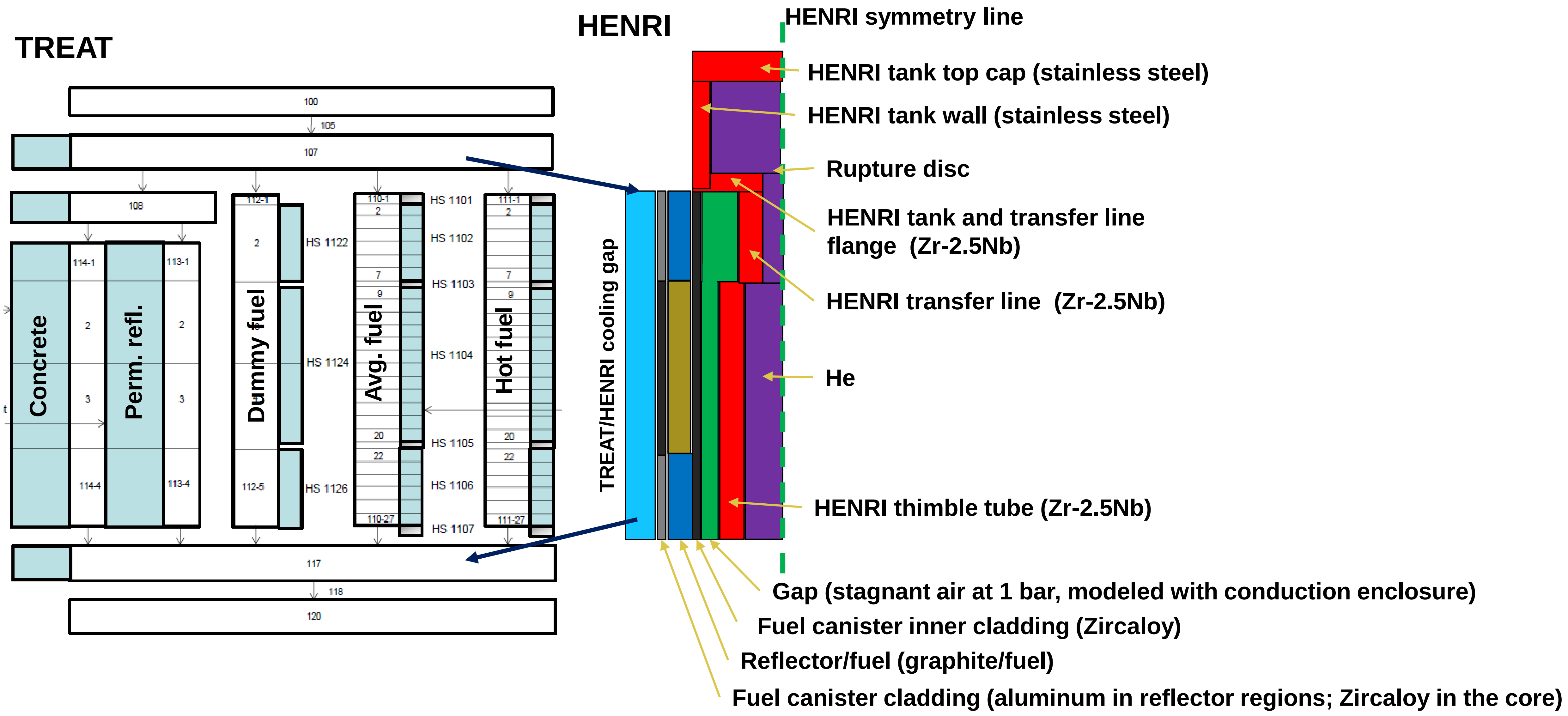
As expected, higher P4/P1 ratios, and larger timesteps and mesh sizes make convergence more difficult.
The convergence study leads to guidelines for the safety analysis:
Acceptable results (±20%) and a still **manageable computational time (~0.1x real-time [for the test problem])**:

- P4/P1 ~ 1000
- Mesh size ~ 3 cm
- Timestep ~ 1e-8 s

HENRI TH model

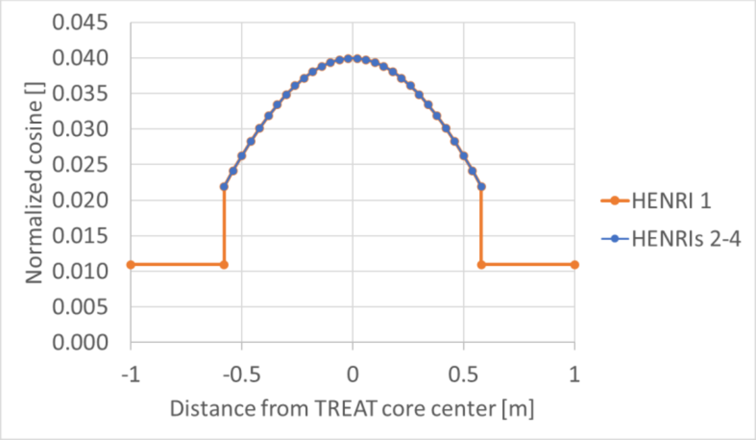
RELAP5-3D model

TREAT HENRI RELAP5-3D model (sketch not to scale!)



TREAT/HENRI RELAP5-3D model (general power model)

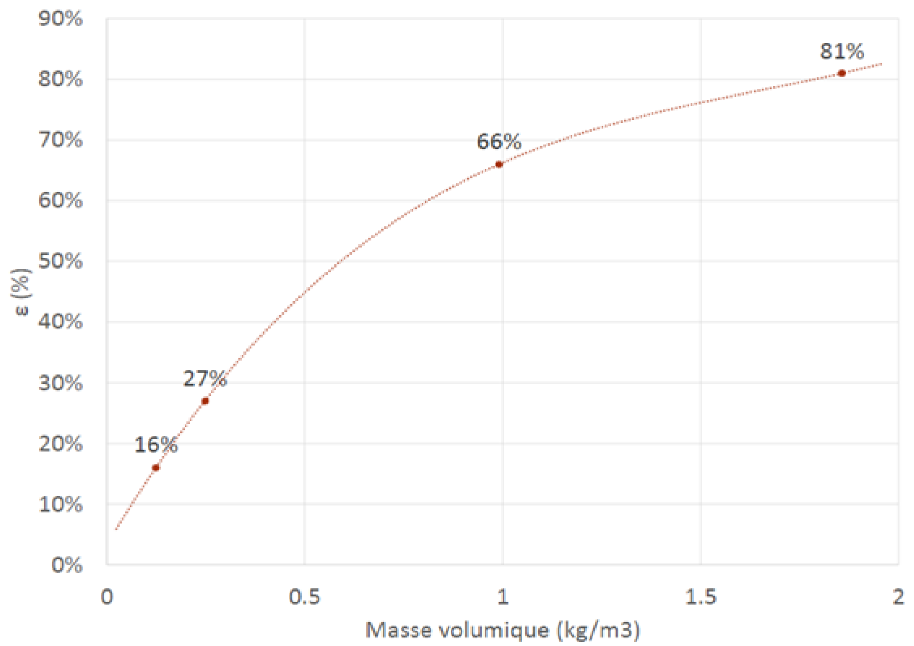
- Power is distributed in the **core and reflector regions** (for the HENRI with the highest PCFs).
- Axially, a chopped cosine with **axial peaking of 1.19** is assumed.
- Each HENRI has **individual heating rates** ([W/g]/MW_TREAT) for the **helium, HENRI tube, inner cladding, fuel,** and **outer cladding**.
- Provided heating rates are assumed at the core center.
- All materials are assumed to have the same axial shape (i.e., the distribution in the assembly is constant over the core length).
- No power is deposited in the stagnant air gap.



	Helium		HENRI tube		Inner cladding		Fuel		Outer cladding	
	250psi nom	250psi 1 HENRI	250psi	250psi 1 HENRI	250psi	250psi 1 HENRI	250psi	250psi 1 HENRI	250psi	250psi 1 HENRI
HENRI 1 upper refl	57.3	58	1.617E-03	1.593E-03	-	-	-	-	-	-
HENRI 1 core	290	283	4.951E-03	4.877E-03	6.751E-03	6.650E-03	1.760E-01	1.730E-01	1.293E-02	1.280E-02
HENRI 1 lower refl	66.8	65.8	1.617E-03	1.593E-03	-	-	-	-	-	-
HENRI 2	231	n/a	4.112E-03	n/a	5.559E-03	n/a	1.424E-01	n/a	1.050E-02	n/a
HENRI 3	280	n/a	4.781E-03	n/a	6.519E-03	n/a	1.699E-01	n/a	1.250E-02	n/a
HENRI 4	239	n/a	4.242E-03	n/a	5.737E-03	n/a	1.473E-01	n/a	1.086E-02	n/a

TREAT/HENRI RELAP5-3D model (He³ heating)

- **Helium heating:**
  - The total helium mass in the core region was computed by RELAP5-3D.
  - The total power deposited in the He was computed per the PCF (with the volume being averaged both radially and axially in the core) ([W/g]/MW_TREAT)
  - A weighing factor was applied to account for the amount of heat absorbed by the gas, with the remaining energy going directly into the HENRI tube.
  - The same axial shape used for the solids was applied.



TREAT/HENRI RELAP5-3D model (He^3 reactivity feedback)

- The model is based on an existing TREAT point kinetic model using the M8 core kinetics and thermal feedbacks in the fuel
- Based on the provided data, the He^3 reactivity was estimated as a function of helium density
- Six axial locations were evaluated via the neutronics calculations

$$He_{feedback}[\$] = M1[kg] * 291.7 \left[\frac{\$}{kg}\right] + M2[kg] * \ 3062.2 \left[\frac{\$}{kg}\right] + M3[kg] * 6075.2 \left[\frac{\$}{kg}\right] + M4[kg] * 5728.1 \left[\frac{\$}{kg}\right] + M5[kg] * 5000.7 \left[\frac{\$}{kg}\right] + M6[kg] * 1998.5 \left[\frac{\$}{kg}\right] + M7[kg] * 0.0 \left[\frac{\$}{kg}\right]$$

Transient Calculations

Identification of the overarching safety scenario

Transients investigated

- 4.5% dk/k reactivity insertion
- TREAT blowers running at a nominal 6000 CFM
- 250/400 psi (25°C) helium in tank
- 1” rupture disc opening in 1 ms
- Helium absorption reactivity and fuel temperature feedbacks considered; CRs re-inserted at 100 s (to avoid re-criticality)

- Scenarios
  - **Base calculation 1**: No HENRIs fire.
  - **Base calculation 2**: All 4 HENRIs fire at around the maximum power.

  - **Malfunction 1**: 1 HENRI fires 0.1 s before RIA insertion begins. 3 HENRIs fire normally
  - **Malfunction 2**: 1 HENRI fires on time, 3 HENRIs fire 1 s late.
  - **Malfunction 3:** 2 HENRIs fires on time, 2 HENRIs fire 1 s late.
  - **Malfunction 4**: 3 HENRIs fires on time, 1 HENRI fires 1 s late.

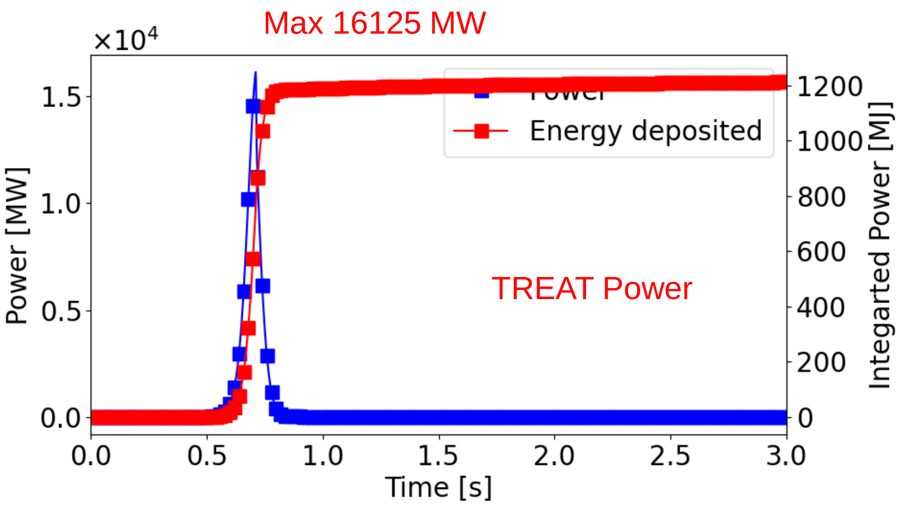
Sensitivities

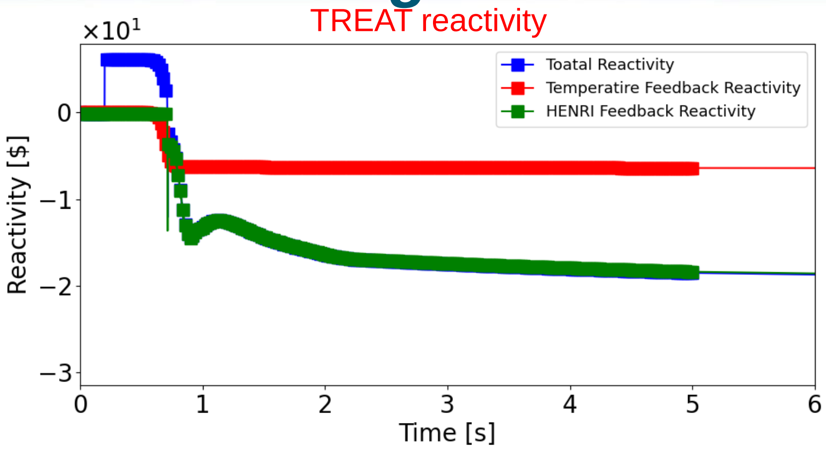
- HENRI fire time: 0.6 s, max power @ 0.71 s, and 0.8 s

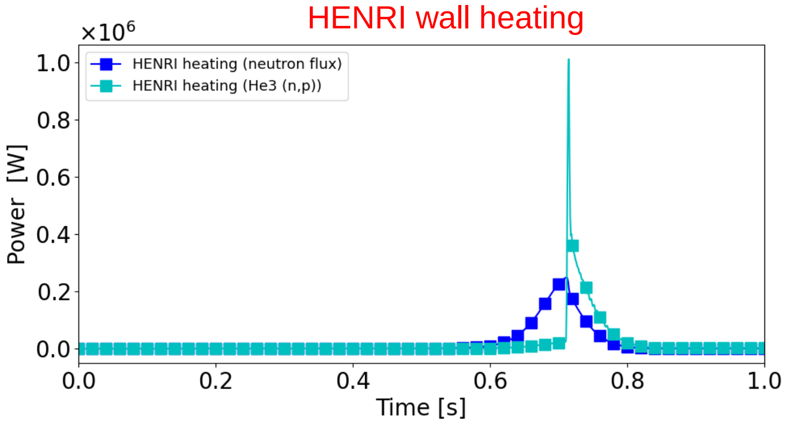
- Location of HENRI transfer line to the thimble connection: (1) nominal length and (2) 56.5 cm higher in the core reflector

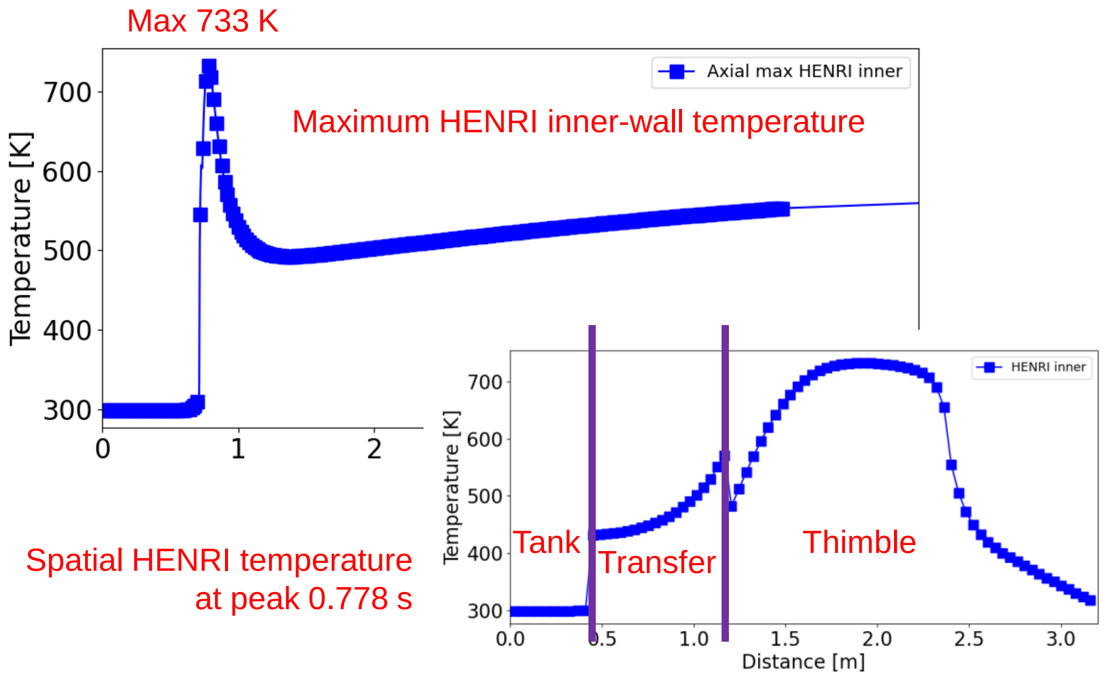
- Initial tank pressures
  - Page 31 of Silvino A. Balderrama Prieto’s master’s thesis identifies 200 PSI as the minimum pressure for reaching the He^3 density necessary to generate the negative reactivity needed to clip the peak to <5 ms.
  - 250 and 400 PSI

Nominal case: All 4 HENRIs fire at the peak, 250 PSI initial loading

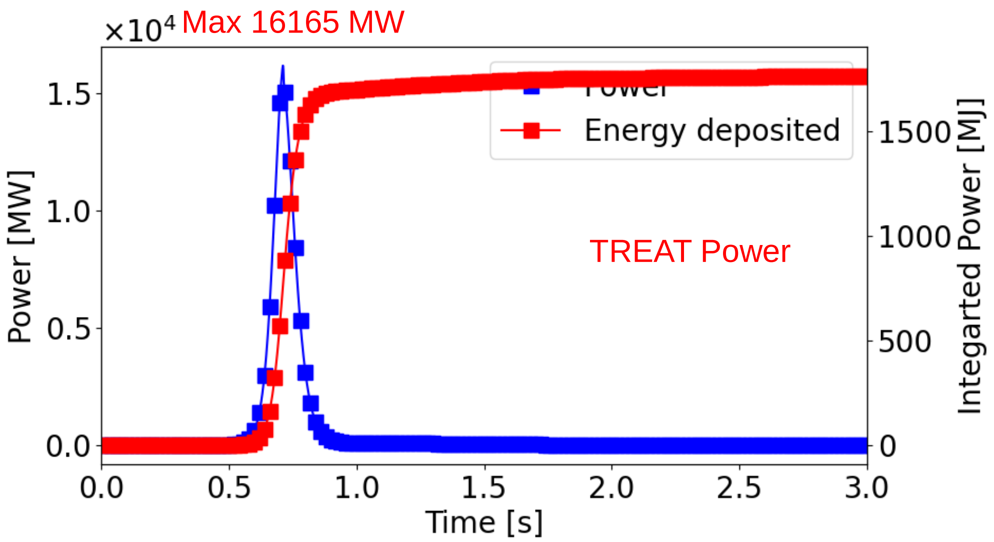


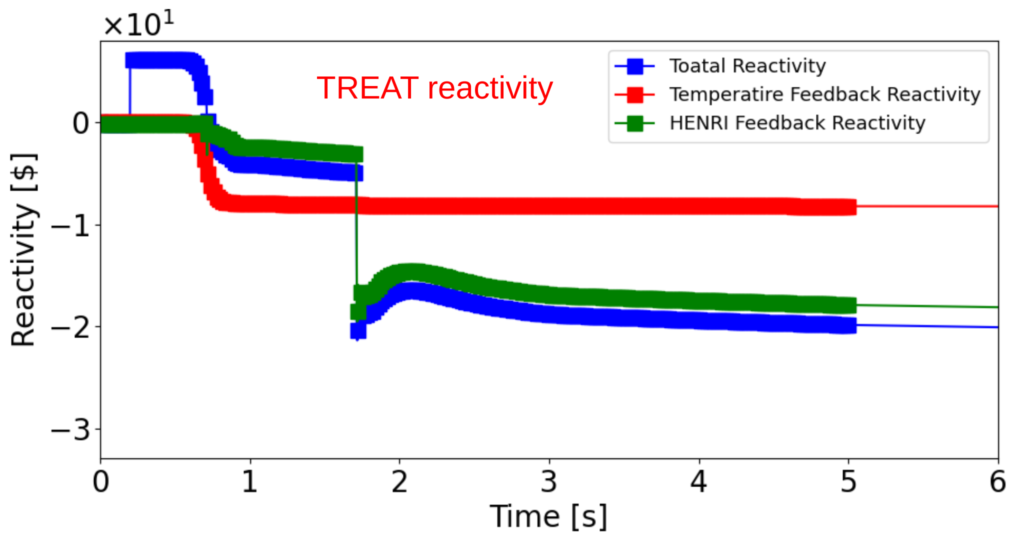


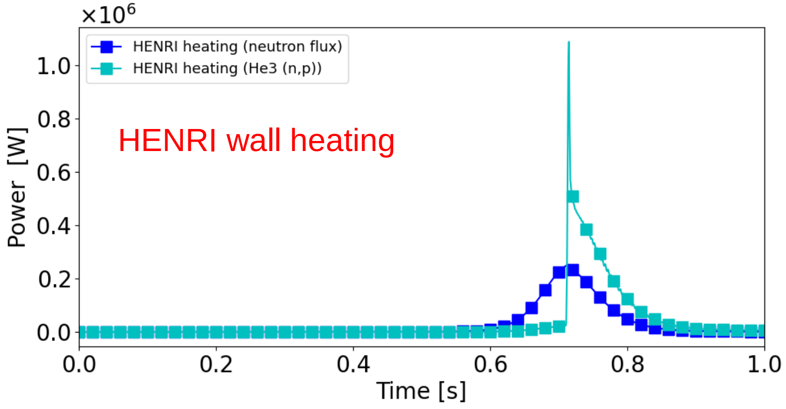


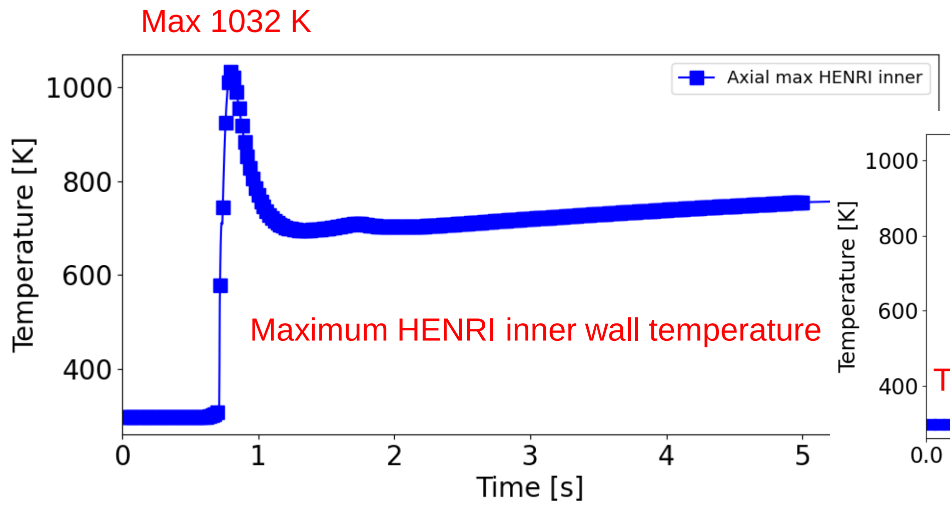


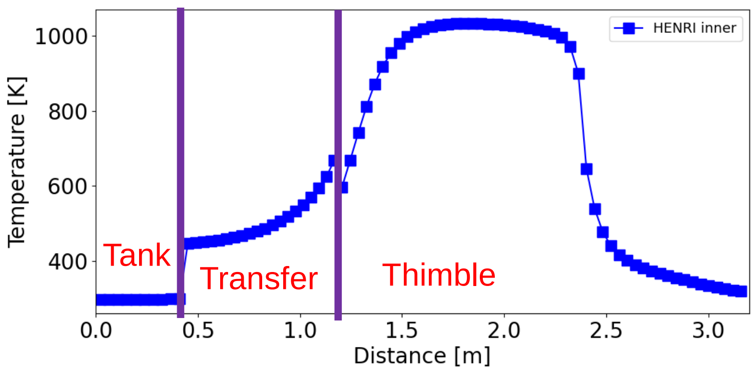
Malfunction 2: 1 HENRI fires normally (0.71 s) (250 PSI) 3 HENRIs fire late (1.71 s)











Summary

Sensitivity	TREAT max power [MW]	TREAT integrated power [MJ]	Max temp [K]
Base calc 1: No HENRIs fire	17330	2100	763
Base calc 2: 4HENRIS at max peak	16125	1200	705
Base calc 2: More tank pressure	16092	1100	829
Base calc 2: Shorter transfer line	16140	1250	641
Base calc 2: More tank pressure & shorter transfer line	16108	1150	718
Base calc 2: 4 HENRIES early 0.1 second	702	27	372
Base calc 2: 4 HENRIES early 0.1 second: More tank pressure	692	25	400
Base calc 2: 4 HENRIES late 0.1 second	16555	1900	716
Base calc 2: 4 HENRIES late 0.1 second: More tank pressure	16555	1900	783
Malf 1: 1 HENRI before RIA starts	0	0	300
Malf 1: 1 HENRI before RIA starts: More tank pressure	0	0	300
Malf 2: 1 HENRI at max, 3 late	16165	1750	954
Malf 2: 1 HENRI at max, 3 late: More tank pressure	16157	1700	1258
Malf 2: 1 HENRI at max, 3 late: Shorter transfer line	16185	1750	883
Malf 2: 1 HENRI at max, 3 late: More tank pressure & shorter transfer line	16173	1700	1063
Malf 3: 2 HENRIs at max, 2 late	16151	1500	860
Malf 3: 2 HENRIs at max, 2 late: More tank pressure	16134	1400	1012
Malf 4: 3 HENRIs at max, 1 late	16138	1300	744
Malf 4: 3 HENRIs at max, 1 late: More tank pressure	16114	1200	950

Conclusions

- **250 PSI:**
  - 4 HENRIs at peak 705 K
  - 3 HENRIs at peak 744 K
  - 2 HENRIs at peak 860 K
  - 1 HENRI at peak 954 K

The worst-case scenario is 1 HENRI firing at peak and 3 firing late

- **400 PSI**
  - 4 HENRIs at peak 829 K
  - 3 HENRIs at peak 950 K
  - 2 HENRIs at peak 1012 K
  - 1 HENRI at peak 1258 K

More tank pressure leads to higher max HENRI temperatures

- **Sensitivity:** All HENRIs fire early or late (within 0.1 s of the peak)
  - HENRIS fire early -> significantly less power deposited -> temperatures stay low
  - HENRIS fire late -> the amount of power deposited approaches case in which no HENRIs fire -> temperatures are the same as for the case in which no HENRIS fire
- **HENRI fires before RIA begins**
  - **TREAT remains subcritical**
- **Shorter transfer line**
  - The amount of power deposited slightly increases and the HENRI temperature slightly decreases.
  - No change in the axial location of max temperature.

The same effect as lowering the tank pressure

- **Use the minimum amount of pressure needed to reach the target peak width.**
- **The worst-case scenario was when 1 HENRI fired at peak power -> 954 K for 250 PSI, and 1258 K for 400 PSI.**
- **Shortening the transfer line has the same effect as lowering the tank pressure.**

INL

Idaho National Laboratory