

Loss of Coolant Accident Commissioning Test Plan

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September 2019



The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

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Transient Irradiation Test Plan

Loss of Coolant Accident Commissioning Test Plan

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1. PURPOSE AND BACKGROUND

The mission of the Accident Tolerant Fuel (ATF) Program is to develop the next generation of Light Water Reactor (LWR) fuels with enhanced tolerance to design basis and beyond design basis accidents (DBAs and BDBAs). The goal of the Fuel Safety Research (FSR) program within the ATF program is the identification and quantification of appropriate nuclear fuel safety criteria for the ATF materials that are being developed. The Loss of Coolant Accident (LOCA) Commissioning Test Plan aims to accomplish this goal by demonstrating the capability to conduct prototypic in-pile LOCA testing at the Idaho National Laboratory (INL) Transient Reactor Test (TREAT) facility.

Loss of coolant accidents (LOCAs) are a family of transients where the reactor system experiences a sudden and unexpected loss of cooling due to a rupture somewhere in the primary circuit of the nuclear steam supply system (NSSS). LOCAs are generally split into large break (LB) and small break (SB) LOCAs. A large break is generally considered any rupture larger than 1 square foot. A small break is one that is less than a foot squared but greater than circular breaks 3/8-inch in diameter. Breaks smaller than this can generally be made up for by the primary reactor coolant charging system. In Pressurized Water Reactors (PWRs), the design basis LB-LOCA is an assumed double-ended break in one of the cold legs between the primary reactor coolant pump and the outer annulus of the reactor vessel. For a Boiling Water Reactor (BWR), the design basis LB-LOCA is a double-ended break in the suction side of one of the recirculation loops. The main phases of the LOCA event are: (1) Blowdown, (2) Refill, and (3) Reflood. Figure 1 shows a qualitative plot of fuel cladding temperature and reactor power during an accident progression.

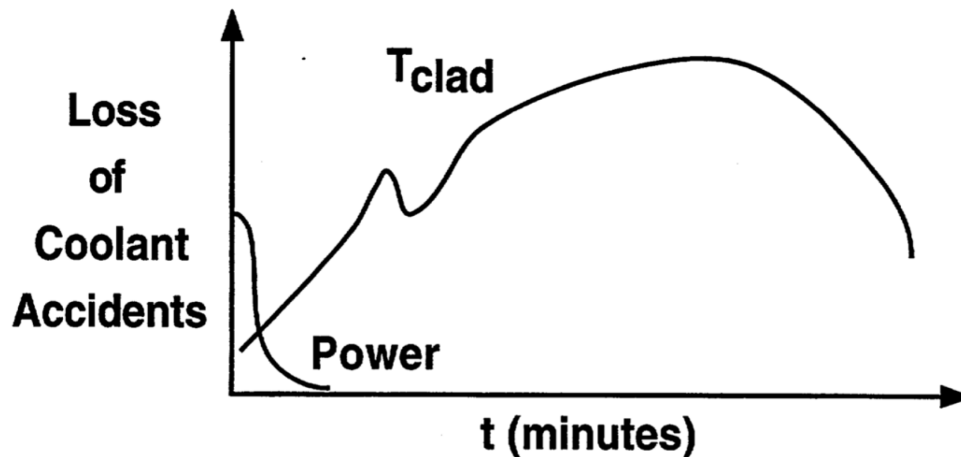


Figure 1. LOCA Fuel Cladding Temperature Trace.

During the blowdown phase, most of the primary coolant is expelled through the break. Voiding in the core causes a shutdown of the reactor. The reactor pressure rapidly drops from an operating value of ~15.5 MPa (PWR) to near atmospheric pressure of 0.1MPa. High pressure safety injection begins; however, most of this coolant is swept around the down-comer and lost out the break. Numerous flow reversals in the core can occur as the core is initially cooled by a resulting two-phase mixture. As the two-phase coolant flow in the reactor drops and the stored energy of fuel redistributes from the fuel pellet to the cladding, the core heats up very rapidly. Following the blowdown phase of the LOCA, the Emergency Core Cooling System (ECCS) begins to refill the core. Initially, the bottom plenum of the core must be refilled, so, during this time, the reactor core continues to heat up in a near adiabatic fashion due to the decay heat being generated in the fuel. Eventually, the ECCS completes the filling of the

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reactor's lower plenum, and coolant begins to move upward and reflood the core. The rate of coolant rise through the core can be very slow, as low as 1 inch per second for some reactors. Initially, the peak cladding temperature continues to increase until a sufficient part of the core is covered. As the lower elevations of the core quench, a two-phase mixture of steam and entrained water droplets provides some enhanced heat transfer to the upper parts of the core. Quench occurs when the liquid water front moves past the fuel rods at a given axial location.

The high-pressure differentials and high temperatures that occur in a LOCA make the cladding highly vulnerable to swelling and rupture behavior. The creep strength of the Zircaloy cladding decreases dramatically with temperature, and rupture generally occurs if the cladding temperature exceeds 700°C for any substantial period of time. For Zircaloy-based claddings, burst generally occurs before there is sufficient swelling to result in coolant channel blockage. In high burnup fuel, the thermal stresses and overpressurization of fission gas bubbles in the fuel can cause fine fragmentation of the fuel into sub-millimeter sized fragments which relocate axially in the fuel rods; this causes an increase in temperature in the ballooned region and dispersal of radioactive material out the burst opening, challenging the core's coolable geometry. This phenomenon is not observed below the Nuclear Regulatory Commission (NRC) burnup limit of 62 GWD/MT rod average burnup, but industry efforts to increase burnup make dealing with this phenomenon an important research objective. As the temperatures of the core increase, the diffusion rate of oxygen and hydrogen in the Zircaloy metal increase and, combined with phase transformations in the Zircaloy metal, result in high temperature embrittlement of the metal. The principal embrittlement mechanisms are either a thinning of the zirconium beta layer due to oxide and oxygen saturated alpha layer growth or the beta layer oxygen concentration exceeding a critical value. LOCA safety limits of 17% cladding reacted, and 1200°C peak cladding temperature are designed to prevent these mechanisms.

2. EXPERIMENT DESIGN AND ANALYSIS

LOCA testing at TREAT will take place in the Super-SERTTA device illustrated below in Figure 2. Super-SERTTA is designed to provide a natural circulation environment where an annular heater produces both a thermal boundary condition to a central rodlet and induces a natural circulation current in an annular flow path. The system is closed and is initialized at room temperature, at a given water level, and with an amount of pre-pressurization based on the desired thermal hydraulic end state (Temperature, Pressure, Water Level). The annular heater begins supplying energy to the system increasing the water temperature and vapor fraction, while decreasing the liquid density. This results in an increase in system pressure and swelling of the water level. Natural circulation begins when the water level rises over the top of the flow tube which separates the flow riser from the down-comer. A plenum gas heater aids in achieving the desired final pressure by heating the gas plenum. Steady state conditions are maintained by means of a cooling coil outside of the capsule removing energy from the liquid in the down-comer. The entire Super-SERTTA capsule is attached to an expansion tank. Fast open valves can be triggered at a given time, mimicking the blowdown conditions in a LWR LB-LOCA.

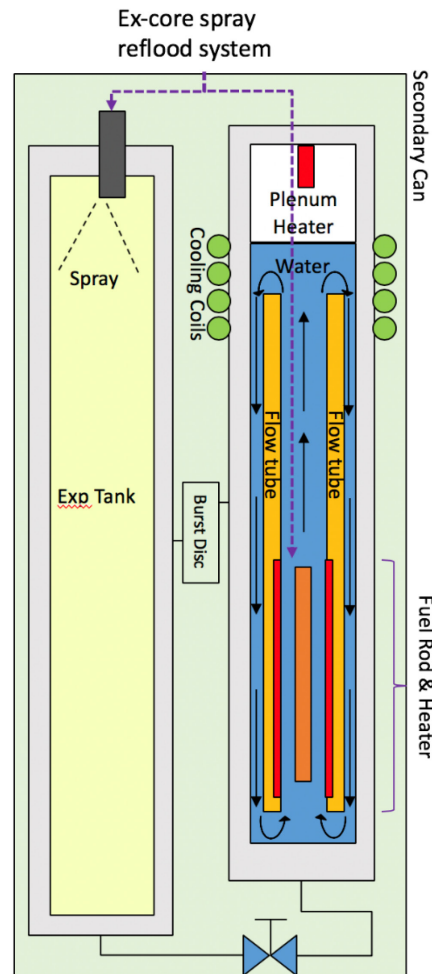


Figure 2. Super SERTTA Schematic.

Super-SERTTA is designed for use with previously irradiated fuel rods which are remanufactured from commercial fuel rods. It is, therefore, built to facilitate a hot cell assembly/disassembly. Most all of the capsule and assembly hardware will be built out of cell and then placed in cell for rodlet loading and final assembly. The rodlet would first be inserted into the inner test train and flow tube and secured via J-slots in the flow tubes inner housing. Then the lower rodlet holder will be attached to both the rodlet and flow tube, resulting in a rodlet that is completely fixed at the bottom and fixed in two directions at the top, but free to expand vertically at the top. The entire flow tube will then be inserted into the Super-SERTTA capsule and outer pressure boundary and secured through a top flange. The hot cell assembly processes are illustrated below in Figure 3.

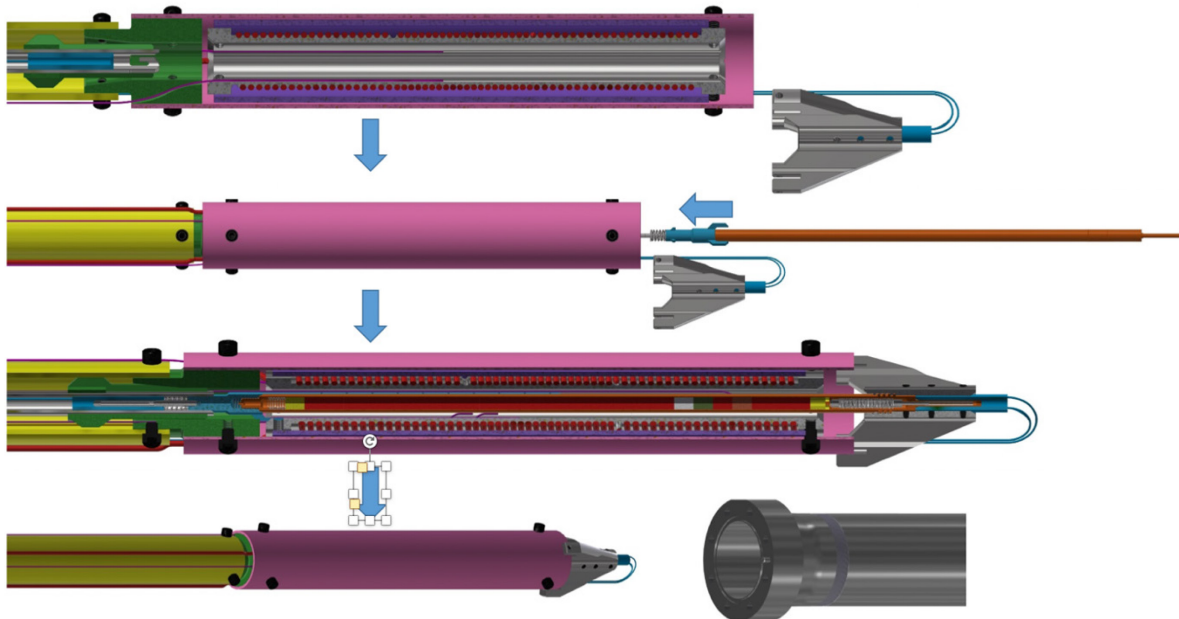


Figure 3. Super SERTTA Hot Cell Assembly Process.

The TREAT LOCA transient tests will be divided into four phases. The first is system initialization, where the thermal hydraulic conditions are established in the test capsule. The second is a period of high-power operations designed to mimic LWR steady state operations and bring as much stored energy as possible into the fuel rod by operating at high linear heat generation rates (LHGRs). In the third phase (LOCA blowdown), valves to the expansion tank will be opened and the reactor power rolled back to those mimicking decay heat. The power level and duration will be dictated by the desired time at temperature conditions for the test rodlet. A sample reactor power profile from the second and third phases of the transient is shown below in Figure 4. Finally, the fourth phase will be the quench stage where an ex-core system will supply water to the capsule, mimicking the response of the ECCS to reflood the rodlet.

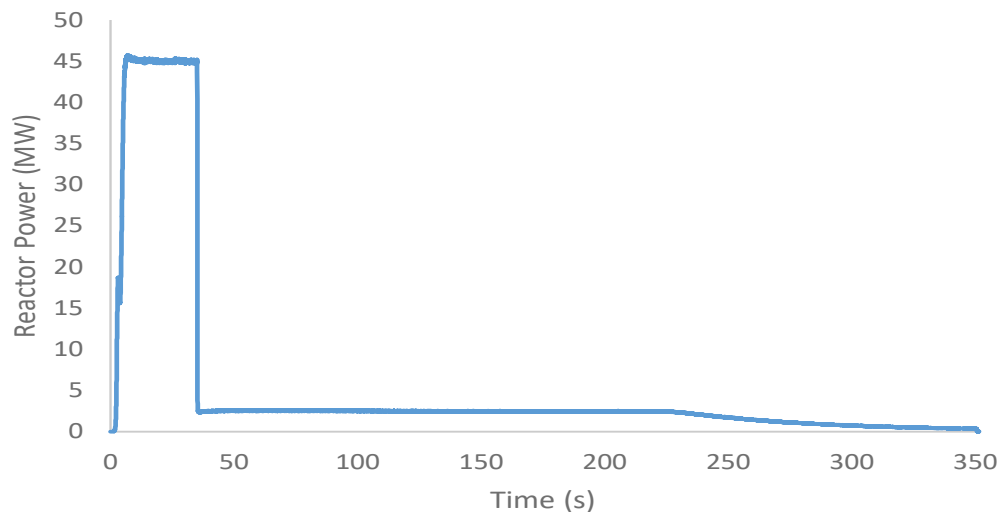


Figure 4. TREAT LOCA Power Profile.

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The Super-SERTTA capsule and test train are designed with extensive in-situ instrumentation. The rodlet cladding temperature will be monitored with attached thermocouples and noncontact pyrometers. Rodlet internal pressure is monitored via a pressure bellows attached to a push rod whose displacement can be measured via an attached linear voltage differential transformer (LVDT). Cladding elongation is also monitored with an LVDT attached to the test train. The environmental conditions of the Super-SERTTA test train are also monitored, including capsule temperature and pressure. The test rodlet in the LOCA commissioning campaign is an unirradiated UO₂-Zircaloy rodlet approximately 300mm in length with standard PWR 17 × 17 dimensions (9.5mm OD). The fuel will have an enrichment comparable to that of a high burnup fuel (~1%). The internal pressure of the rodlet will be dictated by the goals of the specific test being conducted.

The ratio of TREAT reactor power to test rodlet power is referred to as the power coupling factor (PCF). The coupling factor generally has units of W/g-MW. This parameter allows the specification of a reactor power shape for a desired test rod power history. The parameter is strongly influenced by the neutronic characteristics of the test specimen and test capsule. The PCF will likely vary based on the initial enrichment and depletion characteristics of the fuel, the geometry of the fuel pin, temperature of the water, temperature of the fuel, and the void fraction. Scaling factors for each of these variables is a required output from a detailed neutronics analysis. The initial enrichment ranges from 0.711% to 4.9%, fuel burnup ranges from 0 to 80 GWD/MTU, fuel pellet diameters from 7.6mm to 9.1mm in diameter, water temperature from 23°C to 300°C, fuel temperatures from 23°C to 2900°C, and void fractions from 0 to 1. A detailed neutronics analysis should be undertaken as part of the design effort to be capable of prescribing a TREAT reactor power history needed to achieve a desired test rodlet power history.

A systems thermal hydraulic code is necessary to calculate important system parameters such as liquid temperature, pressure, velocity, and void fraction. It is also necessary to calculate the fuel rod cladding and centerline temperatures during the LOCA. The goal of the LOCA test is to match the thermal mechanical boundary conditions of the test rod to those likely to be experienced in a LB-LOCA. These include Internal and External pressure, cladding temperature, and fuel centerline temperature. The thermal hydraulic model will be used to suggest an operating regime for the Super-SERTTA device and the test rodlet power profile, so as to closely mimic those conditions.

3. COMMISSIONING TESTS

The goal of the commissioning tests is to demonstrate the ability to conduct prototypic LOCA testing. The commissioning campaign consists of three phases which should be executed in order. These include:

1. System Initialization
2. Steady State
3. Blowdown and Quench

3.1 System Initialization

The initial tests are designed to demonstrate Super SERTTA's ability to achieve a desired thermodynamic end state with an established natural circulation environment. Based on Dalton's law of partial pressures, conservation of mass of the noncondensable gas, and conservation of mass of the water which can be both liquid and vapor, it is possible to calculate the initial temperature and pressure needed to achieve a desired final temperature and pressure. Figure 5 below shows the results of this exercise assuming a desired end state of 16MPa and 300C. Various initial void fractions lead to various final void fractions based on the amount of pre-pressurization assuming the liquid temperature starts around 20C.

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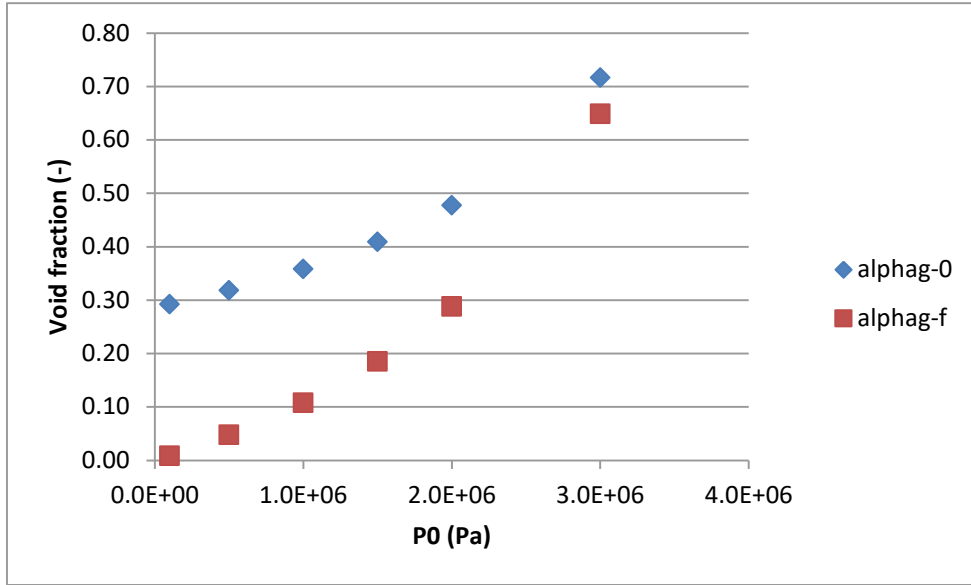


Figure 5. Initial and Final Void Fractions to Connect Thermodynamic Beginning and End States in Super SERTTA.

The RELAP-5 systems thermal hydraulic code was used to predict the behavior of the Super SERTTA device to determine if natural circulation conditions could be established. Results of system pressure, temperature in the lower plenum, and liquid velocity adjacent to the test rod are shown below in Figure 6 for a case of 15 MPa and 290°C in

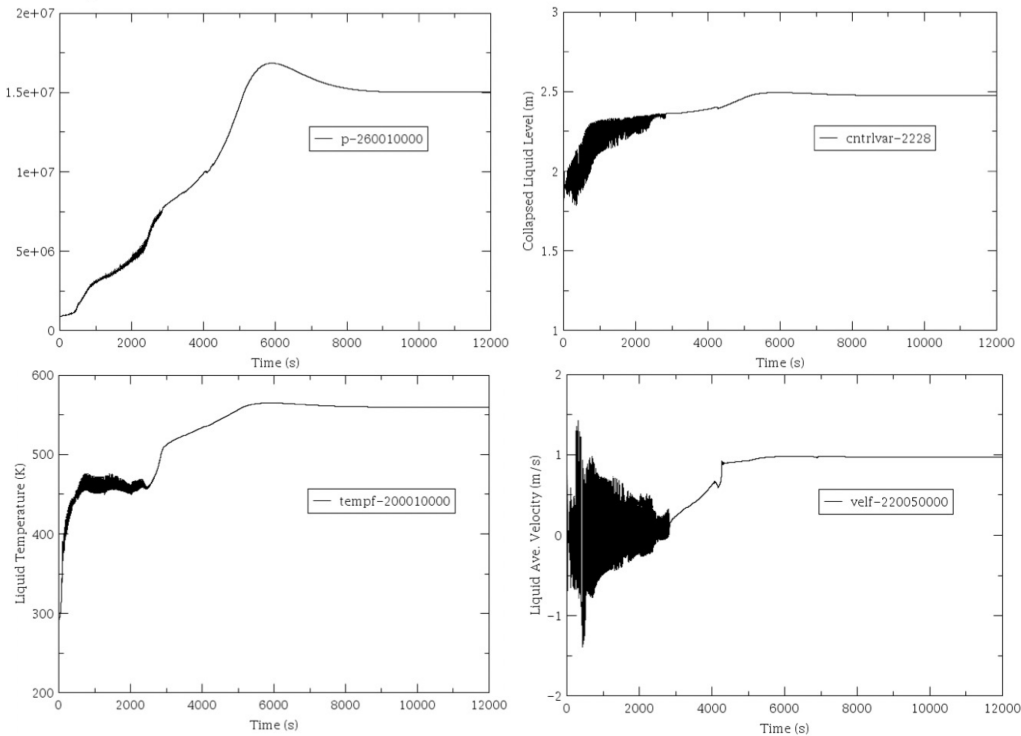


Figure 6. System Pressure, Liquid Level, Liquid Temperature, Liquid Velocity near Test Rod in Super SERTTA Initialization Simulation.

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The test matrix for the system initialization tests includes four tests designed to reach four different thermodynamic end states shown below in Table 1. A dummy fuel rod can be used which could include Zircaloy cladding and Zirconia pellets. The Super-SERTTA system should be charged at an initial liquid level at room temperature and a predetermined pre-pressure based on desired end state, system volume, and Dalton's laws of partial pressure. The annular heater should be run in conjunction with the cooling coil and gas heater to slowly bring the system to the thermodynamic end states described in the test matrix. Then the blowdown valves should be opened, and the system pressure tracked to determine the blowdown rate. Operation of the annular heater should continue during the blowdown to observe heater power and temperature to help determine an appropriate heater power operation that does not exceed the temperature limit of the heater.

Table 1. System Initialization Test Matrix A.

Test Number	Final System Pressure (MPa)	Final System Temperature (°C)
Super-SERTTA-Initial-1	8	250 C
Super-SERTTA-Initial-2	8	280 C
Super-SERTTA-Initial-3	15	280 C
Super-SERTTA-Initial-4	15	310 C

Following these initial tests, a follow-on series of blowdown tests will be conducted at the two different system pressures with different rod internal pressures to observe the ballooning and bursting of the test rod. This test matrix is shown in Table 2. The temperature of the liquid will be determined based on the results of the first four tests and thermal hydraulic modelling. These tests will enable a later comparison of the ballooning and burst behavior with and without the presence of nuclear heat.

Table 2. System Initialization Test Matrix B.

Test Number	System Pressure (MPa) at Final Temperature	Test Rod Pressure (MPa) at Final Temperature
Super-SERTTA-Initial-5	8	2
Super-SERTTA-Initial-6	8	4
Super-SERTTA-Initial-7	15	4
Super-SERTTA-Initial-8	15	8

3.2 Steady State

The goal of the steady state tests is to determine how much stored energy can be placed in the test rod prior to the LOCA. The Super-SERTTA test train will be placed inside the TREAT reactor, and the reactor power will be ramped over 30 seconds to a steady state power level. The annular heater should remain operating at full power during these tests. TREAT will hold that steady state power until it runs out of energy. Plots from a RELAP model below show how these different powers affect the system temperature and pressure in Figure 7, as well as the rodlet cladding and centerline temperature in Figure 8.

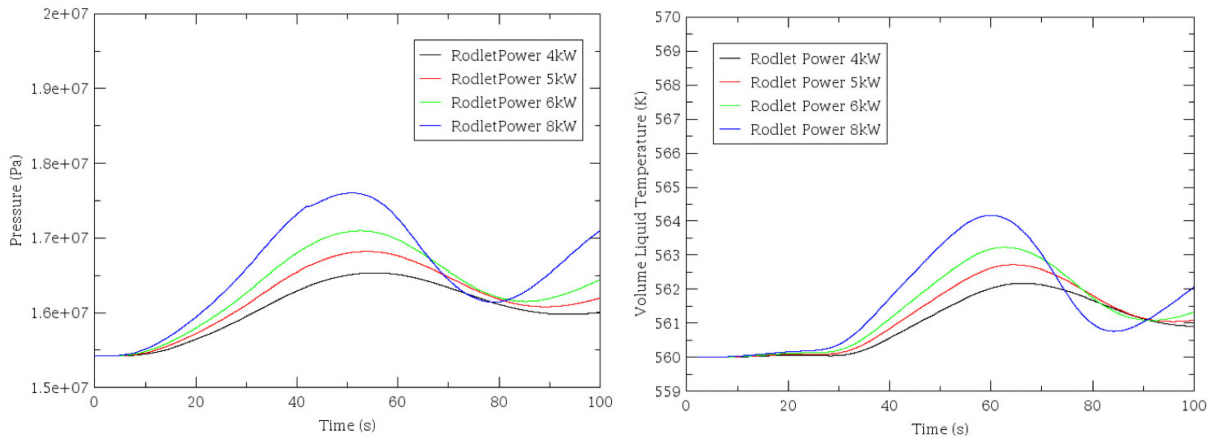


Figure 7. Predictions of Super SERTTA Pressure and Temperature During Steady State Tests.

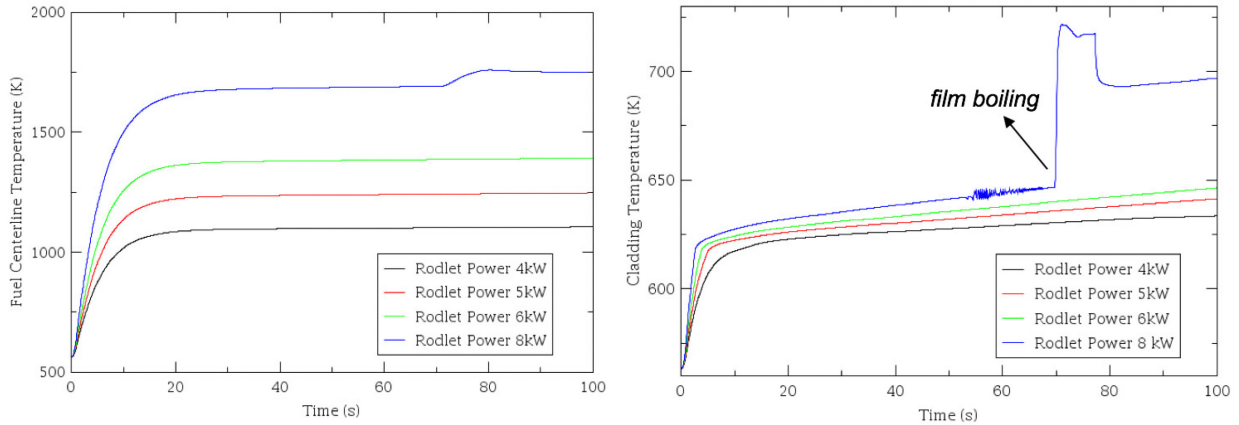


Figure 8. Predictions of Test Rodlet Centerline Temperature and Cladding Temperature During Steady State Tests.

The desired initial system temperature and pressure will have been chosen from the initialization tests which occurred out of pile. The steady state test matrix shown below in Table 3 indicates the rodlet powers. The test rods will not be pressurized in these tests. The rodlet power should be systematically increased until the power which causes film boiling on the rod is reached. The chiller should be ran in such a way as to remove all the energy put into Super-SERTTA by both the rodlet and the annular heater.

Table 3. Steady State Test Matrix.

Test Number	Test Rod Power (kW)
Super-SERTTA-LHGR-1	4
Super-SERTTA-LHGR-2	6
Super-SERTTA-LHGR-3	8
Super-SERTTA-LHGR-4	10

3.3 Blowdown

The goal of the blowdown tests will be to determine the cladding temperature histories that can be achieved during the blowdown phase of the transient. Following a short period of steady state operation, the blowdown valves will be opened, and the reactor power rolled back to that of decay heat levels. The annular heater should remain on throughout the blowdown phase, up to the maximum temperature of the heater. This will provide an insulative boundary condition so that maximum cladding temperatures can be achieved for the heat input. Some predictions of the system pressure as well as fuel and cladding temperature during the blowdown are shown below in Figure 9 for different steady state powers and decay heat levels at 10% of the steady state value. A comparison to an LOCA at H.B. Robinson is shown for clarity.

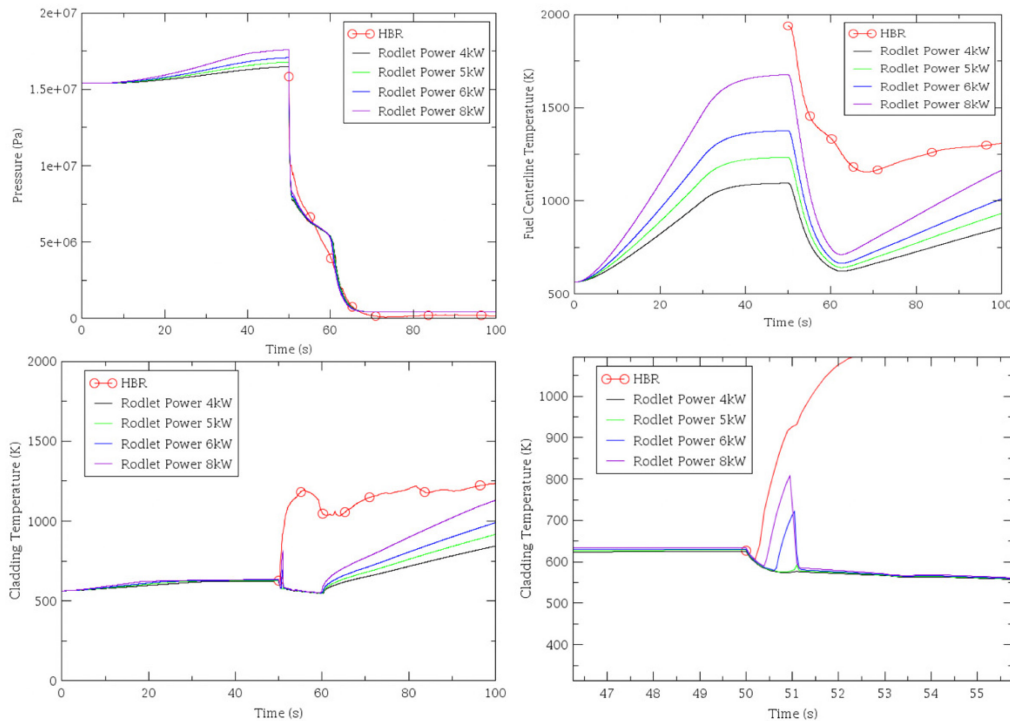


Figure 9. System Pressure, Fuel Centerline Temperature, and Cladding Temperature, During LOCA Blowdown.

The test matrix for the blowdown tests is presented below in Table 4, showing the different rodlet powers that can be used. The high and low cases for the steady state power should be determined from the steady state tests described above. The decay heat powers are percentages of the steady state value. These tests should take place with rods that are not pressurized. Two different reflood rates are also tested. The reflood should take place after peak cladding temperature is achieved and the reactor has reached its energy limit. After cladding temperature histories are determined in these initial tests, balloon and burst tests with pressurized rodlets will take place. These will all occur on the same power profile, which will be selected based on the results of the first four tests. Three different rodlet internal pressures will be used as shown in Table 5.

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Table 4. Blowdown/Quench Test Matrix A.

Test Number	Steady State Power	Decay Heat Power (% of SS)	Reflood Rate (cm/s)
Super-SERTTA-LOCA-1	Low	10%	3
Super-SERTTA-LOCA-2	Low	15%	9
Super-SERTTA-LOCA-3	High	10%	9
Super-SERTTA-LOCA-4	High	15%	3

Table 5. Blowdown/Quench Test Matrix B.

Test Number	Test Rod Internal Pressure (MPa)	Reflood Rate (cm/s)
Super-SERTTA-LOCA-5	4	3
Super-SERTTA-LOCA-6	6	9
Super-SERTTA-LOCA-7	8	3

4. SUMMARY/CONCLUSION

A plan has been presented for the commissioning LOCA tests at TREAT. Commissioning tests demonstrate the range of TREAT's LOCA capabilities. The Super-SERTTA device is designed to mimic LWR LOCA conditions and to be used with previously irradiated test rods. Online instrumentation provides valuable data that can inform fuel safety behaviors during the transient. The test program presented allows for the systematic testing of the operating range of Super-SERTTA and variety of test conditions that will be achieved in future programmatic tests.