Preliminary Feasibility, Design, and Hazard Analysis of a Boiling Water Test Loop Within the Idaho National Laboratory Advanced Test Reactor National Scientific User Facility

2009 Safety Analysis Workshop

Douglas M. Gerstner
Akira Tokuhiro
Bill Danchus
Jeff Smith
Artit Ridluan
Wil Taitano
Brian Gross
Kevin Steuhm
Shawn St. Germain

May 2009

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint should not be cited or reproduced without permission of the author. This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, or any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use, or the results of such use, of any information, apparatus, product or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights. The views expressed in this paper are not necessarily those of the United States Government or the sponsoring agency.
Preliminary Feasibility, Design, and Hazard Analysis of a Boiling Water Test Loop within the Idaho National Laboratory Advanced Test Reactor National Scientific User Facility

Douglas M. Gerstner  
Idaho National Laboratory  
P.O. Box 1625  
Idaho Falls, Id. 83415  
208-526-2099  
douglas.gerstner@inl.gov

Dr. Akira Tokuhiro, Bill Danchus, Jeff Smith, Artit Ridluan, Wil Taitano, Brian Gross, Kevin Steuhm, Shawn St. Germain  
Nuclear Engineering Program  
University of Idaho  
1776 Science Center Drive, Idaho Falls, ID 83402-1575  
208-282-7714  
tokuhiro@uidaho.edu
ABSTRACT

A Boiling Water Test Loop (BWTL) is being designed for one of the irradiation test positions within the Advanced Test Reactor (ATR). The objective of the new loop will be to simulate boiling water reactor (BWR) conditions to support clad corrosion and related reactor material testing. Further it should accommodate power ramping tests of candidate high burn-up fuels and fuel pins/rods for the commercial BWR utilities. The BWTL will be much like the pressurized water loops already in service in 5 of the 9 ‘flux traps’ (region of enhanced neutron flux) in the ATR. The loop coolant will be isolated from the primary coolant system so that the loop’s temperature, pressure, flow rate, and water chemistry can be independently controlled.

The design engineering and feasibility study requires (coupled) analyses of the following: neutronics, thermal-hydraulics, engineering of auxiliary systems and certification for safe normal and transient operation. This document focuses on the general design of the in-core portion of the BWTL; in particular the thermal-hydraulic analysis, design of the auxiliary systems, and preliminary analysis of system hazards. This document may serve as a preliminary draft outline for a future addendum to the ATR Safety Analysis Report (SAR).

A revised SAR is necessary since the design and operation of the BWTL is outside of the currently analyzed Pressurized Water Loop (PWL) and drop in capsule experiments currently in use at ATR. A revised SAR will be required to obtain US Department of Energy (DOE) approval for installation and operation of the BWTL in ATR.
<table>
<thead>
<tr>
<th>TABLE OF CONTENTS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT ...........................................................................................................</td>
<td>2</td>
</tr>
<tr>
<td>LIST OF TABLES .................................................................................................</td>
<td>4</td>
</tr>
<tr>
<td>LIST OF FIGURES ...............................................................................................</td>
<td>4</td>
</tr>
<tr>
<td>1. INTRODUCTION ...............................................................................................</td>
<td>6</td>
</tr>
<tr>
<td>2. BACKGROUND ..................................................................................................</td>
<td>6</td>
</tr>
<tr>
<td>3. SYSTEM DESIGN .............................................................................................</td>
<td>7</td>
</tr>
<tr>
<td>4. PRELIMINARY HAZARD IDENTIFICATION AND ANALYSIS .......................................</td>
<td>26</td>
</tr>
<tr>
<td>5. APPLICATION OF EXPERIMENT SAFETY ANALYSIS PROCESS ..................................</td>
<td>34</td>
</tr>
<tr>
<td>6. PRELIMINARY SAFETY-RELATED SSCE, SAFETY ANALYSIS COMMITMENTS, AND TSR CONTROLS</td>
<td>34</td>
</tr>
<tr>
<td>7. CONCLUSION ..................................................................................................</td>
<td>35</td>
</tr>
<tr>
<td>8. REFERENCES .................................................................................................</td>
<td>35</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 1. BWTL Components and Criteria ................................................................................... 13
Table 2. Preliminary What-If Analysis for the Advanced Test Reactor (ATR) Boiling Water Test Loop (BWTL)....................................................................................................................... 28

LIST OF FIGURES

Figure 1. B-position boiling water loop. ......................................................................................... 8
Figure 2. I-position boiling water loop. .......................................................................................... 8
Figure 3. BWTL Simplified Loop Diagram. .................................................................................. 10
Figure 4. The solid model of the I-position created using Rhinoceros. ......................................... 16
Figure 5. The trimmed-cell mesh of the I-position created using Star-CCM+ automated meshing utility. ..................................................................................................................................... 16
Figure 6. Cropped temperature at 545F (any fluid below 545F is not seen) focused on the outlet. ............................................................................................................................................... 17
Figure 7. The solid model of the B-position created using Rhinoceros. ....................................... 17
Figure 8. The trimmed-cell mesh of the B-position created using Star-CCM+ automated meshing utility. ..................................................................................................................................... 18
Figure 9. Predicted temperature distribution across the B-Position model. ................................. 18
Figure 10. Predicted void distribution of the liquid phase across the B-Position model.............. 19
Figure 11. GAMBIT Mesh of B-12 Channel Flow Section. ......................................................... 19
Figure 12. Specific Heat for Liquid and Vapor Water at P = 0.1 MPa. ........................................ 20
Figure 13. Specific Heat for Liquid and Vapor Water at P = 9, 15, 27 MPa. ................................ 21
Figure 14. Percent Difference for Specific Heat. .......................................................................... 21
Figure 15. Volume Fraction vs. Mass Flow Rate. ......................................................................... 22
Figure 16. Average Cross-Sectional Fluid Temperature across Axial Extent. ............................. 23
Figure 17. Temperature Difference vs. Vapor Fraction. ............................................................... 23
Figure 18. BWTL in B-12 position. .............................................................................................. 24
Figure 19. BWTL with bubbles added; looking from the side on the left and from the top down on the right. ........................................................................................................................................... 25
Figure 20. West OSCC 1-4 rotation direction. ............................................................................. 25
Figure 21. Reactivity change due to void presence in BWTL. .................................................. 26
<table>
<thead>
<tr>
<th>ACRONYMS</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASME</td>
<td>American Society of Mechanical Engineers</td>
</tr>
<tr>
<td>ATR</td>
<td>Advanced Test Reactor</td>
</tr>
<tr>
<td>ATRC</td>
<td>Advanced Test Reactor Critical Facility</td>
</tr>
<tr>
<td>BWTL</td>
<td>Boiling Water Test Loop</td>
</tr>
<tr>
<td>BWR</td>
<td>Boiling Water Reactor</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>DOE</td>
<td>US Department of Energy</td>
</tr>
<tr>
<td>ESA</td>
<td>Experiment Safety Analysis</td>
</tr>
<tr>
<td>GDC</td>
<td>General Design Criteria</td>
</tr>
<tr>
<td>INL</td>
<td>Idaho National Laboratory</td>
</tr>
<tr>
<td>IPT</td>
<td>In-Pile Tube</td>
</tr>
<tr>
<td>LDRD</td>
<td>Laboratory Directed Research and Development</td>
</tr>
<tr>
<td>LOCA</td>
<td>Loss of Coolant Accident</td>
</tr>
<tr>
<td>NRC</td>
<td>Nuclear Regulatory Commission</td>
</tr>
<tr>
<td>NSUF</td>
<td>National Scientific User Facility</td>
</tr>
<tr>
<td>OSCC</td>
<td>Outer Shim Control Cylinder</td>
</tr>
<tr>
<td>PC</td>
<td>Performance Category</td>
</tr>
<tr>
<td>PCS</td>
<td>Primary Coolant System</td>
</tr>
<tr>
<td>PPC</td>
<td>Plant Protection Criteria</td>
</tr>
<tr>
<td>PPS</td>
<td>Plant Protection System</td>
</tr>
<tr>
<td>PWL</td>
<td>Pressurized Water Loop</td>
</tr>
<tr>
<td>QA</td>
<td>Quality Assurance</td>
</tr>
<tr>
<td>RANS</td>
<td>Reynolds Averaged Navier-Stokes</td>
</tr>
<tr>
<td>SAR</td>
<td>Safety Analysis Report</td>
</tr>
<tr>
<td>SSC</td>
<td>Structures, Systems, and Components</td>
</tr>
<tr>
<td>UDF</td>
<td>User-Defined Function</td>
</tr>
<tr>
<td>USQ</td>
<td>Unreviewed Safety Question</td>
</tr>
</tbody>
</table>
1. **INTRODUCTION**

The purpose of this document is to perform a preliminary design and feasibility analysis of the implementation of a boiling water test loop (BWTL) within the Advanced Test Reactor (ATR). The BWTL is being designed for one of the irradiation test positions within the Advanced Test Reactor (ATR). The objective of the new loop will be to simulate boiling water reactor (BWR) conditions to support clad corrosion and related reactor material testing. The design engineering and feasibility study requires (coupled) analyses of the following: neutronics, thermal-hydraulics, engineering of auxiliary systems and certification for safe normal and transient operation. This document will focus on the general design of the in-core portion of the BWTL; in particular the thermal-hydraulic analysis, design of the auxiliary systems, and preliminary analysis of system hazards.

2. **BACKGROUND**

A BWTL was considered in the early 1990’s for operation in an existing ATR flux trap under the Laboratory Directed Research and Development (LDRD) program. The initial project was shutdown in 1996 after it was determined that the phenomena could not be tested safely or data gathered accurately with a mockup assembly placed within the Advanced Test Reactor Critical Facility (ATRC).

A new initiative by the ATR National Scientific User Facility (NSUF) is to install a BWTL within the ATR. The BWTL will be installed in one of the outer ATR irradiation facilities. The location of the BWTL was limited to the large B-positions and the I-positions due to several reasons; the experimental region must be able to contain at least one test the size of a typical BWR fuel rod, the boiling inside the BWTL must not create a reactivity safety concern, and the primary coolant channels must provide adequate cooling without raising its temperature above that observed under normal operating conditions.

A preliminary analysis of the implementation of a BWTL within the ATR was performed (Reference 1). The study focused on the general design of the in-tank test assembly, the neutronics and reactivity safety analysis, and the thermal-hydraulic analysis. This updated analysis performed the following:

1) Carry-out the thermal-hydraulic engineering analyses and design of the BWTL based on the Preliminary Analysis report provided.

2) Determine if additional neutronic analysis based on MCNP/ORIGEN needs to be conducted, carry them out if necessary.

3) Conduct a preliminary evaluation of hazards associated with the BWTL.
3. SYSTEM DESIGN

3.1. System Description

3.1.1. In-Tank BWTL System Design

The general design of the BWTL for the large B and I-positions (see Figures 1 and 2) consists of five components; the experimental region, the inner IPT, the helium insulator gap, the outer IPT, and the primary coolant annulus. The approach that was taken for the design of the boiling water loops was to build the loops from the center of the position outward. The inner diameter for the inner IPT defines the experimental region. The experimental region was designed to be as large as possible to provide flexibility for the size of the experiments. For this study, the experiments were assumed to be fuel pins with an outer diameter of 0.5 in. (1.27 cm), which is typical for a BWR. The diameter of the large B-position is 1.5 in. (3.81 cm), whereas the diameter for the large I-position is 5 in. (12.7 cm).

The goal for the B-position loop was to design a region that could enclose one fuel pin with a boiling water gap at least as thick as the gap found between the pins in a BWR. Since the I-position is larger, multiple fuel pins could be arranged inside the region. The fuel pins were assumed to be arranged with the same lattice pitch as in a BWR (0.64 inch, 1.63 cm). The thickness of the helium insulator gap was based on the thickness of that found in the pressurized water loop.

The boiling water loop and the pressurized water loop both can operate at similar temperatures. Therefore, the helium insulator gap thickness was assumed to be of similar thickness to the pressurized water loop (0.030 in. and 0.050 in. for the B and I positions, respectively). The thickness of the primary coolant annulus was designed to be thick enough to provide adequate cooling for the boiling water loop, while keeping the primary coolant outlet temperature below 160°F (71°C). A thickness of 0.025 in. (0.0635 cm) was assumed for the B-position. The primary coolant annulus in the I-position also contains four rings of booster fuel. The booster fuel was assumed to have the same clad, fuel meat and water gap thickness as the fuel plates in the ATR.
Figure 1. B-position boiling water loop.

Figure 2. I-position boiling water loop.
3.1.2. Out-of-Tank BWTL System Design

Out-of-Tank Loop Components

Outside of the reactor vessel, heat is transferred to the loop coolant from the line heaters and rejected to a quench tank or condenser (some heat is also lost to the surroundings); variable use of the line heaters controls the temperature of the test (see Figure 3).

Condensate, booster and feed pumps provide flow energy to circulate the fluid, overcome frictional losses to pipe walls and equipment/fittings, and serve as a minor heating source for the coolant.

A condenser or quench tank will condense the steam produced in the test loop and remove enough energy to bring the coolant to condensate conditions to allow pumping and to meet thermal constraints for the demineralizer. The tank will be vented to the ATR building stack to remove non-condensable gasses from the system.

Loop Energy Gains/Losses

Prior to reactor startup, each experiment loop is brought to operating temperature with its associated line heaters; when this temperature is attained, electrical supply to the line heaters is adjusted so that loop temperature is just below the boiling point (approximately 530 °F).

After the reactor is brought to power, the line-heater settings are adjusted in conjunction with feed flow rate to achieve the desired channel conditions in the test section.

Loop Pressure

The pressure control valve will throttle steam flow to maintain the test loop at the desired pressure. A pressure relief valve will be installed upstream of the pressure control valve in case of failure of the pressure control valve or for potential transients which could raise pressure faster than the response time of the pressure control valve. The pressure set point of the pressure relief valve will ensure the loop does not exceed its design pressure.

The loop condensate, booster and feed pumps will be required to inject coolant at the rated pressure of the test loop (1050 psig) and overcome head losses in the piping. The speed of the feed pump will be variable and will match feed flow to steam flow to maintain the desired conditions in the test section.

Coolant Chemistry

A cartridge style demineralizer will be installed downstream of the condensate pump to remove any contaminants in the coolant and maintain coolant chemistry. No chemical addition should be required.
Figure 3. BWTL Simplified Loop Diagram.
3.2. Application of ATR General Design Criteria (and 5480.30)

3.2.1. ATR General Design Criteria

The evaluation below discusses the ATR SAR (Reference 2) General Design Criteria (GDC) applicable to the BWTL. Criteria 1 through 5 are essentially generically applicable to all structures, systems, and components (SSC’s) at the ATR and are met by complying with the applicable programs and procedures.

3.2.1.1. GDC 1, Quality Standards and Records

Compliance with the INL Quality Assurance (QA) program satisfies this GDC. The BWTL design control process shall be compliant with ASME NQA-1 among other standards.

3.2.1.2. GDC 2, Design Bases for Protection Against Natural Phenomena

BWTL SSC important to safety shall be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, and floods without loss of capability to perform their safety functions. The design bases for these SSC shall reflect: (1) appropriate consideration of the most severe of the natural phenomena that have been historically reported for the INL and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated, (2) appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena, and (3) the importance of the safety functions to be performed.

3.2.1.3. GDC 3, Fire Protection

BWTL SSC important to safety shall be designed and located to minimize, consistent with other safety requirements, the probability and effect of fires and explosions.

3.2.1.4. GDC 4, Environmental and Dynamic Effects Design Bases

BWTL SSC important to safety shall be designed to accommodate the effects of and to be compatible with the environmental conditions associated with normal operation, maintenance, testing, and postulated accidents, including loss-of-coolant accidents.

3.2.1.5. GDC 5, Sharing of Structures, Systems, and Components

BWTL SSC important to safety shall not be shared with other facilities unless it can be shown that sharing will not significantly impair their ability to perform their safety functions including, in the event of an accident in a shared component or a sharing facility, an orderly shutdown and cooldown of the facility.

3.2.1.6. GDC 14, Primary Coolant System Pressure Boundary

The BWTL primary coolant pressure boundary shall be designed, fabricated, erected, and tested so as to have an extremely low probability of abnormal leakage, of rapidly propagating failure, and of gross rupture.
3.2.1.7. GDC 16, Confinement Design

Reactor confinement and associated systems shall be provided to establish a barrier against the uncontrolled release of radioactivity to the environment and to assure that the confinement design conditions important to safety are not exceeded for as long as postulated accident conditions require.

3.2.1.8. GDC 20, Protection System Functions

The BWTL will not interface with the ATR Plant Protection System (PPS).

3.2.1.9. GDC 30, Quality of the Primary Coolant Pressure Boundary

BWTL components which are part of the primary coolant pressure boundary shall be designed, fabricated, erected, and tested to the highest quality standards practical. Means shall be provided for detecting and, to the extent practical, identifying the location of the source of primary coolant leakage.

3.2.1.10. GDC 32, Inspection of Primary Coolant Pressure Boundary

Components which are part of the primary coolant pressure boundary shall be designed to permit (1) periodic inspection and testing of important areas and features to assess their structural and leak-tight integrity, and (2) an appropriate material surveillance program for the reactor pressure vessel."

3.2.1.11. GDC 50, Confinement Design Basis

The reactor confinement structure, including access openings and penetrations, shall be designed to limit leakage to the environment to be consistent with ATR PPC for radioactive releases.

3.2.1.12. GDC 54, Fluid Systems Penetrating Confinement

This GDC is one of the seven which was modified from the original NRC criteria to adapt to ATR's design. BWTL design and installation shall include sealing the BWTL confinement penetrations.

3.2.1.13. GDC 55, Reactor Coolant Pressure Boundary Penetrating Confinement

Each line that is part of the reactor coolant pressure boundary and that penetrates primary reactor containment shall be provided with containment isolation valves, unless it can be demonstrated that the containment isolation provisions for a specific class of lines, such as instrument lines, are acceptable on some other defined basis.
3.2.1.14. GDC 70, Experiment Facilities

The BWTL shall be designed so that the analyzed fault consequence limits are consistent with the ATR Plant Protection Criteria. Experiment facilities and their associated out-of-reactor SSC important to safety shall meet applicable overall requirements (GDC 1-5).

3.2.2. DOE Order 5480.30

The ATR GDC establish minimum requirements for new construction and modification of safety SSCs. Additional requirements or removal of requirements, for safety SSCs, are also considered in accordance with DOE O 5480.30 (Reference 3). Modification of safety SSCs, due to BWTL installation, is limited to the primary coolant pressure boundary and penetration through the confinement boundary. Appropriate design criteria for these safety SSCs are adequately addressed by the ATR GDC. Therefore, application of additional or revised criteria based on DOE O 5480.30 requirements is not required.

3.3. System Design and Analysis

3.3.1. Structural/Mechanical and Seismic Design and Analysis

The various BWTL components and the criteria they shall be analyzed for are given in Table 1.

Table 1. BWTL Components and Criteria.

<table>
<thead>
<tr>
<th>BWTL Component</th>
<th>Applicable Code/Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-Tank tubing/piping</td>
<td>ASME B31.1 stress</td>
</tr>
<tr>
<td></td>
<td>PC-2 seismic</td>
</tr>
<tr>
<td>In-Vessel components</td>
<td>Thermal expansion</td>
</tr>
<tr>
<td></td>
<td>Sustained loads</td>
</tr>
<tr>
<td></td>
<td>PC-4 seismic loads</td>
</tr>
<tr>
<td></td>
<td>Sustained &amp; seismic</td>
</tr>
<tr>
<td>Tubing/Piping outside the vessel</td>
<td>Thermal expansion</td>
</tr>
<tr>
<td></td>
<td>Sustained loads</td>
</tr>
<tr>
<td></td>
<td>PC-2 seismic loads (PC-4 for nozzle trench &amp; cubicle)</td>
</tr>
<tr>
<td></td>
<td>Sustained &amp; seismic</td>
</tr>
<tr>
<td>Specially (non-standard) designed</td>
<td>ASME B31.1 stress</td>
</tr>
<tr>
<td>components</td>
<td></td>
</tr>
<tr>
<td>Water hammer</td>
<td>Demand/Capacity ratios (D/C)</td>
</tr>
<tr>
<td>Lead shielding</td>
<td>PC-2 seismic event</td>
</tr>
<tr>
<td>Reactor vessel flange</td>
<td>ASME B&amp;PV Section III, Class 1</td>
</tr>
<tr>
<td>In-Vessel tubing vibrations</td>
<td>Frequency higher than previous experiments</td>
</tr>
<tr>
<td>Floor loading</td>
<td>ATR building spec</td>
</tr>
<tr>
<td>Holes in concrete floors</td>
<td>American Concrete Institute</td>
</tr>
</tbody>
</table>
3.3.2. Thermal Hydraulic Design and Analysis

3.3.2.1 Star-CCM+ CFD Analysis

Introduction

Multiphase flow including boiling is a difficult phenomenon to model computationally. Traditionally modeling multiphase flow is conducted using sub-channel lumped parameter codes. These codes rely on empirical correlations to determine the exchange of mass, energy, and momentum at the boundaries of the sub-channel. This technique produces results too coarse for analyzing the detailed intra-assembly flow patterns. Unfortunately many of the alternative approaches such as using the Navier-Stokes equations are not as advanced as the methods employed in today’s sub-channel codes. Generally the two-phase methods employed today by computational fluid dynamic (CFD) methods lack maturity (Reference 4). Currently, Tentner et al. (Reference 5) have applied alternate methods in an attempt to increase the sophistication of methods employed by Reynolds Averaged Navier-Stokes (RANS) based methods, but these alternative methods have yet to be packaged in commercially available software. Though current CFD multiphase methods lack maturity and sophistication as their sub-channel counterparts, there is still great insight to be gained by using CFD methods in both single-phase and multiphase simulations.

Using the commercially available software Star-CCM+ (Reference 6) a single-phase and two-phase CFD simulation of the conceptual boiling-water test loops inside the ATR B-position has been modeled. The construction of a CFD model will not only expedite the design phase, but greatly aid in the safety analysis of the loop. Initially the development of the I-position model was conducted; design changes later moved the loop to the B-position. The analyses conducted on both positions are presented.

Model

The development of both CFD models followed the same pattern in their development. The models are only intended to highlight some abilities of Star-CCM+’s ability to model the boiling water test loop.

I-Position

Preliminary investigation of the test loop was conducted by ATR summer students (Reference 1). The development of the I-position model was conducted first. The dimensions of the I-position are seen in Figure 2. The development of the CFD model began with the creation of the solid model in Rhinoceros (Reference 7). To simplify the analysis, the model consisted of a pipe flow with nine fuel pins that share the pin radius of a typical BWR seen in Figure 4. (Exact dimensions are contained in Reference 1)

The model was then imported into Star-CCM+ to take advantage of the software’s meshing methods. The test loop was meshed using Star-CCM+’s trimmed cell mesh. It has been shown that in pin bundle modeling the trimmed cell approach has the ability to maintain adequate details of the geometry while minimizing element (Reference 8). The mesh is shown in Figure 5, with a total cell count just shy of one million cells.

The tube bundle model boundary conditions consisted of an outer wall and the central pin as adiabatic, and the eight outer pins were of constant heat flux. The bottom of the tube bundle was
set as an inlet velocity and the top of the assembly was a mass flow split boundary and was used instead of a pressure outlet due to the chance of a reversal in flow at outlet. The standard k-ε turbulence model was used to model the single-phase liquid water flow. An inlet condition of 1.5 m/s at a temperature of 530°F with a pressure of 6.825 MPa was used to define the flow.

**I-Position Results**

Only a single-phase analysis with no boiling was conducted on the I-position design due to design changes before the multiphase simulations began. The initial single-phase fluid was chosen to start the study to computationally determine the heat flux required by the heater pins to produce an average outlet temperature of 545°F. The simulation predicted that approximately 2.5 MW/m² was needed to obtain the desired average outlet temperature. Figure 6 shows in detail the simulated temperature distribution in the tube bundle, which show that the fluid along the central test pin reaching 545°F just before the outlet.

**B-Position**

Like the I-position, the B-position model and simulated using the same approach. Seen in Figure 1 is the B-position cross section, and in Figure 7 is the solid model produced in Rhinoceros of the annular pipe flow. A trimmed cell meshing method was used again, but the mesh was much more refined in comparison to the domain of the I-position. The total cell count was ~4.3 million cells and the mesh can be seen in Figure 8. A heavily refined mesh was utilized to set an adequately small time step to capture the dynamics of the implicit unsteady two-phase flow. Multiplying the courant number by 10³, which was approximately 0.05 seconds for this model, then set the time step.

Multiphase liquid-vapor water was used for this simulation. The fluid flow was initially solved as a turbulent steady multiphase mixture to set initial conditions for the unsteady simulation. The turbulence was modeled by standard the two-layer k-ε model, which was chosen again for its particular stability in most flows. The phase change was handled by a sub-cooled boiling model with surface tension and gravity effects considered. The properties were set using isobaric conditions for a pressure of 6.825 MPa. The simulation consisted of an inner heated surface, and an outer adiabatic wall. The bottom inlet velocity was set to 1.658 m/s and the heated surface was set to a constant 15 kW/ft and an initial 2% vapor. The inlet temperature was raised to help the steady solution to 540°F.

**B-Position Results**

Due to time constraints and the lack of available computational power the initial steady simulation was only completed to a max convergence of 1e-3. Figures 9 and 10 show the temperature distribution and volume fraction of the nearly converged solution. It can be seen that the predicted heat flux of 15 kW/ft is inadequate in reaching the average outlet temperature of 545°F even from an increased inlet temperature.

**Summary of Results**

The simulation of the I- and B-position has been preformed. The development of either pin position model needs more time to be used as a valid tool for development of safety analysis. A period of verification and validation must be conducted to show the validity of these models. Much more time must be spent in the optimization of the mesh through sensitivity studies and
comparisons to experimental data. The computational cost from the complexity of the simulation of the B-position made the time constraint not possible for a desktop simulation. The liquid single-phase simulation of the I-position provided design insight into the amount of heat that needed to be put into the bundle to reach an average temperature increase of 15° in the flow channel.

In the B-position we see that the assumed heat flux was inadequate to reach the average desired outlet temperature. The two-phase analysis could be improved with better properties of the materials such as wall roughness.

Overall we have shown that Star-CCM+ does have adequate physical models to make generally design decisions about the boiling water test loop. These models in particular still need to be developed with much more focus on the sensitivity of grid refinement and could lead to better converging models.

Figure 4. The solid model of the I-position created using Rhinoceros.

Figure 5. The trimmed-cell mesh of the I-position created using Star-CCM+ automated meshing utility.
Figure 6. Cropped temperature at 545F (any fluid below 545F is not seen) focused on the outlet.

Figure 7. The solid model of the B-position created using Rhinoceros.
Figure 8. The trimmed-cell mesh of the B-position created using Star-CCM+ automated meshing utility.

Figure 9. Predicted temperature distribution across the B-Position model.
Note: The bottom left image is of the outlet and the right is of the inlet with cross sections at every 2 inches.
3.3.2.2 Fluent CFD Analysis

Analysis

The CFD simulation for the BWTL was performed using the FLUENT CFD simulation tool. The B-12 geometry was considered for the analysis. The total length of the test section is 48 inches with the cross sectional dimensions provided below in Figure 1 and axial view in Figure 11.

Note: For the current stage, only the flow section was modeled. If necessary, conjugate heat transfer of solid/fluid interface can easily be modeled in the future. (source: Reference 1)

Figure 11. GAMBIT Mesh of B-12 Channel Flow Section.

The analysis was based on the following thermal-hydraulic requirements: Mass flow rate of 3.2 kg/sec for single phase liquid water flow, inlet mean fluid temperature of 277C, outlet mean fluid temperature of 285 C, and a linear heat rate of 6.04 kW/ft for the heating element.
Material Properties

The CFD simulation was based on default material properties of liquid water at atmospheric conditions (pressure of 0.1 MPa and temperature of 300 K). The vapor material properties were used for default atmospheric conditions except that the temperature was that for vapor (pressure of 0.1 MPa and temperature of 373K). Additionally, constant material properties were adopted for all temperature ranges. This assumption is quite reasonable for low operating pressures. The effects of low pressure on the specific heat of water is shown in Figure 12.

![Figure 12. Specific Heat for Liquid and Vapor Water at P = 0.1 MPa.](source: http://webbook.nist.gov/chemistry/fluid/)

The assumption of constant material properties will not work for higher operating pressures especially for those of BWTL. The effects of high pressures on the specific heat of water is shown in Figure 13.
Figure 13. Specific Heat for Liquid and Vapor Water at P = 9, 15, 27 MPa.

(source: http://webbook.nist.gov/chemistry/fluid/)

The percent different of the specific heat with the reference temperature for the specific heat being 300 K is shown for the three tentative operating pressure in Figure 14.

Figure 14. Percent Difference for Specific Heat.

Note: For engineering analysis 25% errors can be tolerated, and the analysis may work using mixed mean material properties. The validity of the experiment will depend on the constant material property at a specified reference temperature.
**Volume Fraction and Mass Flow Rate**

The analysis was based on varying volume fraction ratio of the liquid and vapor phase of the water without boiling taking place. By adjusting the liquid/vapor volume fraction at the inlet, a parametric study on the temperature change was performed. Refer to Figure 15.

![Figure 15. Volume Fraction vs. Mass Flow Rate.](image)

As seen, a linear trend line can be observed for the relationship between the mass flow rate and vapor fraction. The simulation is based on a specified constant velocity inlet boundary condition hence from the incompressible continuity equation, this relationship should hold.

**Results**

This section will provide the results obtained from the constant material property analysis with specified volume fraction ratio at the inlet with no flow boiling occurring across the axial extent of the domain as shown in Figure 16.
Figure 16. Average Cross-Sectional Fluid Temperature across Axial Extent.

Figure 17. Temperature Difference vs. Vapor Fraction.
**Conclusion**

As seen from Figure 17, even with an average 50% vapor fraction through the channel (which is unrealistic) the maximum temperature difference achievable was 4.7 K, which is only about 60% of the target. From curve fitting, the target temperature difference of approximately 8 K is achieved at a vapor fraction of 70%. The vapor phase has a significantly lower specific heat as seen from Figure 12. In order to achieve the target temperature difference, several realistic options are available. The mass flow rate may be decreased and/or the linear heat rate may be increased.

**Future Goals**

Future goals include the implementation of flow boiling. A user-defined-function for flow boiling was included in Reference 1. A great amount of time went into fixing the bugs included throughout the code, but with no success. To perform a realistic analysis of the BWTL, flow boiling, in addition with coupled thermal-hydraulic, neutronics, and thermal-mechanical analysis must be performed. To-date, no such code exists. The INL multi-physics-methods-group is currently pursuing the development of a code environment that allows the entire coupling, but is still at the least, few years down the road. The immediate near term goals for the FLUENT simulation will be in successfully implementing the flow boiling UDF and performing parametric studies in varying mass flow rate and operating pressure.

3.3.3. Neutronics Design and Analysis

The primary concern with respect to the neutronics is a change in reactivity due to void production in the test loop. By assuming the BWTL will produce roughly 5-10% void by volume, a model of the BWTL within an MCNP reference model of the ATR was generated. The B-12 position was chosen specifically and is shown in Figure 18 with the addition of a heating element, composed of zircalloy, in the center and two SS 348 tubes separated by a gap filled with helium surrounding the heating element and the main flow of water. The gap between the outermost tube and the beryllium shield was filled with water. This served as the base model for the BWTL without the presence of voids.

![Figure 18. BWTL in B-12 position.](image)
With the BWTL mockup embedded within the ATR model, several Monte Carlo calculations for criticality were performed using MCNP5 ver. 2.5. The reference model was modified with the addition of ~7% of the main flow water volume being spherical steam bubbles of three different diameters ranging from 0.0625 cm to 0.18 cm. Assuming the BWTL would be operating at the BWR typical pressure of 1040 psia and temperature of 538°F, the density of the bubbles was assigned 0.037 g/cm³. These bubbles were arranged in planes of four surrounding the heating element and increased in size towards the outlet. This is shown in Figure 19.

![Figure 19. BWTL with bubbles added; looking from the side on the left and from the top down on the right.](image)

With all the OSCC’s left in the original position, 51.8 degrees, the west OSCC’s 1-4 were rotated every 30 degrees in the fashion shown in Figure 20. With each rotation, the criticality of the ATR was calculated with 95% confidence with and without the bubbles present in the BWTL.

![Figure 20. West OSCC 1-4 rotation direction.](image)

By assuming the delayed neutron fraction for the ATR to be 0.0075, the amount of reactivity in *dollars* could be calculated and is shown in Figure 21.
Figure 21. Reactivity change due to void presence in BWTL.

Figure 21 shows reactivity to be at a positive maximum of 8.7 cents at 30 degrees and a negative maximum of -7.4 cents at 210 degrees, with an overall average of 2 cents.

4. PRELIMINARY HAZARD IDENTIFICATION AND ANALYSIS

Identification of hazards and preliminary evaluations of these hazards were performed and are summarized in the following sections. Further hazard analysis and evaluation of the impact of the BWTL on the existing postulated accidents and analyses presented in the ATR SAR (Reference 2) will be completed at a later date as part of the final design process. The goal of the preliminary hazard analysis is to identify potential accident conditions and recommendations regarding the preliminary design and operation of the BWTL.

4.1. Methodology

A preliminary qualitative hazard evaluation was performed to identify the potential hazards associated with operation of the BWTL in the ATR. Based on the complexity of design and level of associated hazards, the What-If hazard evaluation methodology was used. The What-If was broken into the various sections of the BWTL: 1) In-tank Section, 2) Out-of-Tank Section, 3) the BWTL itself. Table 2 provides the results of the What-If analysis.

4.2. Hazard Analysis Summary

4.2.1. Hazard Identification Summary

Hazards evaluated in the What-If analysis include 1) the radioactive, fissile, and hazardous material in the BWTL experiment assembly, and 2) kinetic energy, potential energy, and pressure hazards associated with BWTL equipment that could lead to release of radioactive material from the experiments or release of PCS water to occupied areas of the ATR.
4.2.2. Preliminary Hazard Categorization

The ATR is classified as a Hazard Category 1 facility and is documented in Chapter 20 of the ATR SAR (Reference 2). The BWTL will be part of the ATR Reactor and, therefore, carries the same hazard category (i.e. Hazard Category 1). Future fueled experiments loaded into the BWTL will require that the hazard categorization of the individual experiments be analyzed in the associated Experiment Safety Analysis (ESA) for determining additional safety analysis requirements. However, the individual experiment hazard categorization would not result in a change to the hazard categorization of the ATR or the BWTL.

4.2.3. Hazard Evaluation Summary

Table 2 summarizes the preliminary hazard events associated with the BWTL. The hazard events are broken in the various sections of the BWTL: 1) In-tank Section, 2) Out-of-Tank Section, and 3) the BWTL itself. The hazard events in each of the sections generally involve:

- Reduced, increased, or no coolant flow in the BWTL,
- Rupture/leakage of BWTL piping/tubing in-tank and out-of-tank,
- Contamination to the BWTL or to ATR primary coolant system,
- Experiment reactivity outside of ATR analyzed envelope, and
- BWTL component failure (other than piping).
## Table 2. Preliminary What-If Analysis for the Advanced Test Reactor (ATR) Boiling Water Test Loop (BWTL).

<table>
<thead>
<tr>
<th>Event No.</th>
<th>Hazard/ Energy Source</th>
<th>What-If…</th>
<th>Consequence</th>
<th>Safeguards</th>
<th>Notes, Actions, or Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>In Tank Section</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-1</td>
<td>Radioactive/ Hazardous Material</td>
<td>human error or equipment failure results in failure of BWTL piping/tubing above core?</td>
<td>BWTL steam is released into PCS before coolant enters core from above.</td>
<td>System design to ASME requirements.</td>
<td>This may be a new Condition 3 accident requiring analysis in the SAR addendum.</td>
</tr>
<tr>
<td>A-2</td>
<td>Radioactive/ Hazardous Material</td>
<td>human error or equipment failure results in reduced, or no coolant flow through loop?</td>
<td>Insufficient cooling of BWTL experiment region.</td>
<td>Measure flow in containment system. Control system design to monitor and shutdown test loop on low or no flow.</td>
<td></td>
</tr>
<tr>
<td>A-3</td>
<td>Radioactive/ Hazardous Material</td>
<td>human error or equipment failure results in increased coolant flow through loop?</td>
<td>Insufficient BWR conditions in experiment region.</td>
<td>Measure flow in containment system. Control system design to monitor and shutdown test loop on low or no flow.</td>
<td></td>
</tr>
<tr>
<td>A-4</td>
<td>Radioactive/ Hazardous Material</td>
<td>human error or equipment failure results in failure in experiment fuel?</td>
<td>Contamination to the loop coolant.</td>
<td>System design to ASME requirements. Control system design to monitor and shutdown test loop on high activity levels.</td>
<td></td>
</tr>
<tr>
<td>A-5</td>
<td>Radioactive/ Hazardous Material</td>
<td>human error or equipment failure results in piping/tube vibrating and breaks off in-tank?</td>
<td>Possible blockage of an ATR fuel channel, and ATR fuel damage.</td>
<td>System design to ASME requirements.</td>
<td>This event is analyzed in the ATR SAR and should be bounded.</td>
</tr>
<tr>
<td>A-6</td>
<td>Radioactive/ Hazardous Material</td>
<td>system exceeds design exposure and breaks due to possible radiation embrittlement?</td>
<td>Possible blockage of an ATR fuel channel, and ATR fuel damage.</td>
<td>System design to ASME requirements.</td>
<td>This event is analyzed in the ATR SAR and should be bounded.</td>
</tr>
<tr>
<td>Event No.</td>
<td>Hazard/ Energy Source</td>
<td>What-If…</td>
<td>Consequence</td>
<td>Safeguards</td>
<td>Notes, Actions, or Recommendations</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------</td>
<td>----------</td>
<td>-------------</td>
<td>------------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>A-7</td>
<td>Radioactive/ Hazardous Material</td>
<td>human error or equipment failure results in totally voiding IPT/piping?</td>
<td>Reactivity change.</td>
<td>System design to ASME requirements.</td>
<td>This event is mentioned but not analyzed in the ATR SAR. This may be a new Condition 3 accident requiring analysis in the SAR addendum.</td>
</tr>
<tr>
<td>A-8</td>
<td>Radioactive/ Hazardous Material</td>
<td>human error or equipment failure results in failure of BWTL pressure tube?</td>
<td>Contamination or steam release to the PCS coolant.</td>
<td>System design to ASME requirements.</td>
<td>Low activity levels should be handled by PCS cleanup systems.</td>
</tr>
<tr>
<td>A-9</td>
<td>Radioactive/ Hazardous Material</td>
<td>human error or equipment failure results in overpressurization and failure of BWTL piping/tubing?</td>
<td>Contamination or steam release to the PCS coolant.</td>
<td>System design to ASME requirements.</td>
<td>Low activity levels should be handled by PCS cleanup systems.</td>
</tr>
<tr>
<td>A-10</td>
<td>Radioactive/ Hazardous Material</td>
<td>the reactor vessel flange fails?</td>
<td>Contamination or steam release to the occupied areas or to vessel.</td>
<td>System design to ASME requirements.</td>
<td>Should be bounded by LOCA analysis currently in SAR.</td>
</tr>
<tr>
<td>A-11</td>
<td>Radioactive/ Hazardous Material</td>
<td>human error or equipment failure results in heating element shutdown; malfunction?</td>
<td>Insufficient BWR conditions in experiment region.</td>
<td>System design to ASME requirements. Control system design to monitor and shutdown test loop on loss of heating.</td>
<td></td>
</tr>
<tr>
<td>A-12</td>
<td>Radioactive/ Hazardous Material</td>
<td>human error or equipment failure results in heating element overpower?</td>
<td>Insufficient BWR conditions in experiment region.</td>
<td>System design to ASME requirements. Control system design to monitor and shutdown test loop on loss of heating.</td>
<td></td>
</tr>
<tr>
<td>Event No.</td>
<td>Hazard/Energy Source</td>
<td>What-If...</td>
<td>Consequence</td>
<td>Safeguards</td>
<td>Notes, Actions, or Recommendations</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------------</td>
<td>------------</td>
<td>-------------</td>
<td>------------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td>A-13</td>
<td>Radioactive/Hazardous Material</td>
<td>human error or equipment failure results in heating element underpower?</td>
<td>Insufficient BWR conditions in experiment region.</td>
<td>System design to ASME requirements. Control system design to monitor and shutdown test loop on loss of heating.</td>
<td></td>
</tr>
<tr>
<td>A-14</td>
<td>Radioactive/Hazardous Material</td>
<td>gas leakage into loop occurs due to an insulating jacket failure during normal pressurized operation?</td>
<td>Insufficient BWR conditions in experiment region.</td>
<td>System design to ASME requirements Control system design to monitor and shutdown test loop on loss of heating.</td>
<td></td>
</tr>
<tr>
<td>A-15</td>
<td>Natural Phenomena</td>
<td>an seismic event occurs resulting in failure of BWTL piping/tubing above core?</td>
<td>Possible blockage of an ATR fuel channel, and ATR fuel damage.</td>
<td>System design to PC-2 requirements. Should be bounded by seismic analysis currently in SAR.</td>
<td></td>
</tr>
<tr>
<td>A-16</td>
<td>Flammable/Combustible Materials</td>
<td>a short occurs in loop heater?</td>
<td>Insufficient BWR conditions in experiment region.</td>
<td>System design to ASME requirements. Control system design to monitor and shutdown test loop on loss of heating.</td>
<td></td>
</tr>
</tbody>
</table>

Out-of-Tank Section

<table>
<thead>
<tr>
<th>Event No.</th>
<th>Hazard/Energy Source</th>
<th>What-If...</th>
<th>Consequence</th>
<th>Safeguards</th>
<th>Notes, Actions, or Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-1</td>
<td>Radioactive/Hazardous Material</td>
<td>human error or equipment failure results in FE#3 high/low malfunction?</td>
<td>Insufficient BWR conditions in experiment region.</td>
<td>Equipment design to vent to condenser Control system design to monitor and shutdown test loop</td>
<td></td>
</tr>
<tr>
<td>B-2</td>
<td>Radioactive/Hazardous Material</td>
<td>human error or equipment failure results in FE#4 high/low malfunction?</td>
<td>Insufficient BWR conditions in experiment region.</td>
<td>Equipment design to vent to condenser Control system design to monitor and shutdown test loop</td>
<td></td>
</tr>
<tr>
<td>B-3</td>
<td>Radioactive/Hazardous Material</td>
<td>human error or equipment failure results in Pressure Control Valve malfunction?</td>
<td>Insufficient BWR conditions in experiment region.</td>
<td>System design to ASME requirements. Control system design to monitor and shutdown test loop.</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Preliminary What-If Analysis for the Advanced Test Reactor (ATR) Boiling Water Test Loop (BWTL).

<table>
<thead>
<tr>
<th>Event No.</th>
<th>Hazard/ Energy Source</th>
<th>What-If…</th>
<th>Consequence</th>
<th>Safeguards</th>
<th>Notes, Actions, or Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-4</td>
<td>Radioactive/ Hazardous</td>
<td>human error or equipment failure results in</td>
<td>Insufficient BWR conditions in</td>
<td>System design to ASME requirements.</td>
<td>Control system design to monitor and shutdown test loop if required.</td>
</tr>
<tr>
<td></td>
<td>Material</td>
<td>condenser malfunction?</td>
<td>experiment region.</td>
<td>Control system design to monitor and shutdown test loop if required.</td>
<td></td>
</tr>
<tr>
<td>B-5</td>
<td>Radioactive/ Hazardous</td>
<td>human error or equipment failure results in</td>
<td>Insufficient BWR conditions in</td>
<td>System design to ASME requirements.</td>
<td>Control system design to monitor and shutdown test loop if required.</td>
</tr>
<tr>
<td></td>
<td>Material</td>
<td>Condensate Pump malfunction?</td>
<td>experiment region.</td>
<td>Control system design to monitor and shutdown test loop if required.</td>
<td></td>
</tr>
<tr>
<td>B-6</td>
<td>Radioactive/ Hazardous</td>
<td>human error or equipment failure results in</td>
<td>Insufficient BWR conditions in</td>
<td>System design to ASME requirements.</td>
<td>Control system design to monitor and shutdown test loop if required.</td>
</tr>
<tr>
<td></td>
<td>Material</td>
<td>demineralizer malfunction?</td>
<td>experiment region.</td>
<td>Control system design to monitor and shutdown test loop if required.</td>
<td></td>
</tr>
<tr>
<td>B-7</td>
<td>Radioactive/ Hazardous</td>
<td>human error or equipment failure results in</td>
<td>Insufficient BWR conditions in</td>
<td>System design to ASME requirements.</td>
<td>Control system design to monitor and shutdown test loop if required.</td>
</tr>
<tr>
<td></td>
<td>Material</td>
<td>booster pump malfunction?</td>
<td>experiment region.</td>
<td>Control system design to monitor and shutdown test loop if required.</td>
<td></td>
</tr>
<tr>
<td>B-8</td>
<td>Radioactive/ Hazardous</td>
<td>human error or equipment failure results in</td>
<td>Insufficient BWR conditions in</td>
<td>System design to ASME requirements.</td>
<td>Control system design to monitor and shutdown test loop if required.</td>
</tr>
<tr>
<td></td>
<td>Material</td>
<td>line heater malfunction?</td>
<td>experiment region.</td>
<td>Control system design to monitor and shutdown test loop if required.</td>
<td></td>
</tr>
<tr>
<td>B-9</td>
<td>Radioactive/ Hazardous</td>
<td>human error or equipment failure results in</td>
<td>Insufficient BWR conditions in</td>
<td>System design to ASME requirements.</td>
<td>Control system design to monitor and shutdown test loop if required.</td>
</tr>
<tr>
<td></td>
<td>Material</td>
<td>feedwater pump malfunction?</td>
<td>experiment region.</td>
<td>Control system design to monitor and shutdown test loop if required.</td>
<td></td>
</tr>
<tr>
<td>B-10</td>
<td>Radioactive/ Hazardous</td>
<td>human error or equipment failure results in</td>
<td>Insufficient BWR conditions in</td>
<td>System design to ASME requirements.</td>
<td>Control system design to monitor and shutdown test loop if required.</td>
</tr>
<tr>
<td></td>
<td>Material</td>
<td>isolation valve malfunction?</td>
<td>experiment region.</td>
<td>Control system design to monitor and shutdown test loop if required.</td>
<td></td>
</tr>
<tr>
<td>Event No.</td>
<td>Hazard/ Energy Source</td>
<td>What-If…</td>
<td>Consequence</td>
<td>Safeguards</td>
<td>Notes, Actions, or Recommendations</td>
</tr>
<tr>
<td>----------</td>
<td>---------------------------------------</td>
<td>--------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td>B-11</td>
<td>Radioactive/ Hazardous Material</td>
<td>human error or equipment failure results in piping failure and small loop LOCA outside of reactor confinement?</td>
<td>Contamination or steam release to the occupied areas.</td>
<td>System design to ASME requirements.</td>
<td>Should be bounded by LOCA analysis currently in SAR.</td>
</tr>
<tr>
<td>B-12</td>
<td>Radioactive/ Hazardous Material</td>
<td>loss of power occurs?</td>
<td>Insufficient BWR conditions in experiment region.</td>
<td>Control system design to monitor and shutdown test loop if required.</td>
<td></td>
</tr>
<tr>
<td>B-13</td>
<td>Radioactive/ Hazardous Material</td>
<td>loss of plant air occurs?</td>
<td>Insufficient BWR conditions in experiment region.</td>
<td>Control system design to monitor and shutdown test loop if required.</td>
<td></td>
</tr>
<tr>
<td>B-14</td>
<td>Radioactive/ Hazardous Material</td>
<td>loss of plant demineralized water occurs?</td>
<td>Insufficient BWR conditions in experiment region.</td>
<td>Control system design to monitor and shutdown test loop if required.</td>
<td></td>
</tr>
<tr>
<td>B-15</td>
<td>Radioactive/ Hazardous Material</td>
<td>failure in the control system occurs?</td>
<td>Insufficient BWR conditions in experiment region.</td>
<td>Control system design to monitor and shutdown test loop if required.</td>
<td></td>
</tr>
<tr>
<td>B-16</td>
<td>Natural Phenomena</td>
<td>an seismic event occurs resulting in failure of BWTL piping/tubing resulting in small loop LOCA?</td>
<td>Contamination or steam release to the occupied areas.</td>
<td>System design to PC-4 requirements.</td>
<td></td>
</tr>
<tr>
<td>B-17</td>
<td>Natural Phenomena</td>
<td>seismic event occurs resulting dislodging and damage of lead shielding?</td>
<td>Exposed unshielded areas.</td>
<td>System design to PC-4 requirements.</td>
<td></td>
</tr>
</tbody>
</table>

**BWTL Experiment Section**

<table>
<thead>
<tr>
<th>Event No.</th>
<th>Hazard/ Energy Source</th>
<th>What-If…</th>
<th>Consequence</th>
<th>Safeguards</th>
<th>Notes, Actions, or Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-1</td>
<td>Radioactive/ Hazardous Material</td>
<td>human error or equipment failure results in wrong or excess experiment material?</td>
<td>Reactivity change.</td>
<td>Current ATR programs. Control system design to monitor and shutdown test loop if required.</td>
<td>Rad. monitors at 4 &amp; 5 will detect activity</td>
</tr>
<tr>
<td>Event No.</td>
<td>Hazard/ Energy Source</td>
<td>What-If…</td>
<td>Consequence</td>
<td>Safeguards</td>
<td>Notes, Actions, or Recommendations</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------</td>
<td>----------</td>
<td>-------------</td>
<td>------------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>C-2</td>
<td>Radioactive/ Hazardous Material</td>
<td>human error or equipment failure results in wrong or excess experiment material?</td>
<td>Fuel pin swelling resulting in reduced loop coolant flow.</td>
<td>Current ATR programs. Control system design to monitor and shutdown test loop if required.</td>
<td></td>
</tr>
<tr>
<td>C-3</td>
<td>Radioactive/ Hazardous Material</td>
<td>human error or equipment failure results in wrong or excess experiment material?</td>
<td>Fuel pin overpressurization and release to loop coolant system.</td>
<td>Current ATR programs. Control system design to monitor and shutdown test loop if required.</td>
<td></td>
</tr>
</tbody>
</table>
The unique hazard events identified in Table 2 that may challenge the ATR Plant Protection Criteria (PPC) are the following:

**Experiment reactivity outside of ATR analyzed envelope**

Event A-1 postulates that human error or equipment failure results in failure of BWTL piping/tubing above core. BWTL steam is released into PCS before coolant enters core from above. Events A-5 and A-6 postulate that human error or equipment failure results in totally voiding IPT/piping. Voiding may result in a change in reactivity. These events require further safety analysis in order to verify compliance with the ATR PPC.

5. **APPLICATION OF EXPERIMENT SAFETY ANALYSIS PROCESS**

Chapter 10 (Experiments and Irradiation Facilities) of the ATR SAR (Reference 2) describes three basic types of irradiation experiments conducted in the reactor vessel. The BWTL will be a separate type of irradiation experiment that utilizes a system of piping and components much like the pressurized water loops already in service in 5 of the 9 ‘flux traps’ (region of enhanced neutron flux) in the ATR. The BWTL coolant will be isolated from the primary coolant system so that the loop’s temperature, pressure, flow rate, and water chemistry can be independently controlled in order to simulate BWR conditions.

The contents of individual experiments for BWTL insertion and irradiation are not known at this time but will vary. Therefore, an ESA is required to address experiment conditions similar to the ESA prepared for other ATR experiments. The ESA must also address experiment handling and the consequences of postulated failures during handling.

6. **PRELIMINARY SAFETY-RELATED SSCS, SAFETY ANALYSIS COMMITMENTS, AND TSR CONTROLS**

6.1. **Safety-Related SSCs**

Due to the use of an ATR B-position, BWTL piping will need to exit the reactor through system piping penetrations through a reactor vessel L-flange. The flange will be required to maintain the ATR PCS boundary during postulated PC-4 seismic events. The preliminary analysis therefore designates the flange as safety-related and Seismic Category 1 since they function as part of the PCS pressure boundary and limit the postulated LOCA break size in response to a seismic event.
7. **CONCLUSION**

The BWTL will provide the ATR with the ability to simulate BWR conditions during reactor operation. The preliminary feasibility and design analysis of the BWTL has been evaluated. The analysis supports the implementation of a BWTL in one of the ATR B-positions. The hazard evaluation in this document indicates that further safety analysis is required to ensure that several postulated hazard events are bounded by the existing safety analysis. A preliminary safety-related SSC has been identified. Further hazard and accident analysis is required to further identify TSR controls. In addition, BWTL operation must be supported by a corresponding ESA as discussed in Section 5.0.

8. **REFERENCES**

6. Star-CCM+ v3.06.006, distributed by CD-adapco Group, Inc., Melville, NY
7. Rhinoceros v4.0, distributed Robert McNeel & Associates, Seattle, WA
APPENDIX A

BWTL COMPONENT DESCRIPTIONS
BWTL COMPONENT DESCRIPTIONS

Condensate Pump-1
  Type – AC motor driven centrifugal pump, self cooled
  Voltage – 120 or 220
  Design Flow Rate – 5 gpm
  Inlet pressure – 2 psig
  Outlet pressure – 160 psig
  Manufacturer – TBD
  Cost – TBD

Booster Pump-1
  Type – AC motor driven centrifugal pump, self cooled
  Voltage – 120 or 220
  Design Flow Rate – 5 gpm
  Inlet pressure – 160 psig
  Outlet pressure – 600 psig
  Manufacturer – TBD
  Cost – TBD

Feedwater Pump-1
  Type – AC motor driven centrifugal pump, self cooled
  Voltage – 220
  Design Flow Rate – 25 gpm
  Inlet pressure – 600 psig
  Outlet pressure – 1100 psig
  Manufacturer – TBD
  Cost – TBD

Isolation Valve-1
  Type – Manually operated globe valve
  Size - TBD
  Manufacturer – TBD
  Cost – TBD

Isolation Valve-2
  Type – Manually operated globe valve
  Size - TBD
  Manufacturer – TBD
  Cost – TBD

Pressure Control Valve-1
  Type – Solenoid operated control valve
  Size - TBD
  Manufacturer – TBD, Target Rock?
  Cost – TBD
Pressure Relief Valve-1
  Type – Spring loaded/self actuated or pilot-actuated relief valve
  Size - TBD
  Manufacturer – TBD, Target Rock?
  Cost – TBD

Radiation Detector
  Type – Ion chamber radiation monitor
  Manufacturer – TBD
  Cost – TBD

Demineralizer
  Type – Cartridge type
  Resin Type – TBD
  Manufacturer – TBD

Quench Tank
  Type – TBD
  Size – TBD
  Material – TBD
  Cooling – TBD

Line heater-1
  Type – Electric inline heating element
  Voltage – TBD
  Power – TBD
  Inlet Temperature – 400F
  Outlet Temperature – 530F
  Manufacturer – TBD

Line heater-2
  Type – Electric inline heating element
  Voltage – TBD
  Power – TBD
  Inlet Temperature – 120F
  Outlet Temperature – 400F
  Manufacturer – TBD

In Tube Heater element
  Type – Electric inline heating element
  Voltage – TBD
  Power – TBD
  Inlet Temperature – 530F
  Outlet Temperature – 545F
  Manufacturer – TBD
Flow Element-1
  Type – Venturi Tube
  Manufacturer – TBD

Flow Element-2
  Type – Venturi Tube or ultrasonic
  Manufacturer – TBD

Pressure Indicator-1
  Type –
  Range – 2-200 psig
  Manufacturer – TBD

Pressure Indicator-2
  Type –
  Range – 100-800 psig
  Manufacturer – TBD

Pressure Indicator-3
  Type –
  Range – 100-1200 psig
  Manufacturer – TBD

Pressure Indicator-4
  Type –
  Range – 100-1200 psig
  Manufacturer – TBD

Temperature Element-1
  Type – RTD
  Range – 80 – 150F
  Manufacturer – TBD

Temperature Element-2
  Type – RTD
  Range – 80 – 600F
  Manufacturer – TBD

Temperature Element-3
  Type – RTD
  Range – 80 – 600F
  Manufacturer – TBD
Temperature Element-4
Type – RTD
Range – 400 – 600F
Manufacturer – TBD

Temperature Element-5
Type – RTD
Range – 400 – 600F
Manufacturer – TBD

Temperature Element-6
Type – RTD
Range – 400 – 600F
Manufacturer – TBD

Temperature Element-7
Type – RTD
Range – 400 – 600F
Manufacturer – TBD

Pipe
Material – Stainless Steel (type?)
Size – Feedwater ¼”, Steam 3” - preliminary
Supplier - TBD