# EXPERIMENTS ON HELIUM-3 NEGATIVE REACTIVITY INSERTION -HENRI- PROTOTYPE

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**ABSTRACT**

The restart of the TRansient REactor Test (TREAT) facility combined with the shutdown of the Halden reactor in Norway lead to an increased interest in mimicking Reactivity Initiated Accident (RIA) events conditions for Light Water Reactor within TREAT itself. One of the engineering challenges for this task is to increase the energy deposition rate on the tested fuel element by shortening the width of the power burst from its current 89 msec down to 40 msec. One of the options proposed by Idaho National Laboratory consists of pressurizing rapidly a specially designed hollow control rod with Helium-3. The insertion of negative reactivity in the form of Helium-3, a strong neutron absorber, must be well predicted and repeatable. In this prospect, an out-of-pile prototype, the Helium Negative Reactivity Insertion (HENRI) facility, has been designed and built at Oregon State University to assess the feasibility, the repeatability and the control of such process. Tests have been performed to assess the effect of the driving pressure and the minimum opening area. These tests, although performed with rupture disks, helped shed light on the physics occurring in the system and gain confidence in the predictability of the helium density evolution. The latter is critical to characterize properly the effect of the Helium-3 injection on the overall core reactivity.

**KEYWORDS**
TREAT, Control Rod, Helium-3, Pulse, Shock Wave

## 1. INTRODUCTION

The Transient Reactor Test (TREAT) facility is a nuclear reactor located at the Materials and Fuels Complex west of Idaho Falls. This facility has the primary purpose of testing fuels under transient conditions and supporting the development of accident-tolerant fuel [1]. It can reach a maximum energy deposition of 2500 MJ, and various shape of transient could be achieved with the combination of control rod insertion and negative reactivity temperature feedback [2]. Currently, the full width at half maximum (FWHM) of the pulse that the TREAT facility is capable of generating with the sole negative temperature feedback is about 100 ms [2]. To produce pulses more representative of postulated Reactivity Insertion Accident (RIA) for Light Water Reactor (LWR) the width of the pulse should be reduced to value ranging from 30 to 60ms [3] and the maximum power increased. A limited number of research reactors are susceptible to produce transient representative of LWR. Figure 1 presents a comparison of the transient conditions that can be created in contemporary reactor. None of them is actually capable of reproducing the proper combination of FWHM and energy deposition expected from either type of LWR reactors for a RIA event. Note that the US Power Burst Facility (PBF), although the closest to achieve this goal is out of consideration as it has been decommissioned. TREAT has developed pulse-clipping technique using the control rod system to decrease the FWHM down to 89ms [3], denoted as a red dashed line in Figure 1. A further reduction in the FWHM would bring TREAT capability near BWR conditions.

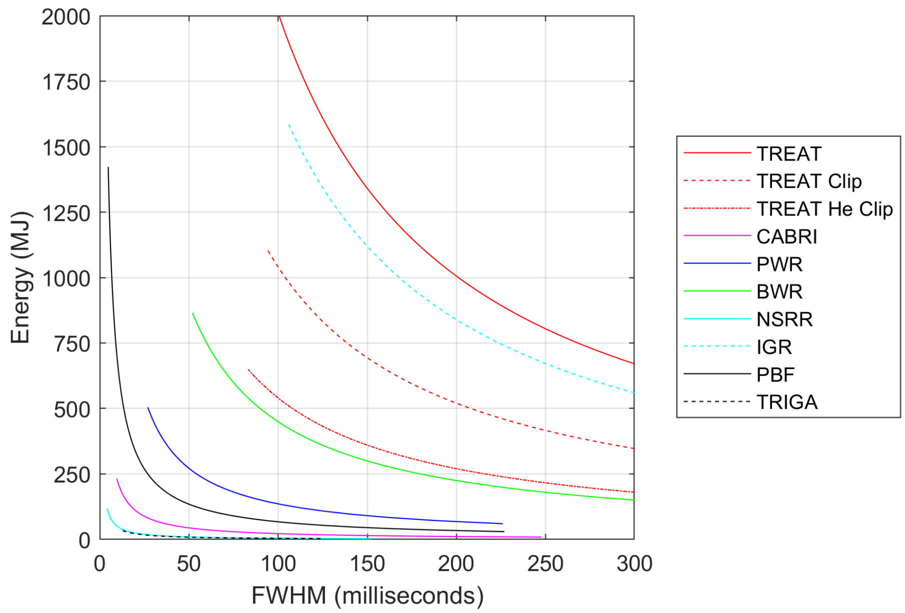


**Figure 1. Comparison of contemporary reactor transient conditions [4].**

Early work from Crawford [5] suggested the use of a strong neutron absorber gas, $^3$Helium, for clipping a high-power pulse in the TREAT facility. Such system would be capable of inserting a negative reactivity of -5% Δk/k in lieu of a current control rod. The original calculation results showed a FWHM reduced to 40-60 ms for a total energy deposition of 1,600 MJ, well below the 2,500 MJ limit. The peak power was calculated to be 20,000 MW. Such pulse becomes more representative of what one can expect during a postulated RIA in a LWR, depicted in red dotted line in Figure 1.

The applicability of $^3$Helium for such purpose is not completely new. It has been used for decades at the CABRI reactor in Cadarache, France, although the approach is reverse. While it is proposed to insert negative reactivity in the TREAT reactor, negative reactivity is removed from the CABRI reactor. In the latter, Helium-3 is initially present in four pressurized cylinders inserted in the core. Fast and precisely-controlled depressurization of these cylinders trigger the increase in reactivity leading ultimately to the desired pulse width and power [6,7,8]. This system has been updated and is currently used under the OECD /NEA CABRI International Project (CIP).

For the TREAT facility, initial calculations of the reactivity worth run with MCNP showed that a $^3$Helium pressure of 1.72 MPa (250 psi) in cartridge volume of 1167 cm$^3$ was sufficient to reach the desired negative reactivity of 5% Δk/k. This corresponds to an atomic density of 3.35E+20 atoms/ cm$^3$. To ensure proper pulse clipping with the $^3$Helium, the injection time was estimated to 5 ms [4]. With these goals in place, Oregon State University has been tasked to model, design and test an out-of-pile prototype cartridge to assess the feasibility and repeatability of the physical process, identify and solve any engineering issue associated with such a device. This paper presents the experimental facility design, the results of the first two test series and discusses the potential issue associated with this fast acting control device.

## 2. TEST FACILITY AND EXPERIMENTAL PROCEDURE

### 2.1. HENRI assembly

The Helium-3 Negative Reactivity Insertion, or HENRI, facility has been designed and built at Oregon State University to test the fast pressurization of a cartridge that would be installed in place of a fuel assembly in the TREAT reactor. Beyond the abovementioned requirement (3.35E+20 atoms/cm$^3$ in 5ms), additional geometrical constraints had to be considered. The system must ultimately fit in the reactor core. The assembly is thus limited to a 10.2 x 10.2cm square footprint in the reactor itself and to a 61.0 cm long and 20.4 cm diameter cylinder above the reactor and below the biological shield.
The HENRI facility consists of four parts as presented in Figure 2. Note that in TREAT the high-pressure side of the assembly would be located at the top of the facility.

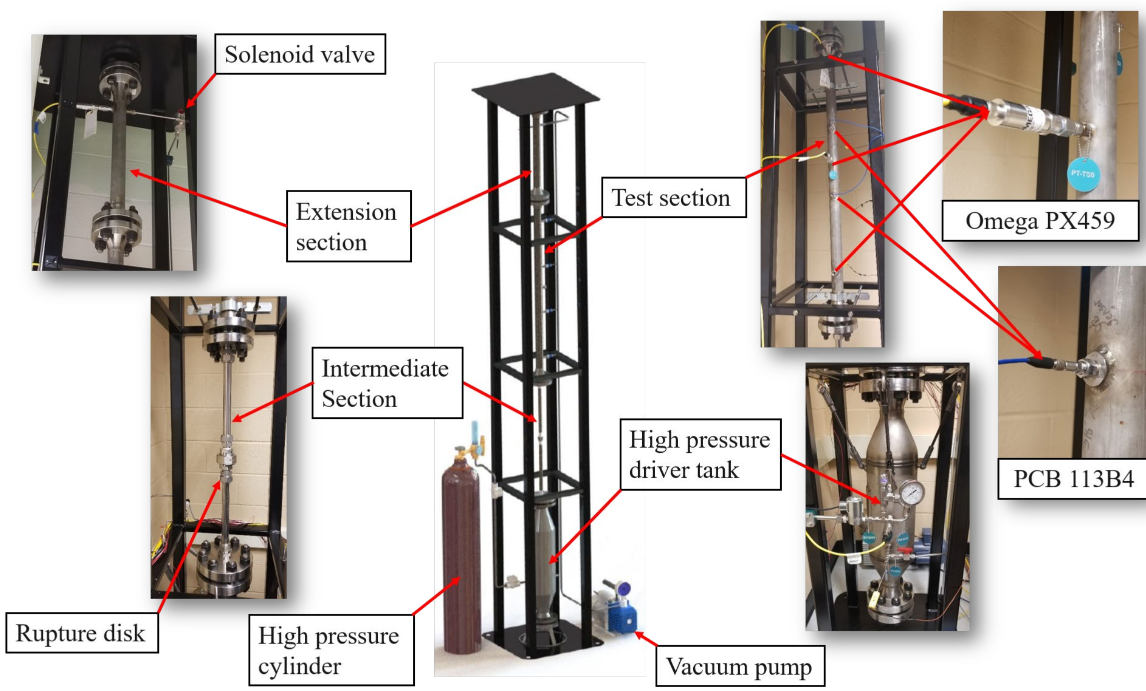


**Figure 2. 3D Rendering of the out of-of-pile HENRI system.**

The driver tank located above the core region. It holds the reserve of $^3$He in the form of pressurized gas. The tank is rated to 9.93 MPa (1440 psig) at 311 K (100°F) for a total volume of 8700 cm$^3$.

The intermediate section that would be located in the upper reflector of the core. In the initial phase of the project, it consists of a tube connected to a rupture disk holder that allows for a fast opening and transport of the helium from the driver tank to the test section. Four sizes of disks were tested with three different size disk holders, Figure 3. 17.47mm (11/16”) FPB-V fragmenting disks from Zook rated at 3.5, 5.16 and 6.9MPa were tested in the 1/2” screw type holder. 12.7mm (1/2”) SFAZ-02 non-fragmenting disks rated at 6.9MPa were tested in the same ½” screw type holder. Connection to the flanges was done through 19mm (3/4”) stainless steel tubing with a 1.65mm (0.065”) wall thickness. A 19mm (3/4”) and 25.4mm (1”) SFAZ-UT non-fragmenting disk rated 6.9 MPa (1000psi) were used with a 19mm (¾”) and 25.4mm (1”) union type holder, respectively. Holders were connected to the flanges through 25.4mm (1”) and 31.75mm (1-1/4”) stainless steel tubing, respectively, with a 3.05 mm (0.120”) wall thickness. The remaining part is made of 3/4” stainless steel tube with an inner diameter of 15.75 mm (0.62”). This intermediate section is 762 mm (30”) in length from the flange of the driver tank to the flange of the test section.


**Figure 3. Rupture disks and holders.**

The test section that would be located in the active core. It consists of a 1219 mm (48”) long, 1 ½” sch. 40 stainless steel pipe. The corresponding volume is 1600 $cm^3$.

The extension section that would be located in the lower reflector part of the core region. It is a straight 610 mm (24”) long continuation of the test section. The corresponding volume is 800 cm3. The additional volume and length proved to be critical when it comes to reaching quickly the desired atomic density in the entire active core region [9]. The extension section can be removed to shorten the overall length of the cartridge.

The driver tank is connected to a high-pressure helium cylinder via one manual and one solenoid valve. Note that $^4$He is used in place of $^3$He in our study due to its lower cost. A ball valve can be installed in the intermediate section in place of a rupture disk for low differential pressure (<1.7 MPa) tests and instrumentation and software shakedown. From the other side of the disk, the intermediate section is connected to the test section and extension section, which can be maintained under vacuum conditions using a vacuum pump connected at the end of the extension section. Before initiating the test, a solenoid valve isolate the test section from the vacuum pump.

### 2.2. Instrumentation

The instrumentation implemented in the HENRI facility must record fast transients that last for few milliseconds. This requires fast response time from the sensor side and fast acquisition rate from the data acquisition system. The main quantities to be measured are the dynamic pressure and temperature along the test section. Indeed, a figure of merit for a successful design is the ability to increase the density to 2.2 kg/m3 (3.35 E+20 atoms/cc) in the active core portion of the test section as fast as possible. The density is inferred from both pressure and temperature measurements. Figure 4 shows the sensors position in the out-of-pile HENRI system.

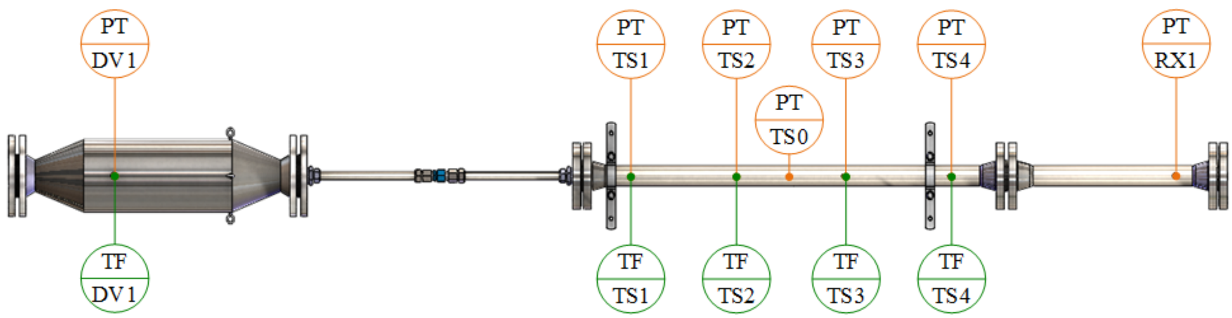


**Figure 4. Instrumentation of the out-of-pile HENRI system**

The pressure is measured using two types of sensors. The static pressure in the driver tank (PT-DV1 in Figure 6) and test section (PT-TS0, PT-TS1, PT-TS4, PT-RX1) are measured with Omega PX 459 absolute pressure transducers with a 0.05 % accuracy. The response time is claimed to be less than 1 msec. A dynamic pressure is measured along the test section (PT-TS2 PT–TS3) with 113B4 piezoelectric pressure transducers from PCB. The response time is claimed to be less than 1μsec. PCB sensors are powered through a PCB-482C signal conditioner. Issues associated with a sensitivity drift of the PCB sensors lead to the use of Omega's at the position TS1, TS4 and RX1 initially allocated to PCB sensors. Nonetheless, redundancy and diversity is ensured with the current sensors configuration.
The temperatures (TF) are measured with 1/16" diameter k-type thermocouples from Omega protruding about 12 mm (1/2") into the gas phase. Two type of thermocouple were used, sheathed (TS2 TS3 and TS4) and exposed (DV1, TS1 and RX1) thermocouples. Note that it is not expected to measure the actual temperature, due to the fast change of the gas temperature and the low response time of the thermocouple but to observe any possible stratification and mixing within the test section. An illustration of the response time difference between sheathed and exposed thermocouples inserted in a stagnant warm environment is presented in Figure 5.

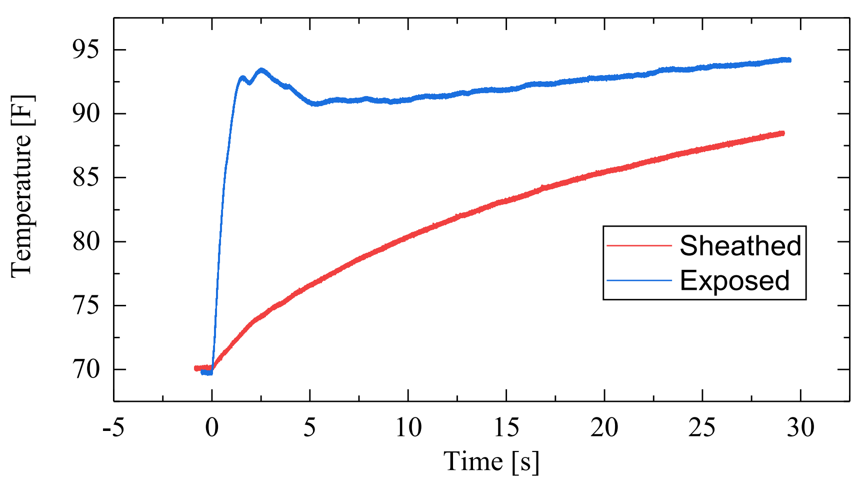


**Figure 5. 1/16" K-type thermocouple time response in hot stagnant air.**

In an effort to improve the time response, special thermocouples designed by Medtherm will be tested. They consist of 0.002” wires of k-type thermocouple with an exposed junction. This should decrease the response time down to 10 msec. Additional post-processing will be necessary to infer the true temperature value of the gas, thus the local density.

All output signals are acquired by National Instrument PXIe system composed of a PXIe-1085 chassis and one PXIe-4303 acquisition card. The latter acquires the static and dynamic pressure and temperature. The card has a 51.2k sample/s/channel acquisition rate with a 24-bit resolution. This allows for fast acquisition of temperature signal necessary to obtain accurate post-processing correction. All the solenoid valves are controlled through Labview.

### 2.3. Test procedure

Each test run on the HENRI facility follows the same general procedure, which begins with installing the burst disk into the burst disk holder, then installing the burst disk holder into the facility between the driver tank and the test section. The valve connecting the test section to the vacuum pump is open and the test section is brought under vacuum (~ 10 Pa). The vacuum pump is disconnected from the test section by closing the solenoid valve. Then the driver tank is pressurized with $^{4}He$ to approximately 345 kpa (50 psia) below the stamped bursting pressure of the disk. If the disk has not yet burst at this step, the line between the helium cylinder and the driver tank is pressurized to a higher pressure than the burst pressure, normally 6.9 MPa (1000psia) to 10.3MPa (1500 psia). After this line is pressurized, the driver tank is “bumped” by opening the solenoid valve from the line to the driver tank. The solenoid valve is immediately closed. This process is repeated until the disk bursts. The data are constantly written in a buffer and recorded once the bust is initiated

### 2.4. Test matrix

The initial test matrix was developed to study various parameter of the design, namely the initial driver tank pressure, the rupture disk size and the test section geometry. The current paper will only focus on the first two.

**Table I. Test Matrix**

| Driver tank Pressure kpa (psia) | Rupture disk diameter mm (in) | Rupture disk type - | Test section geometry - | Test Number |
|---|---|---|---|---|
| 3447 (500) | 17.47 (11/16) | fragmenting | cylindrical | #15 |
| 5160 (800) | 17.47 (11/16) | fragmenting | cylindrical | #16 |
| 6895 (1000) | 17.47 (11/16) | fragmenting | cylindrical | #17 |
| 6896 (1000) | 12.7 (1/2) | non fragmenting | cylindrical | #12 - #13 |
| 6897 (1000) | 19.05 (3/4) | non fragmenting | cylindrical | #10 - #11 |
| 6898 (1000) | 19.05 (3/4) | non fragmenting | cylindrical without reflector | |
| 6899 (1000) | 25.4 (1) | non fragmenting | cylindrical | #14 |
| 6900 (1000) | 25.4 (1) | non fragmenting | annular rough | |
| 6901 (1000) | 25.4 (1) | non fragmenting | annular smooth | |

## 3. RESULT AND DISCUSSION

The first round of test conducted on the out-of-pile HENRI system was focused on the experimental procedure development, timing and instrumentation testing. The following two series focused on the effect of the driver tank pressure and the rupture disk surface area.

### 3.1. Driver Tank Initial Pressure

The first series of tests presented here was used to determine a relationship between driver pressure (PT-DV1) and test section pressurization speed. In this series the 17.47mm (11/16") FPB-V fragmenting disks from Zook rated at 3.5, 5.6 and 6.9MPa were used. Pressures were measured in the driver tank (PT-DV1), at the inlet and outlet of the active core region (PT-TS1 and PT-TS4, respectively) and at the end of the extension section (PT-RX1). The pressure evolution are presented in Figure 6.

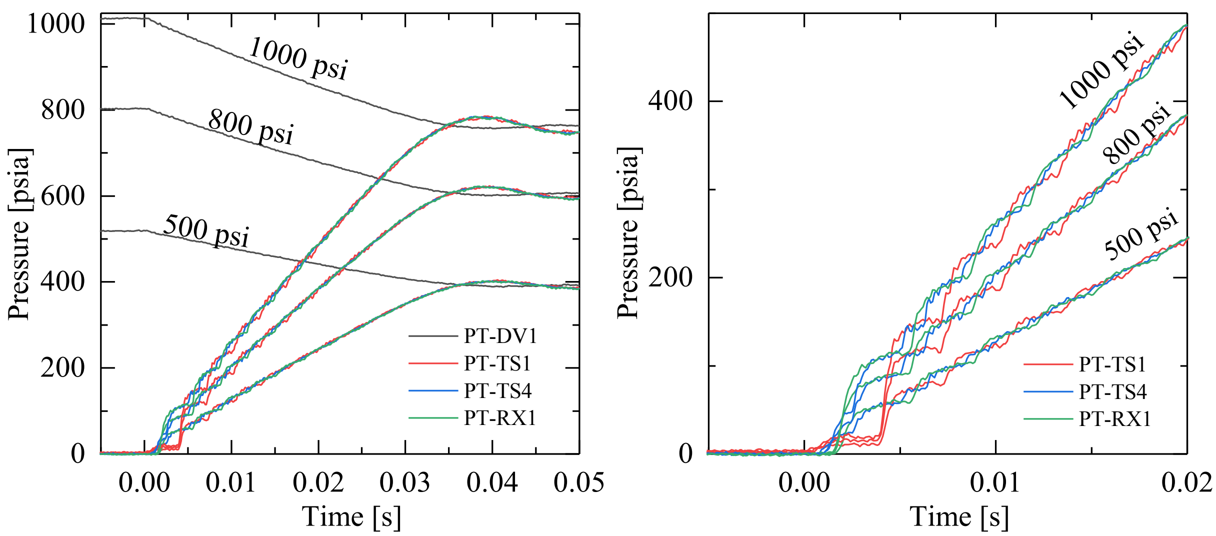


**Figure 6. Pressure evolution measured in the out-of-pile HENRI test section for 17.47mm diameter rupture disk at 3.5, 5.6 and 6.9 Mpa initial pressure in the driver tank.**

The rupture of the disk initiate the formation of a shock wave similar to what one can expect in a shock tube. The shock propagate at high speed through the test section while a density interface moves "slower" behind. For all three tests, the pressure increased initially in step, characteristic of the shock wave travelling through the cylindrical test section. A closer view of the initial pressure increase is presented on Figure 6, right. Initial pressure increase is recorded at PT-TS1 almost instantly followed by PT-TS4 and PT-RX1. The latter presents a higher pressure steps as the initial shock wave followed shortly by the reflective wave pass through the sensor position increasing the pressure twice before reaching the test section with PT-TS4 and PT-TS1 last. None of the test reached the goal of 1.72Mpa (250 psia) in 5ms with only a minimum of 10ms for an initial pressure of 6.9 MPa in the driver tank. Note that the pressure cannot be considered as an indicator of the actual atomic density as temperature is expected to plays a dominant role in the process. In fact, both the propagation of the shock wave and the fast pressurization are synonymous of temperature increase in the gas phase. As mentioned above in the instrumentation section, thermocouple response time is an issue when it comes to measure properly the instantaneous temperature and thus the density of the gas at a given location. Despite their inherent limitation, important information can be extracted from the thermocouple measurements, which are presented in Figure 7.

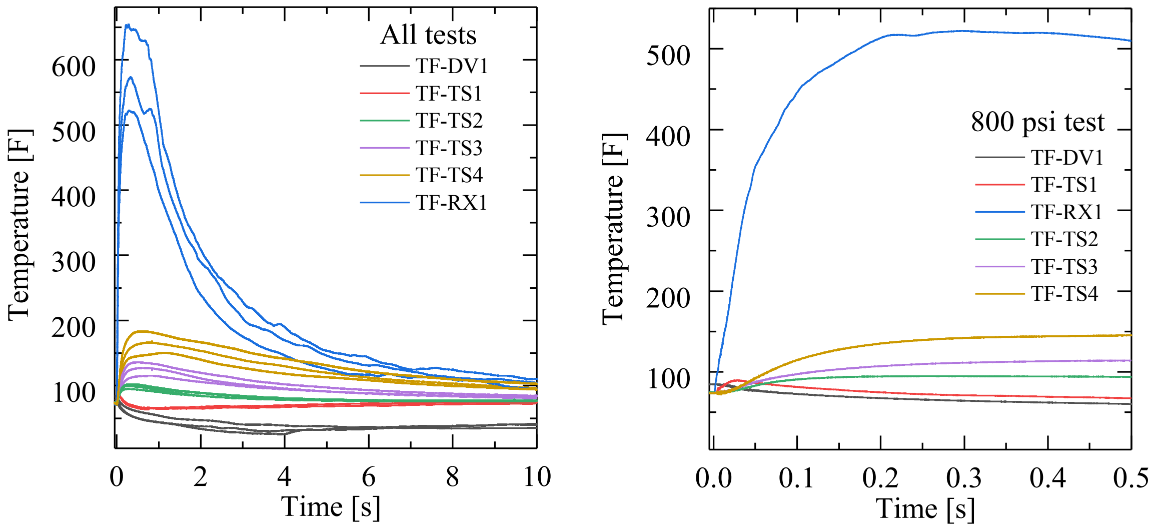


**Figure 7. Temperature evolution measured in the out-of-pile HENRI test section for 17.47mm diameter rupture disk at 3.5, 5.6 and 6.9 Mpa initial pressure in the driver tank.**

Figure 7, left presents the temperature evolution of all sensors for all three tests. Sensors are depicted in different colors while test can be differentientated via the temperature amplitude. For a given sensor the highest amplitude corresponds to the highest initial pressure in the driver tank whereas the lowest temperature corresponds to the lowest pressure. Figure 7, right presents a closer view of the test conducted at 3.5 MPa. First remarkable observation is the sharp increase measured in the extension section at TS-RX1. Temparature increeases from 294K (70F) to more than 533 K (500F) in less than 0.3s. CFD calculation conducted within the project [10] shows that temprature above 1000K (1340F) could be expected in this process. The second observation is related to the temperature gradient along the test section. In all three tests a temperature stratification seems to have formed and remained past the pressure equilibrium ( time>50ms). This suggests that a density stratification should be expected as well. Finally, the temperature recorded at the inlet of the test section shows initially a sharp increase followed rapidly by a decline in temeprature, which followed the trend of the driver tank temprature. This temperature evolution is a signature of the density interface; denser and colder helium flows from the driver tank upward in the test section.

In order to facilitate the pressure evolution prediction and optimize the final design, the measured pressure were normalized to the initial driver tank pressure, $P_{DV1\_init}$.As shown in Figure 8, it appears that for a given sensors, the pressure curves of the three tests lay on top of each other. The normalized amplitude of the pressures as well as the timing of the pressure jumps (characterisitc of the shock wave propagation) coincide. This allows for a easy prediction of the pressure increase as a function of the initial driver tank pressure. At t=5ms, the normalized pressure for PT-TS1, PT-TS4 and PT-RX1 is about 0.112, which means that an initial driver tank pressure of 15.4 MPa (2230 psia) is necessary to reach the goal of 1.72 MPa (250 psia) in 5ms with a 17.147mm (11/16”) fragmenting rupture disk.

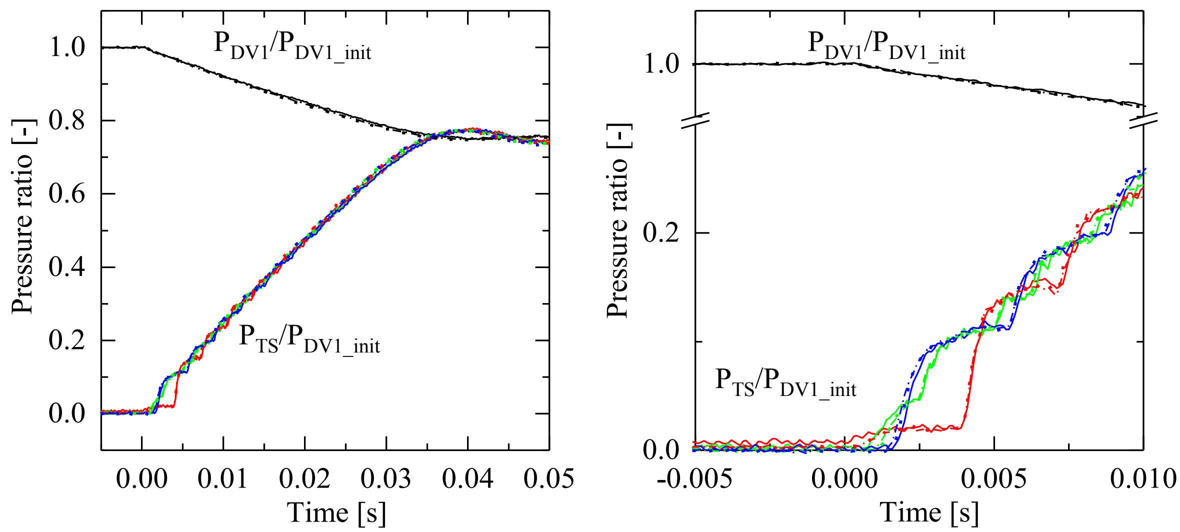


**Figure 8. Normalized Pressure evolution measured in the out-of-pile HENRI test section for 17.47mm diameter rupture disk at 3.5, 5.6 and 6.9 Mpa initial pressure in the driver tank.**

### 3.2. Rupture Disk Diameter

The second series of tests presented here was used to determine the relationship between rupture disk surface area and the test section pressurization speed. The pressure evolution of selected sensors is presented for three size of rupture disk rated at 6.9 Mpa (1000 psia). Note that the pressure of rupture for the disks varies quite significantly from one test to another underlying a lack of predictability of the process timing. As already observed for the non-fragmenting 17.47 mm (11/16”) disk, the 12.7 mm (1/2”) disk failed to reach the 1.72 Mpa (250 psia) within 5ms. Increasing the disk diameter to 19.05 mm lead to a significant decrease in the pressurization time. The pressure reaches 2.07 MPa (300 psi) in 5ms. Further increase in diameter up to 25.4mm (1”) leads to a further increase in pressure ranging from 3.65 Mpa (525 psia) for PT-TS4 to 4.3 MPa (630 psia) for PT-TS1. Although the pressure increases with increasing rupture disk size, the timing of the shock wave seems to remain the same as one would expect if friction and heat transfer are neglected. In an ideal shock tube the shock wave propagation is only function of the initial pressure on both side of the rupture disk.

For the large size rupture disk, large oscillation are observed in the pressure trace and within them smaller amplitude oscillation. It is projected that the combination of shock waves propagating back and forth between the driver tank and the extension section create this oscillatory pattern, which is observed within the driver tank as well. Note that for such large diameter rupture disk, the presence of exposed thermocouple in the test section is discouraged as it would shattered under the strength of the shock. This was already observed for the 12.7mm diameter disk at 6.9 Mpa (1000 psia). On the other hand, an exposed thermocouple in the driver tank is only subject to the limited flow of the rarefaction wave, which allows us to observe the temperature transient in the tank. Temperature oscillation similar to the one observed in the pressure trace in the test section were observed and are still under investigation.

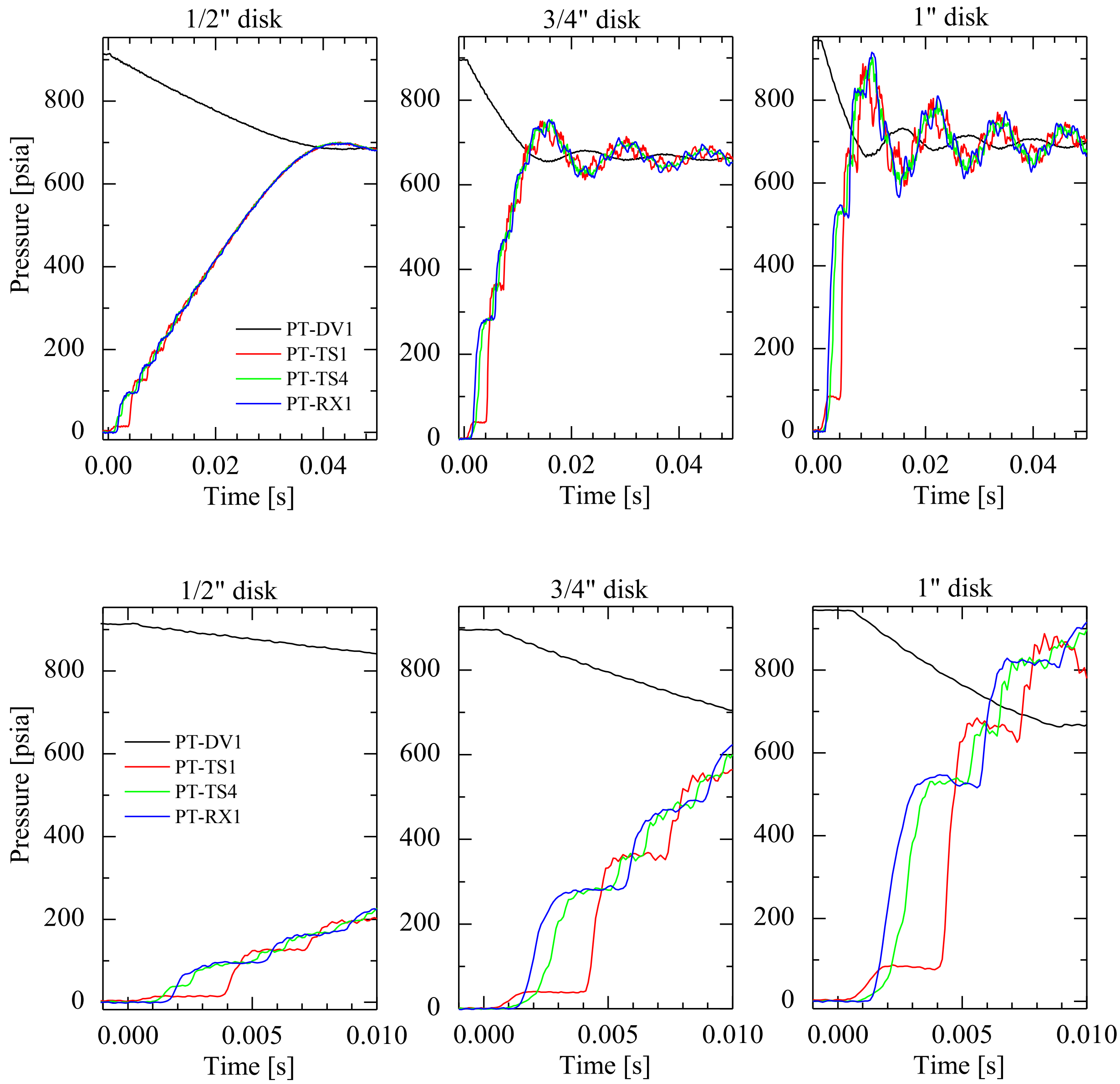


**Figure 9. Pressure evolution measured in the out-of-pile HENRI test section for 12.7 (1/2"), 19.05 (3/4") and 25.4(1") mm diameter rupture disk at 6.9 Mpa initial pressure in the driver tank.**

### 3.3. Repeatability

The test repeatability was verified using the 12.7 mm (1/2") rupture disk rated at 6.9 MPa (1000 psia)**.** In both test the disk ruptured at a lower pressure, 6.3 Mpa (913 psia). The pressure trace along the test section are presented in Figure 10 for both TEST #12 and #13. The pressure evolution was almost undistinguishable from one test to another apart from some small difference captured at the early stage of the pressurization process for sensor PT-TS4 and PT-RX1. This confirms the potential to create a strongly predictable process assuming the timing of the initiating event (in our case the disk rupture) is well controlled.

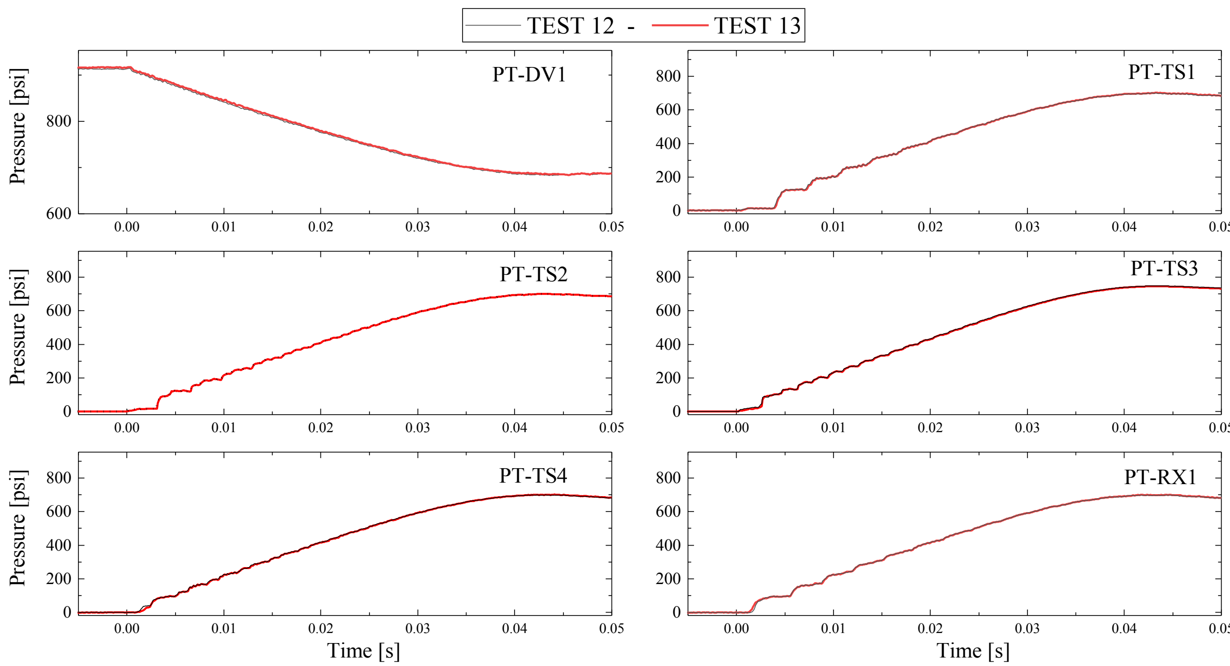


**Figure 10. Pressure evolution measured in the out-of-pile HENRI test section for 12.7 (1/2mm diameter rupture disk at 6.9 Mpa initial pressure in the driver tank for two distinct test, TEST #12 and #13.**

### 3.4. Future Work

To complete the parametric study for the out-of-pile HENRI system, additional tests will be conducted by varying the test section geometry from cylindrical to annular. In fact, due to the high neutron cross-section of $^3$He (5330 barn), a self-shielding effect is expected for large thickness of gas. Considering both the cost of $^3$He and the necessary fast pressurization, an annular geometry seems appropriate. Test without the extension section will also be conducted to confirm the necessity of its presence, which allows for the high-density gas to propagate down the entire depth of the core. Another test will be conducted to assess the effect of the friction by varying the roughness of the annular test section.
Parallel to this experimental campaign, efforts are pursued to design a fast actuated valve that would allow for a repeatable and precise timing of the events. Initial testing of the valve is on-going and test will be repeated to verify the time characteristic of its actuation [11] when implemented in the out-of-pile HENRI system.
Finally, modeling effort using star CCM+ is on-going to support both the design and the prediction of reactivity when coupled with neutronic calculation [10].

## 4. CONCLUSIONS

The reproduction of RIA events for light water reactors using the TREAT reactor is essential for better understanding of the fuel behavior under this transient event. RIA events can be better simulated if the TREAT reactor is able to increase its pulse amplitude and reduce its FWHM without exceeding the licensed maximum energy deposition limit. Efforts has been made by Idaho National Laboratory and Oregon State University to design and build a new test facility capable of verifying the feasibility and repeatability of inserting negative reactivity in the TREAT reactor using $^3$He. Initial tests have shown that the insertion of negative reactivity, corresponding to an atomic density of 2.2 kg/m$^3$ of $^3$He, could be completed within 5 ms under proper design. A driver pressure of 6.9 Mpa with an aperture of 19.05mm (3/4”) seems appropriate as a base design with a cylindrical test section. Additional test with an annular test section will be conducted.

Additionally a new fast opening valve is being developed to ensure reliability a precise timing of the process.

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