FEASIBILITY ASSESSMENT FOR DEVELOPING AN INTEGRAL LOCA TESTING CAPABILITY AT THE TRANSIENT RESEARCH TEST (TREAT) REACTOR

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ABSTRACT

The study of Light Water Reactor (LWR) fuel performance in Loss of Coolant Accidents (LOCAs) has been a significant and evolving field since the beginning of the commercialization of LWR technology. The following paper presents the results of feasibility assessment to develop an in-pile, integral LOCA testing capability using the recently restarted TREAT reactor located at the Idaho National Laboratory (INL). Critical performance objectives for the testing platform are derived from a review of known LWR fuel degradation phenomena in LOCA scenarios. Advanced modeling and simulation tools were then used to gain additional insight into both the system performance and fuel performance characteristics of LOCA testing at TREAT. Results show that TREAT is well suited to conduct in-pile integral LOCA testing.

1 Introduction

The Transient Reactor Test facility (TREAT) located on the Idaho National Laboratory (INL) site was constructed in the late 1950's and has provided thousands of transient irradiations before being placed in standby in 1994. Thanks to a successful restart effort, TREAT will soon resume its crucial role in nuclear-heated safety research. The latter half of TREAT's historic operation was best known for integral-scale testing of fuel specimens under postulated reactor plant accident conditions, and while most of this later testing was devoted to Sodium Fast Reactor (SFR) fuel research, integral testing did occur with Light Water Reactor (LWR) fuel. An example of this integral testing was the Fuel Rod Failure (FRF) experiments conducted in 1972 [1]. In these experiments nine rod LWR bundles were nuclear heated to clad temperatures of 1200 °C resulting in significant ballooning and bursting behavior in the fuel rods and significant oxidation induced embrittlement of the Zircaloy cladding. These tests exposed the fuel rods to conditions that would be expected in a severe Loss of Coolant Accident.

Loss of Coolant Accidents (LOCAs) are some of the most severe accidents that can be experienced by commercial Light Water Reactor (LWR) fuel. The specific nature and sequence of events for the accident is dependent on the reactor type (PWRs vs BWRs), size of the break, location of the break, and the response of the Emergency Core Cooling System (ECCS). One of the most frequently analyzed and limiting LOCAs is the double-ended guillotine break in a cold leg of a PWR between the reactor coolant pump and the reactor vessel. These are often referred to as Large Break (LB-LOCAs). These LOCAs result in the maximum cladding temperatures, lowest external pressures, and longest oxidation times for the nuclear fuel.

While the knowledge of LWR fuel behavior in LOCAs and associated experimental needs have changed since the FRF experiments in 1972, much of the bulk infrastructure required for such testing remains the same. With the restart of TREAT in 2017 the opportunity presents itself to establish an integral LOCA testing mission at the facility. The following assessment shows that TREAT is well-suited for replicating the phenomena that are most relevant to integral testing of LWR fuel in LOCA conditions today. In addition, the advent of the Accident Tolerant Fuel (ATF) program provides additional motivation for establishing such a capability to test new fuel designs in a prototypic manner and compare against baseline data [2].

2 Development of Performance Criteria for Integral LOCA Testing

2.1 Important Fuel Performance Phenomena in LOCAs

The two fundamental fuel performance phenomena that have been historically addressed in both separate effects and integral LOCA research programs are cladding ballooning and burst, and cladding embrittlement due to high temperature steam oxidation [3]. As industry has continually moved to increasing the burnup of LWR fuels an additional phenomenon has become important to high burnup fuels, that is fuel pellet fragmentation, relocation, and dispersal [4].

The first fuel performance phenomena to be rigorously investigated was cladding balloon and burst behavior under large plastic deformations. Plastic deformation of Zircaloy cladding can cause significant problems for reactor safety. If neighboring rods have large hoop strains (>32%) that are axially aligned, they will come into mechanical contact with each other. This has the potential to cause large coolant channel blockages. Early integral testing focused on understanding of this phenomena though experimental programs such as FEBA, SEFLEX, THETIS, FLECHT, SEASET, and more recently through programs such as ACHILLES. The results of these programs are summarized well in the State of the Art Report on Nuclear Fuel Behavior in LOCA Conditions issued by Nuclear Energy Agency [5]. The general result is that blockages as large as 90% remain coolable, though some more challenging scenarios may still exist.

At the same time that early integral testing was showing the resilience of LWR fuel to flow blockage scenarios it was discovered that the Zircaloy cladding experienced oxidation induced embrittlement in the high temperature steam environment far below its melting point of 1850 °C. As the Zircaloy cladding heats up it undergoes a phase change from the HCP alpha structure to a BCC beta structure. Oxygen migrates into the Zircaloy substrate and due to the beta phases' low oxygen solubility, part of the substrate transforms back into the alpha phase but with a high oxygen concentration. This oxygen rich alpha phase is brittle at room temperature leaving the load bearing properties of the cladding to reside in the beta phase. Upon cooling the beta phase transforms back into the alpha phase. This region of the cladding is often referred to as the prior beta phase. The fuel cladding's bulk behavior is brittle if this prior beta layer becomes too thin due to prolonged oxidation or if unacceptably high concentrations of oxygen or hydrogen permeate into this layer due to their increased solubility at excessive cladding temperatures. For these reasons, the current Nuclear Regulatory Commission criteria are a limit on total oxidation set at 17% Effective Cladding Reacted (ECR) and a limit on peak cladding temperature at 1204°C. A summary of these LOCA embrittlement criteria and their historical development is given by Hache and Chung [6].

During the LOCA the fuel can fragment and axially relocate into the ballooned region of the cladding causing increases in cladding temperature and oxidation rate at that location. Recent experiments on high burnup fuel have also shown that for fuel rods with very high burnups (> 80

MWD/kgU) fuel fragmentation results in very fine fragments or pulvers. [4]. Upon burst these fine fragments can be expelled to the coolant causing a high release of radionuclides to the environment as well as an additional mechanism for coolant channel blockage.

The Nuclear Regulatory Commissions (NRC) has published Phenomenon Identification and Ranking Tables (PIRTs) for LOCAs in LWRs containing high burnup fuel [7]. The PIRT identifies important transient testing phenomena affecting cladding ballooning, burst, and embrittlement as well as fuel fragmentation, relocation and dispersal. For the integral testing section of the PIRT the important phenomena are grouped into subcategories on: (1) Fuel rod selection, (2) Conduct of test, and (3) Parameters and variables measured. Phenomena are ranked both in terms of importance and in terms of present knowledge.

Understanding those phenomena that are ranked with high importance and low knowledge will be the goal of TREAT's integral LOCA testing mission. These phenomena include: (1) fuel rod burnup, (2) in-situ or posttest evidence of fuel relocation and residual fuel cladding bonding, (3) plateau temperature, rewet initiation, cooldown rate, and quench rate. The PIRT also notes several items that are judged to be essential to integral testing. The effects of these phenomena are well known and understood, however they need to be controlled properly in the integral test in order to achieve accurate results. These include having a well-defined oxygen potential (saturated steam environment), and the incorporation of axial constraints.

2.2 Performance Criteria for TREAT LOCA Testing Mission

Following a review of LWR fuel degradation mechanisms in LOCAs and a review of the critical phenomena identified in the NRC PIRT, the following critical performance criteria where developed for the TREAT Integral LOCA testing program:

1. Ability to test high burn-up fuel pins, including the ability to remanufacture pins from high burnup commercial fuel.
2. Ability to reach peak cladding temperatures up to and above the current limit of 1204°C, using primarily internal (nuclear) heating.
3. Ability to simulate the refill and re-flood stages of the transient to achieve desired cooldown and quench rates in the fuel cladding.
4. Ability to maintain a 100% steam atmosphere during the refill and reflood phases of the test.
5. Ability to incorporate axial restraints and introduce axial and azimuthal temperature variations.
6. Ability to observe fuel axial relocation following burst event, at minimum obtain data posttest and if possible obtain this data in-situ.
7. Ability to obtain key transient performance measurements in-situ including cladding temperature at various axial and azimuthal locations, as well as fuel rod plenum pressure, and if possible pressure at the bottom of the fuel rod.

3 Overview of TREAT Irradiation Testing Capabilities

TREAT is an air-cooled reactor and contains fuel assemblies comprised of uranium dispersed in graphite blocks and encapsulated in a zirconium alloy. The fuel assemblies have a square cross section of 10.2 x 10.2 cm. Aluminum-sheathed unfueled graphite blocks are attached to the top and bottom of each fuel column; forming a discrete fuel assembly with 1.2 m of active core length. Along with control rod, experiment, and graphite reflector assemblies, these fuel assemblies are placed on a 19×19 grid plate with 361 available positions; creating a configurable core that can be adjusted to suit particular nuclear parameters or experimental objectives. Four slots can be opened through the vertical concrete shield walls and permanent graphite reflector surrounding the above-grade core to provide various capabilities. Two slots are currently in use, one for a neutron radiography beam, and the other for a fuel motion monitoring system (commonly referred to as the hodoscope) capable of collecting spatially-resolved data for fast neutrons born in experiment specimens. The radiography beam provides the capability to detect fuel relocation following the transient without moving the test train. The hodoscope may even be able to provide evidence of fuel fragmentation and relocation in-situ with near term improvements to the instruments resolution.

The reactor is best suited to self-contained experiment devices, which can be transported in shielded casks and lowered directly into the core with plug in connections for power, instrumentation, and other necessary leads. The ability to accommodate test devices by simple "lower in" installation through the rotating shield plug in the top of the reactor enables testing of various types of specimens, including high burnup fuel with little downtime between experiments. Highly radioactive experiments can be assembled nearby in hot cell facilities, transported in shielded casks, and returned to the hot cell for disassembly. Experiment devices typically displace one or two adjacent fuel assemblies in the reactor core, creating a test cavity of either 10.2 x 10.2 cm or 10.2 x 20.4 cm in the center of the core with 1.2m of active core height. While larger experiment devices can be installed they may require facility modifications. Figure 1 shows a schematic of an experiment test train inserted into the TREAT core.

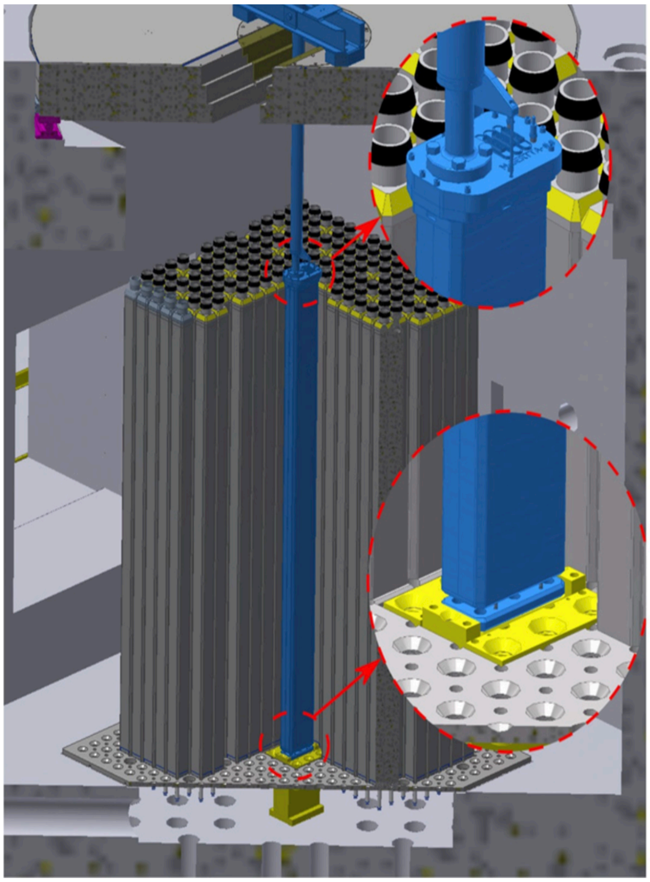

Fig 2. Rendering of TREAT Core with a Loaded Test Train

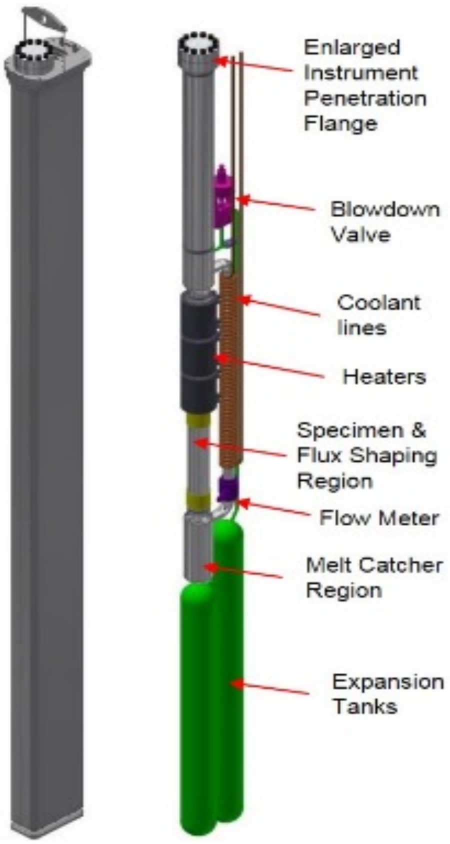

Fig 1. Conceptual rendering of Super SERTTA Device

The TREAT Integral LOCA experiment platform named “Super-SERRTA” is planned to fit within the 10.2 x 20.4 x 120 cm geometry. This facilitates TREAT’s ability to test high burnup pins due to the supporting infrastructure of experiment handling casks and the rotating shield plug. TREAT is a graphite moderated core with limited cooling capability. At a certain point during the transient the energy deposited in the TREAT core will raise the temperature of the graphite blocks sufficiently for the negative temperature coefficient to shut down the reactor. This limit is currently estimated to be 2500 MJ. Given certain assumptions about reactor power coupling to linear heat rate in the fuel it can be shown that TREAT can provide ~20 seconds of steady state power (10 – 20 kw/m) to a nuclear fuel rod sufficient to establish a semi prototypic radial temperature distribution in the fuel. Following the steady state period, the reactor can run an additional ~200 seconds at low linear power (1%-10% nominal) simulating the decay heat in the fuel.

An initial conceptual design for Super SERRTA is a natural circulation loop as illustrated in Figure 2. The coolant flows up through a heater section and passed the fuel test specimen into an upper plenum. Above the upper plenum is a gas plenum region which acts as a pressurizer for the system. From the upper plenum the coolant flows into a downcomer which is wrapped in a helical cooling coil. The system is complete with a blowdown valve and blowdown tank with an approximate volume of 21 Liters. A cold-water spray is attached to the blowdown tank which is used to condense the water vapor in the tank so the system can achieve post blowdown pressures that are close to atmospheric.

4 Results of Modeling and Simulation

A RELAP5-3D model of the system was developed to determine the thermal hydraulic parameters of the Super-SERRTA loop and compare against the thermal hydraulic conditions present in a representative PWR LOCA. The results were then used as input to a BISON fuel performance model to help quantify how differences in thermal hydraulic behavior of the TREAT LOCA test loop would affect the balloon and burst behavior of a test rodlet.

4.1 RELAP5-3D Simulation of Super-SERRTA System Performance

The RELAP5 model for Super-SERRTA showed that at steady state the system reaches a natural circulation velocity of 0.5 m/s which is about 10% of a commercial PWR coolant velocity. In order to maintain a sufficient DNB margin so as not to expose the test rodlet to film boiling prior to the blowdown, the rod power was required to be limited to 13.2 kW/m. A comparison of the conditions replicated in the TREAT experiment loop versus those in a model of the H.B Robinson NPP [8] are presented in Table 1. As can be seen in the table the main difference between the steady state thermal hydraulic environment of the Super-SERRTA device and a prototypic PWR are the differences in initial coolant velocity and resulting linear power in the fuel.

Parameter	H. B. Robinson	Super-SERRTA
Steady State Pressure, (MPa)	15.7	15.0
Steady State Coolant Temperature, (K)	576.5	579.8
Steady State Fluid Coolant Velocity, (m/s)	4.74	0.519
Steady State Fuel Linear Power, (kW/m)	41.3	13.2

Tab 1: Comparison of TH Conditions for a Commercial PWR and a Treat LOCA Experiment.

A 100 second large break LOCA simulation was run in both the H.B. Robinson model and the Super-SERRTA model. The blowdown was initiated at 30 seconds in both cases. Results show that the system pressure response is nearly identical to that of a prototypic PWR with the exception that the final blowdown pressure is higher in Super-SERTTA. The use of a cold-water spray in the blowdown tank helps remedy this difference.

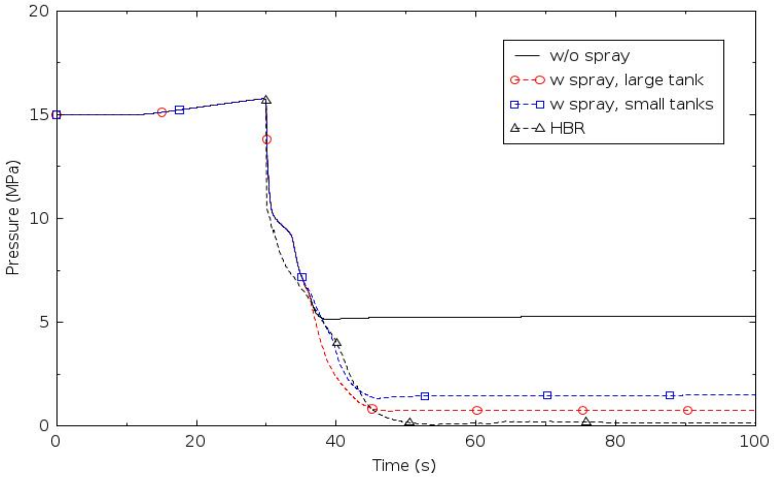

Fig 3. Comparison of System Pressure Response During Blowdown [8]

It is also necessary to generate a prototypic cladding temperature in Super-SERRTA. Oxidation behavior as well as balloon and burst of Zircaloy cladding in LOCAs are strongly temperature dependent. Much of the initial temperature rise in LWR fuel cladding during LB-LOCAs is due to the redistribution of stored energy in the fuel pellet. As the steady state linear powers in Super-SERRTA are lower than the hot rod in a PWR, the Super-SERRTA rod is held at nominal steady state power for an additional 6 seconds following the blowdown in order to inject more heat in the rodlet. The results show, that by using this technique, similar temperature ramp rates and plateau temperatures can be achieved. However, the temperature rise in Super-SERTTA is delayed by several seconds, which can affect the microstructure, and mechanical properties of the oxide. Super-SERRTA also has a smaller volume fraction of hot liquid above the test rodlet than a commercial PWR and so the Super-SERRTA rodlet does not see any temporary cooling effects as a result of flow reversals.

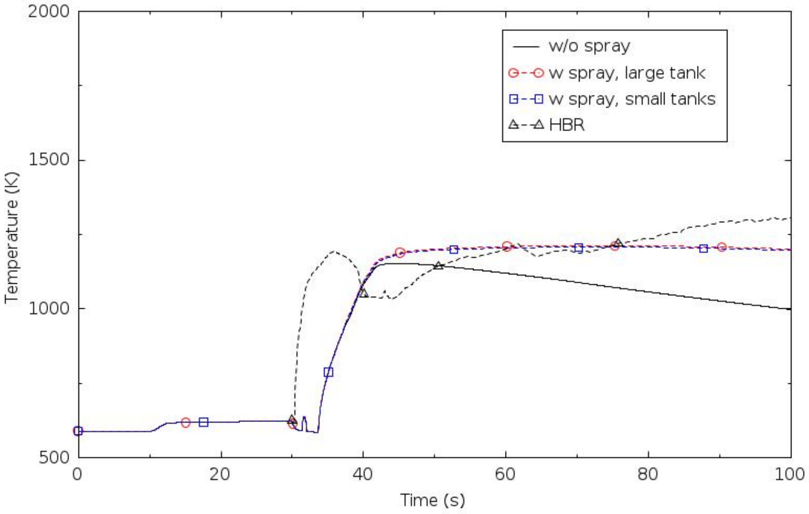

Fig 4. Comparison of Peak Cladding Temperature During LOCA *[8]*

4.2 Results of BISON Fuel Performance Model

The effects of the different cladding temperature histories on the balloon and burst behavior in the cladding were evaluated using the BISON fuel performance code. The same linear power histories are used in the BISON simulations and the cladding temperatures calculated from the RELAP5 simulations were used as boundary conditions on the cladding. BISON's cladding failure algorithm contains two criteria for failure. If either criterion is met the cladding is considered failed. The first criterion is an overstress criterion, and the second is a maximum strain rate criterion if the cladding strain rate exceeds $2.78 \cdot 10^{-2}\ s^{-1}$. Previously published work comparing this failure model to the failure of Halden IFA-650 experiments has shown good agreement between the failure model and experimental results [9]. Results of cladding strain for fresh UO_2-Zircaloy rods is shown below in Figure 5.

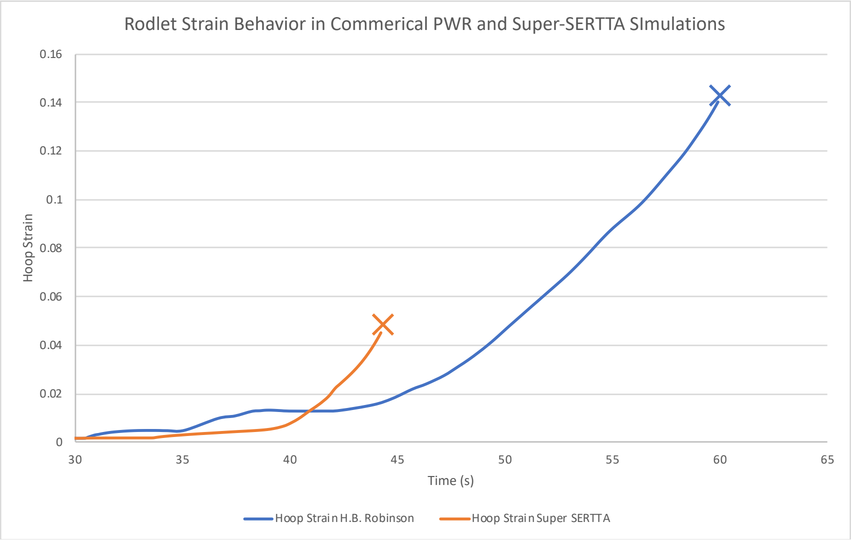

Fig 5. Comparison of Balloon and Burst in LOCA Simulation

The results show an early burst at low overall strain as a result of the temperature history in Super-SERTTA versus the more prototypic temperature history. In an actual experiment the low strain would result in very limited fuel relocation. The main cause of this discrepancy is that the cladding in the H.B. Robinson simulation is actually cooling down towards the end of the blowdown, as a result of the flow reversal. At the same time that this cooling is taking place, the system pressure falls below the internal plenum pressure in the fuel rod, providing the driving force for the balloon. Following the flow reversal, the fuel continues to heat up albeit more slowly. This slower temperature rise promotes a slow strain rate and thus a larger balloon before burst. By contrast the initial fast temperature rise in the Super-SERTTA simulation takes place when there is already azimuthal tensile stress in the cladding due to the fall in system pressure below the rodlet's internal pressure. As such the cladding strain rate increases nearly proportionally to the temperature increase and the fast strain rate leads to burst at lower overall strain.

In an actual LB-LOCA, cladding temperature histories are expected to vary and as such the size of balloons and burst conditions will vary. A slower average cladding temperature rise could be achieved in the Super-SERTTA experiments by reducing the fission power in the experiment during blowdown but still maintaining some minimum power level later in the test to achieve desired Peak Cladding Temperatures. The results in these simulations show the use of advanced modeling and simulation tools to predict how manipulations to system parameters affect desired fuel performance outcomes. Parametric studies using the RELAP5 and BISON models in techniques similar to those described in this section can be used to determine power sequences, and blowdown conditions required for specific experiments to obtain more prototypic strains.

5 Summary

The results of the initial assessment to conduct in-pile integral LOCA testing at TREAT are promising. TREAT's unique infrastructure and availability of co-located hot cells allow for the efficient testing of high burnup fuel. On-site radiography and the fast neutron Hodoscope will allow for detailed investigations of fuel fragmentation and relocation in high burnup rods. The results of initial system modeling show that a natural circulation loop can fit within TREAT's spatial constraints and provide a thermal hydraulic environment that is an adequate representation of the LOCA environment. The differences in environment can be accounted for through relatively simple fuel performance modeling and system parameters can be adjusted to replicate phenomena of interest to a specific experiment. Detailed design of the TREAT LOCA device is now underway with operational capability and first LOCA experiments expected by 2021.

6 Works Cited

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