EXPERIMENTAL INVESTIGATION OF THERMAL HYDRAULIC LIMITS OF BWR RCIC SYSTEM OPERATION UNDER LONG-TERM OPERATION

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ABSTRACT

The Reactor Core Isolation Cooling (RCIC) System in Boiling Water Reactors with the Mark I containment uses a turbine-driven pump to provide makeup water to the reactor core in containment isolation events. It requires minimal electrical power in order for the controller to operate the system. As a result, it had previously been expected to fail when the station batteries deplete during Station Blackout scenarios -- nominally by 4-8 hours in current safety analyses. However, the system has been observed to operate beyond battery depletion; in the accidents at Fukushima Daiichi, the RCIC System was able to operate long after the loss of all AC and DC power.

To obtain a better understanding of the RCIC System's operational limits, an experimental facility was constructed and operated at the Laboratory for Nuclear Heat Transfer Systems at Texas A&M University. The capacity for significant, perhaps limiting, thermal stratification to occur in the Suppression Pool as a result of prolonged RCIC System operations was confirmed. Such stratification is highly dependent upon operational conditions and turbine exhaust sparger design. In cases of severe thermal stratification, the apparent thermal capacity of the Suppression Pool can be effectively reduced, and lower regions of the pool would have limited -- if any -- heat absorption. With reduced steam condensation from the RCIC turbine, the containment could pressurize before the bulk of the pool is saturated.

KEYWORDS
Station Blackout (SBO), Boiling Water Reactor (BWR), Reactor Core Isolation Cooling (RCIC) System, thermal stratification, Suppression Pool

1. INTRODUCTION

In nuclear power plant Station Blackout analyses for Generation II Boiling Water Reactors (BWRs), battery failure in 4-8 hours had previously been expected to result in the termination of Reactor Core Isolation Cooling (RCIC) System operation. The RCIC System, which provides cooling water to the reactor via a steam-turbine driven pump, draws steam from the reactor and exhausts into the Suppression Pool. Theoretically, DC (battery) power is required for the turbine controller to operate. However, in the

Fukushima Daiichi accidents in Japan at Units 2 and 3, the RCIC System performed successfully for much longer than expected – 19.5 hours in Unit 3, and nearly 3 days in Unit 2. The RCIC System continued working long after the loss of critical DC power, even though operators were unable to take direct manual control or otherwise intervene in that time due to conditions in the room housing the system.

In order to better understand the RCIC System and its true limits of long-term operation, an experimental model of the system was constructed at the Laboratory for Nuclear Heat Transfer Systems at Texas A&M University. This experimental program will attempt to discern the thermal hydraulic limitations of the RCIC System, focusing on such key parameters as pool temperatures and RCIC pump performance. A facility description and experimental results will be presented in this paper.

This knowledge will be applied in the future to make recommendations to improve overall safety. These may include, but are not limited to, changes in system hardware, altered control system action setpoints and new operational procedures. The US nuclear industry could benefit greatly from the results of this research as it aims to demonstrate the actual capabilities of the RCIC System and further elevate the safety of the 19 BWRs in the US that are equipped with a RCIC System and Mark I Containment.

The potential for thermal stratification to adversely affect system performance is high, and stratification is therefore a major point of interest in this research. When thermal stratification occurs, the hot regions may lead to containment pressurization or cause local equipment to reach operational limitations before they would in a uniformly mixed pool. For example, when a pump draws suction from a sufficiently hot region, it may cavitate or lose its seal. The result could be a reduction of the effective heat capacity of the Suppression Pool or otherwise limited its ability to condense steam.

Such concerns regarding the thermal distribution in the Suppression Pool have not been ignored in the past. Testing ca. 1978 at the Monticello Nuclear Generating Station examined pool mixing with regard to T-quencher designs. With a traditional design and no forced pool circulation, steam injection tests revealed a temperature difference from the Suppression Pool's top to bottom of 52 °F. The stratification vanished when forced mixing was introduced as well as with special modifications to the T-quenchers [1, 2].

More recently, testing in Japan has shown potential for pool stratification resulting from RCIC System operation. In scaled tests at the University of Tokyo, researchers found significant time-dependent thermal stratification present in their system [3-4].

Observations of the temperature distributions during RCIC turbine discharge are shown in this paper. The detailed mechanics of the thermal stratification in the Suppression Pool will be explored in future experiments at this facility.

2. RCIC SYSTEM EXPERIMENT

The experiments presented herein were conducted at the Laboratory for Nuclear Heat Transfer Systems at Texas A&M University. A facility was designed to model a simplified RCIC System, and includes analogs to the reactor, RCIC turbine, RCIC pump, turbine exhaust spargers, and the Suppression Chamber which contains the Suppression Pool. The facility can be operated under a variety of conditions, including atmospheric venting and pre-pressurization, varied power levels, and water injection into the steam line.

2.1. Facility Description

The experimental system is applicable to RCIC Systems in use in BWR plants with a Mark I containment. Steam is supplied by the steam generator and directed to the Suppression Pool through one of two sparger systems. Water can be injected into the steam line upstream of the RCIC turbine analog to simulate reactor overfill scenarios. From the Suppression Chamber, typically filled halfway with water, a RCIC pump draws suction from the outlet at the bottom of the vessel. The pump suction is at the opposite end of the Suppression Chamber from the spargers. The water from the pump is directed to the steam generator, closing the loop, and into the steam line upstream of the RCIC turbine analog. The entirety of the system is well-insulated, thermally isolating it from the outside environment. Applicable flows, pressures, and temperatures are all monitored and recorded by the Data Acquisition (DAQ) system. A simplified P&ID is shown in Figure 1.

A semi-H2TS scaling analysis by Vierow [5] gives this facility a volumetric scale of 1:1000, with some distortions. The Suppression Chamber is not toroidal, and may not reveal the full horizontal thermal profile of the Mark I Containment. The Suppression Chamber diameter scale is 1:5.6. For the steam and water flows, the high power limit scales to 1:375 when compared to a 400 GPM RCIC System. The steam flow through the RCIC sparger analog produces a maximum mass flux of 50.1 kg/m^2s; this covers the lower range of mass fluxes in full systems. The Reynolds number, therefore, is not preserved; however the mode of steam condensation in the water pool during extended operation is reproduced.

2.1.1. Steam supply

The steam supply in this facility is an electric steam generator. It is an ASME-rated pressure vessel with electric immersion heaters, and can supply up to 157 kW of heater power in increments as small as 2 kW. The outlet is connected to a moisture separator to dry the steam exiting the pressure vessel.

The steam generator is operated through a control panel that adjusts heater powers directly; they are not operated by a pressure regulator. Control of the heater power ensures better control of the steam flow, which is further regulated by a manually operated globe valve downstream of the separator.

2.1.2. Suppression Chamber and Suppression Pool

The Suppression Chamber is a 5,300 liter (1,400 gallon) horizontal cylindrical, ASME-rated pressure vessel. Its internal diameter is approximately 150 cm (59 in.), and has a peak internal length of nearly 310 cm (122 in.). The Suppression Pool is the pool of water within the Suppression Chamber.

An internal structure has been assembled inside the vessel to support both the spargers and the thermocouples placed throughout. It is intended to be minimally intrusive, but may display localized effects on the water mixing. Both the vessel and the internals are made of 304 stainless steel.

The thermocouples in the pool, shown in Figure 2, have been placed to provide insight into the 3-dimensional temperature profile. Nine thermocouples are located along the centerline of the vessel, 30.5 cm apart and 38 cm above the vessel bottom. At three axial locations, an additional four thermocouples have been added: an upper one (56 cm above vessel bottom, along the centerline, directly above the middle and lower thermocouples), a lower one (20 cm above the vessel bottom, and a left and right thermocouple (even with the middle one at 38 cm, but placed outward toward the side of the vessel by ±30.5 cm from the centerline). In addition, two thermocouples sit in the airspace in the vessel, and another one reads the temperature at the vessel outlet near the front head at the bottom of the vessel. All thermocouples used are Omega Type T thermocouples with Special Limits of Error (±0.5 °C).

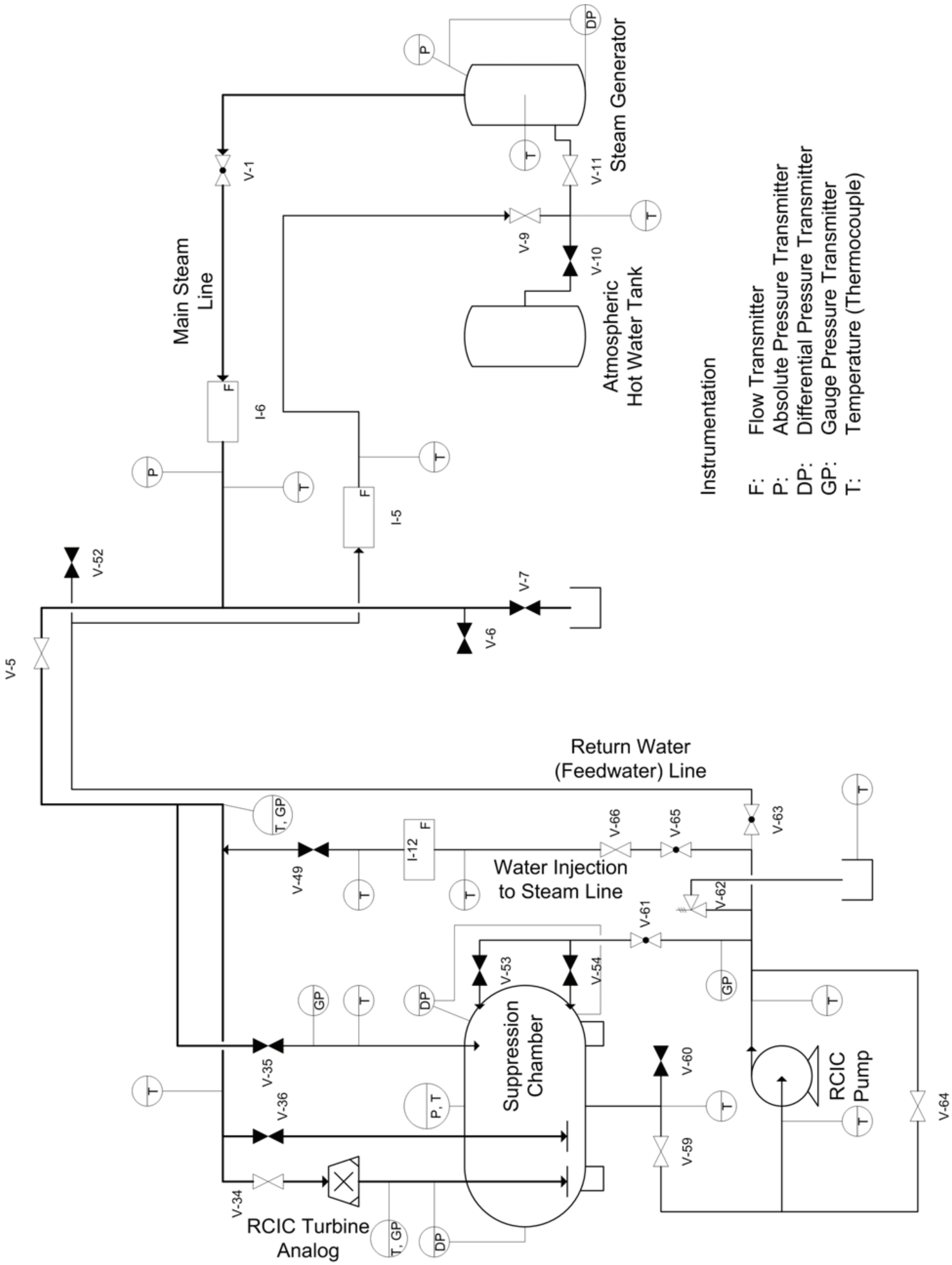

Figure 1. Simplified System P&ID

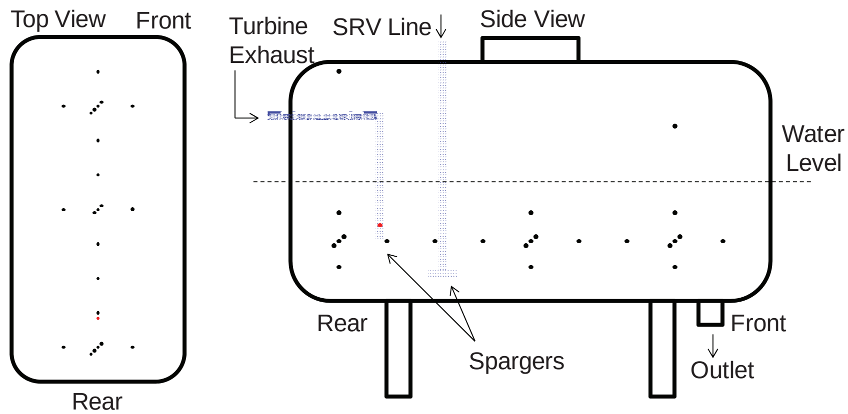

Figure 2. Vessel Internal Thermocouple Layout

2.1.3. Turbine analog

A scaled version of the Terry turbine used in BWR RCIC systems was not available for use in this experiment. The current analog is an orifice plate, meant to provide a measure of similarity to the steam nozzles in the actual turbine. The bore size is 11 mm (7/16 in.), and there is a square loop of pipe immediately following the orifice. Such an assembly was deemed suitable for these tests as the turbine employed in plant systems is of a very low thermodynamic efficiency.

2.1.4. Pump

The RCIC pump in a real system is a multistage centrifugal pump driven directly by the turbine [6]. The analog used in this experiment is a multistage (five stage, closed-impellor) centrifugal pump driven by an electric motor.

2.1.5. Spargers

Two steam spargers are installed in the analog to the Suppression Pool. One sparger, downstream of the RCIC Turbine analog, is a vertical pipe (1.5-inch Schedule 40 NPS) open at the bottom. Its outlet is approximately 39 cm above the very bottom of the vessel, and is centered nearly 61 cm horizontally from the center of rear vessel head. A thermocouple is installed in the flow path shortly upstream (9 cm) of the outlet, and a shield on the bottom of the pressure vessel is installed directly below (38 cm from) the sparger outlet.

The second sparger, representing a Safety/Relief Valve (SRV) discharge line, is placed above the bottom centerline of the vessel approximately 95 cm horizontally from the center of the rear head. It consists of a 1-inch NPS tee with the outlets oriented along the centerline of the vessel toward either head. The outlets are nearly 18 cm apart, with the tee in the middle, and are open-ended 1-inch NPS Schedule 40 pipe. The center is 18 cm above the bottom of the vessel. It connects to the steam line at a branch-off point shortly upstream of the RCIC Turbine analog. This sparger is similar to the old-style ramshead devices used on SRV lines before the advent of the T-quencher.

2.1.6. Instrumentation and data acquisition

All temperatures in the system are measured using Omega Type T thermocouples with Special Limits of Error (±0.5 °C). In addition to the thermocouples in the Suppression Chamber, temperatures are measured in the steam generator, at the flow meters, upstream and downstream of the water injection point in the steam line, between the RCIC Turbine analog and the spargers, on the inlet and outlet of the pump, and at the point where return water is injected into the steam generator.

Flow rates are measured on the steam line, on the water injection line to the steam line, and on the water injection line to the steam generator. Steam flow is measured with a Foxboro model 83 vortex flow meter with full pressure and temperature compensation. Water flows are measured with magnetic flow meters: a Yamatake MagneW 3000 PLUS on the water return line to the steam generator, and a Badger M2000 on the water injection line to the steam line.

Pressures are measured using Honeywell three STA940 absolute pressure transmitters and three Honeywell STD924 differential pressure transmitters. An additional set of Dwyer gauge pressure transmitters are used as monitors for the operator rather than as data instruments. Absolute pressures are measured on the steam generator, Suppression Chamber, and at the vortex flow meter on the steam line. Differential pressures are measured from the top to the bottom of both the steam generator and Suppression Chamber to estimate their water levels, and from the outlet of the RCIC turbine analog (upstream of the sparger) to the bulk Suppression Chamber vapor space to monitor the flow behavior through the sparger in conjunction with the line's thermocouples.

Signals from each thermocouple and 4-20 mA instrument are collected and recorded by the DAQ. DAQ consists of National Instruments (NI) SCXI hardware, including SCXI-1102/b/c modules and an NI data acquisition card in a PC. LabVIEW programs have been developed to collect and record the data gathered by the hardware, and all data are written to text files at 0.1 s intervals.

2.2. Operation and Test Details

The tests conducted and described here were operated at one of three constant heater powers in the steam generator: 57 kW (here, low power), 107 kW (medium power), and 157 kW (high power).

In the standard RCIC System alignment, the Suppression Chamber is filled to approximately half capacity with an initial air volume above the pool at atmospheric pressure. The steam generator produces steam, which is directed through the turbine analog and to the RCIC sparger. Pressure increases in the Suppression Chamber as heat is absorbed by the Suppression Pool. Water is drawn from the Suppression Pool via the RCIC pump and injected into the steam generator at the same mass flow rate as steam is sent to the pool, completing a closed loop. No water is injected into the steam line in the standard alignment. Tests with variations on the standard alignment are planned. It should be noted that, although the initial RCIC System aligns to draw pump suction from the Condensate Storage Tank (CST), no CST alignment is tested here; all tests align to the Suppression Pool.

Testing with the other sparger, akin to SRV operations with a simple ramshead device, has also been conducted. The standard alignment is comparable to the standard alignment of the RCIC turbine-sparger analogs, as are its potential variations.

2.2.1. Key parameters

Data from system operations are gathered at all of the locations described above. However, some data are of particular interest. These are the time-dependent spatial pool temperatures, steam flow rate, and turbine analog characteristics.

The tests are conducted at a constant electric power in the steam generator and a return water injection rate set to maintain a constant steam generator level; the main steam control valve is set to maintain sufficient pressure in the system to provide flow through the vortex flow meter with enough superheat to ensure accurate measurements by the vortex flow meter. As a result, steam flow rates gradually increase as the feedwater (coming from the Suppression Pool) warms up. This flow rate increase is due to less of the steam generator power being needed to bring the return feedwater to saturation temperature. The increase in the steam flow rate is not large, and does not appear to significantly impact the results.

The pretest warmup period of a test is considered to have ended when the middle thermocouple in the middle cluster in the pool first registers 40^{o} C after system alignment and warmup. The test ends after the re-convergence of stratified pool temperatures to a near-uniform value or when the equipment reaches operational limits. In all cases, the bulk pool temperatures rise to a minimum of 90^{o} C.

2.2.2. Tests conducted

Data from the following tests have been gathered and are presented here:

1. RCIC Standard Alignment test at 57 kW
2. RCIC Standard Alignment test at 107 kW
3. RCIC Standard Alignment test at 157 kW
4. SRV Standard Alignment at 157 kW

Additional series of tests shall be conducted in the future to determine the effects of pressure and water injection into the turbine/reactor overfill.

2.3. Results

Most, but not all, of the tests conducted showed non-negligible thermal stratification for a period in the Suppression Pool. The stratification appeared to be influenced by both sparger design and power level. The stratification was almost entirely in the vertical direction.

2.3.1. RCIC standard alignment test at 57 kW

In this low-power standard alignment RCIC System test, steam condensation in the pool was very loud and violent initially. Its intensity tapered off near the end. A semblance of the ferocity of the condensation at the sparger's outlet can be inferred from Figure 3, noting the dramatic changes in differential pressure across the sparger and the fluctuations in the temperature reading near its outlet. As the test progressed, the loud noises of violent steam condensation gradually diminished; this was reflected in the data. The frequent swings in the temperature data at the sparger outlet are believed to be the result of the condensation's vigor; it would appear to be severe enough to draw the surrounding subcooled water backward into the sparger during sudden, frequent, and violent void collapse. This is indicative of chugging oscillations.

Vertical thermal stratification appeared in this test (Figures 4 and 5), in which the average steam flow rate was above 23 g/s. The behaviors of the top and mid levels of the pool were generally consistent, having a maximum temperature difference of 1.4 °C. The mid to low-level temperature differences were larger, reaching 9.3 °C at around 10,000 s, and the outlet was separated from the low levels by a maximum of nearly 23 °C at about 12,000 s.

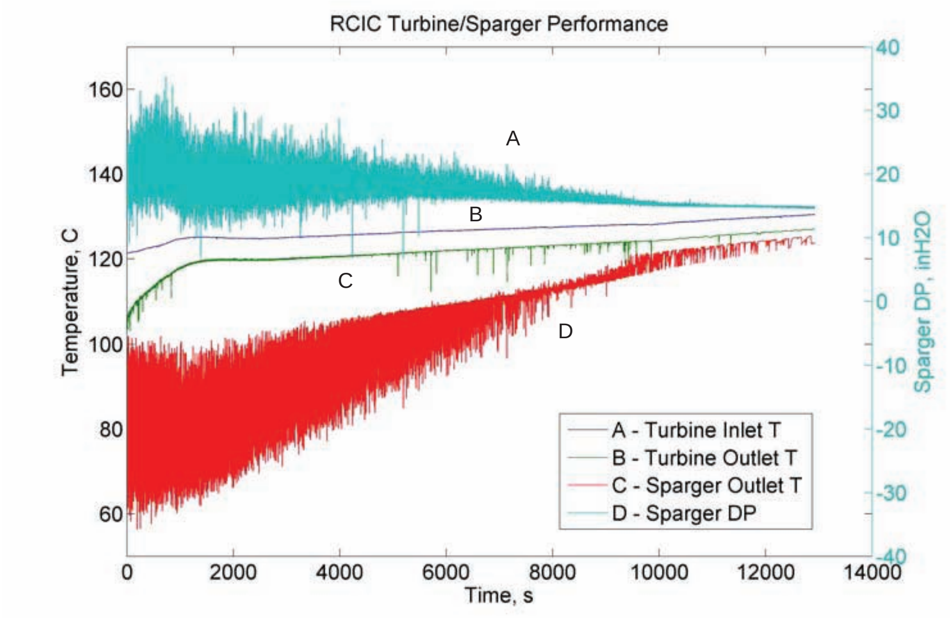

Figure 3. Turbine Analog Performance, 57 kW Test

As seen in Figures 4 and 5, the temperature profiles at the middle and front thermocouple clusters vary only slightly. The same is true of the rear cluster (not shown). This reinforces the notion that there are vertical thermal layers forming along the pool length, not simply hot spots.

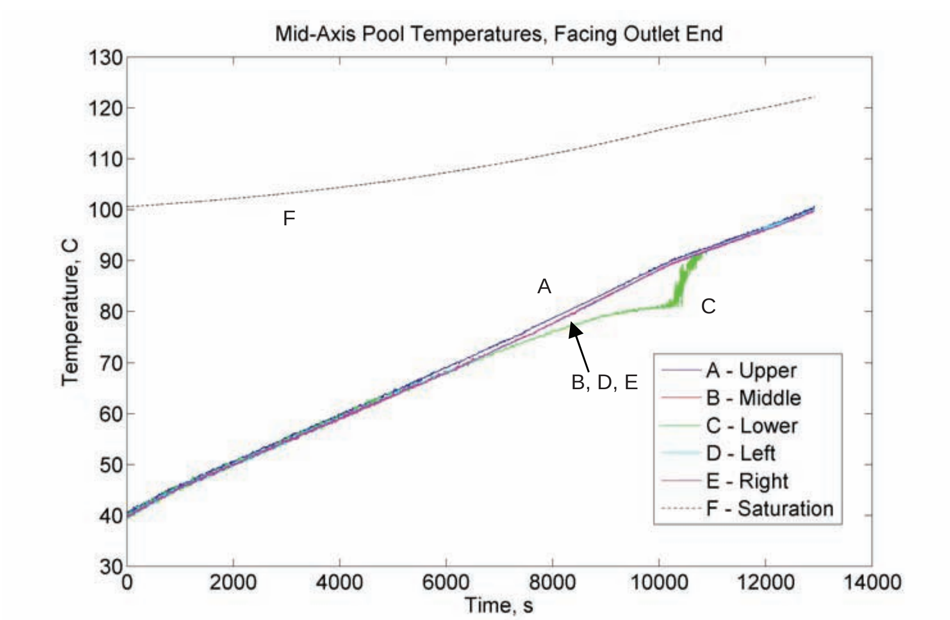

Figure 4. Mid-Pool Thermal Profile (57 kW)

A partial repeatability test was performed. While it did not run to full completion, it did express the same thermal profile behavior. The top and mid-levels were within 2.1 °C, while the mid to lower levels separated by less than 11 °C (compare to 1.4 °C and 9.3 °C).

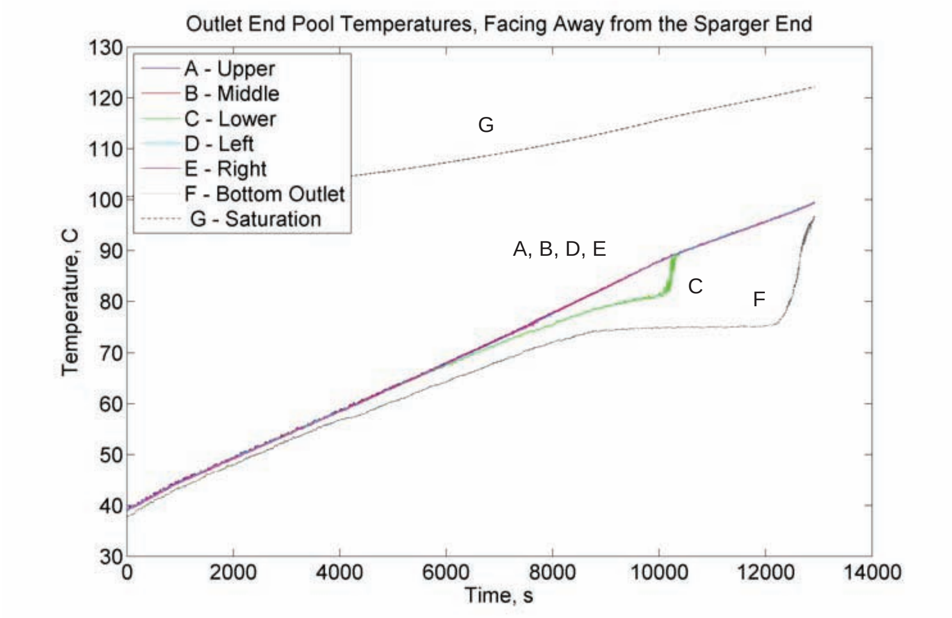

Figure 5. Pool Front End Thermal Profile (57 kW)

2.3.2. RCIC standard alignment test at 107 kW

Of the tests presented here, the 107 kW RCIC alignment is perhaps the most interesting in its features because it showed the clearest mid-level pool thermal stratification. The average steam flow rate was near 45 g/s. The stratification can be seen in Figure 6.

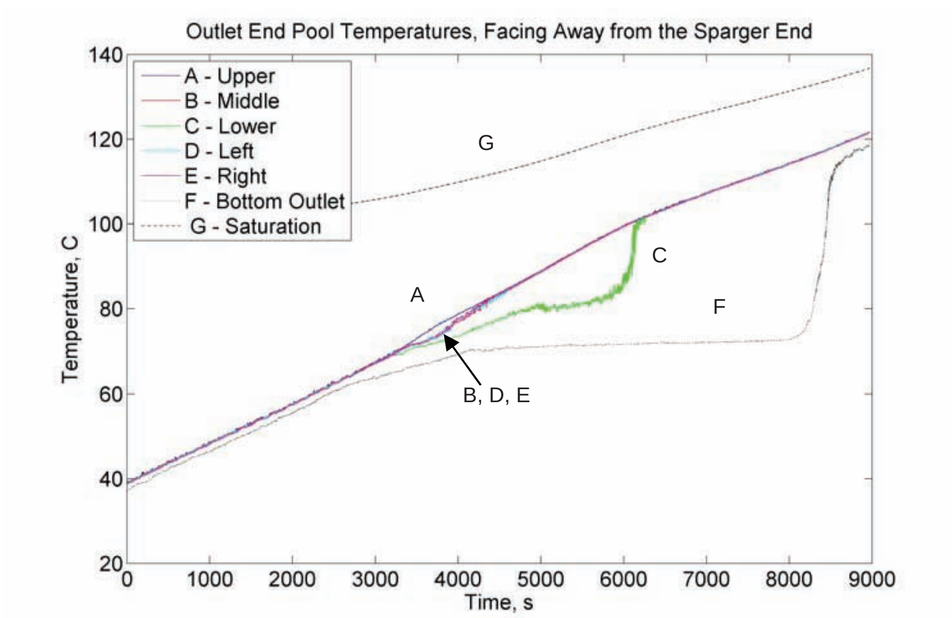

Figure 6. Greatest Stratification Profile (107 kW)

The stratification from the upper to middle regions, though present, was not severe and maximized at 3.1 °C. The greatest difference between the middle and lower regions, however, was much larger: at nearly 21 °C. This, however, was only about half of the difference observed between the lower regions and the outlet, which reached more than 43 °C before suddenly vanishing. In a repeatability test, the top and middle regions remained within 2.8 °C, the middle and lower regions separated by nearly 24 °C, and the lower and outlet regions again saw differences greater than 43 °C.

As the test progressed, the warming of the pool combined with the sealing of the airspace produced a pressurization profile seen repeatedly in these tests. The profile developed in this test, shown in Figure 7, is characteristic of all those presented here with limited variations; the steam line pressure in the SRV test trends much closer to the Suppression Chamber pressure.

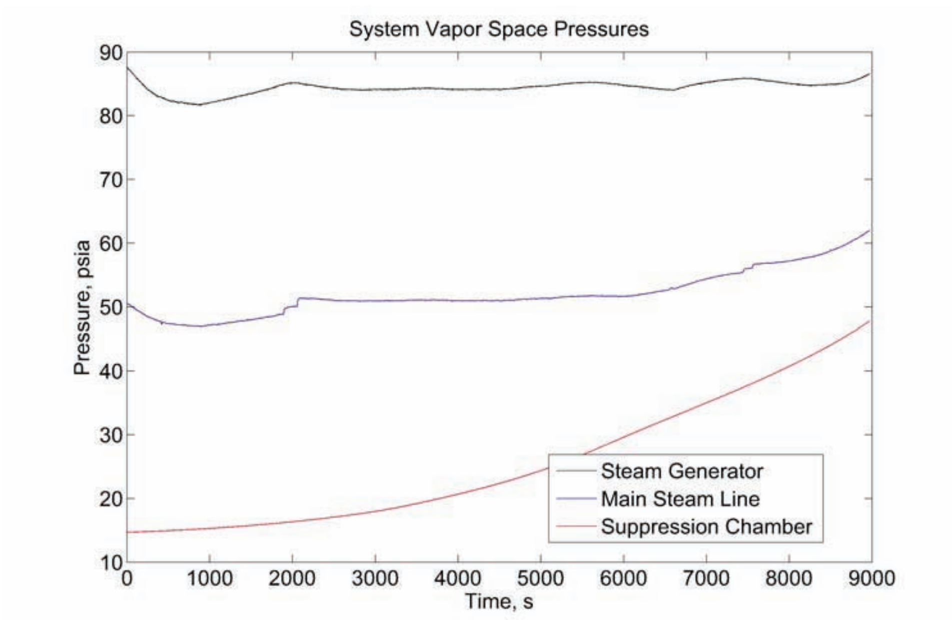

Figure 7. Pressurization Profile (107 kW)

As with the 57 kW test, the initial stages with high pool subcooling produced apparently violent condensation. Once again, the severity decreased as the pool warmed up. However, there was a period where the intense condensation bursts seemed to slow down and transition to a different, milder interaction. The beginning of the transition period appeared to roughly coincide with the shifts seen in sparger outlet temperature and differential curves shown in Figure 8.

2.3.3. RCIC standard alignment test at 157 kW

Running the system at 157 kW produced stratification generally less severe than the 107 kW test but more severe than the 57 kW test. Running this alignment and power is somewhat more challenging than others due to operating near equipment limits, but still achievable. Steam and feedwater flow rates were maintained near 66 g/s.

Thermal stratification from the top to middle region and middle to lower regions was comparable to the stratification developed in the 57 kW test, with peaks of more than 2 °C and 9.5 °C, respectively. The lower to outlet temperature difference, however, rivaled that of the 107 kW test and both tests produced a peak greater than 43 °C. This is illustrated in Figure 9.

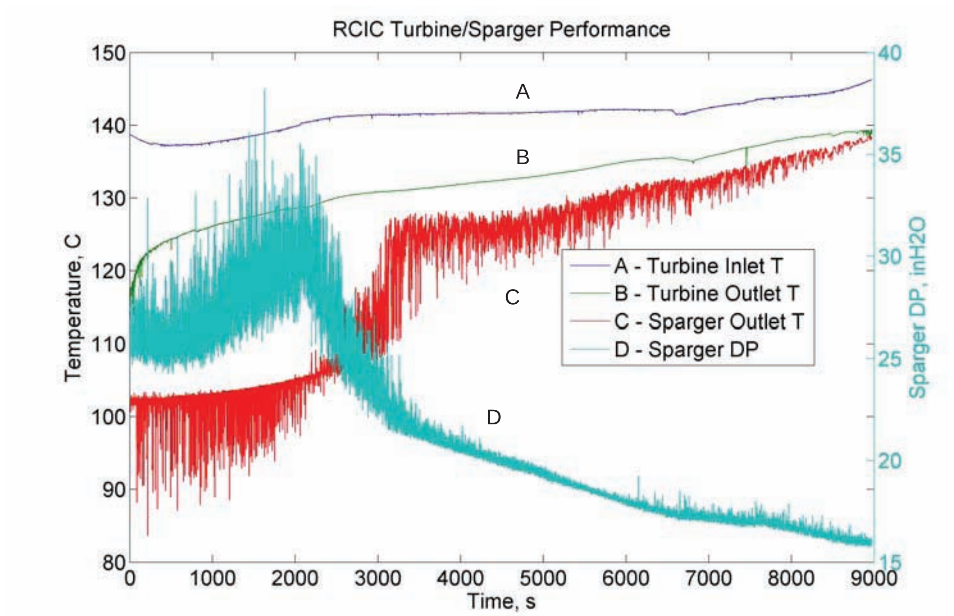

Figure 8. Turbine Analog Performance with Transition Period (107 kW)

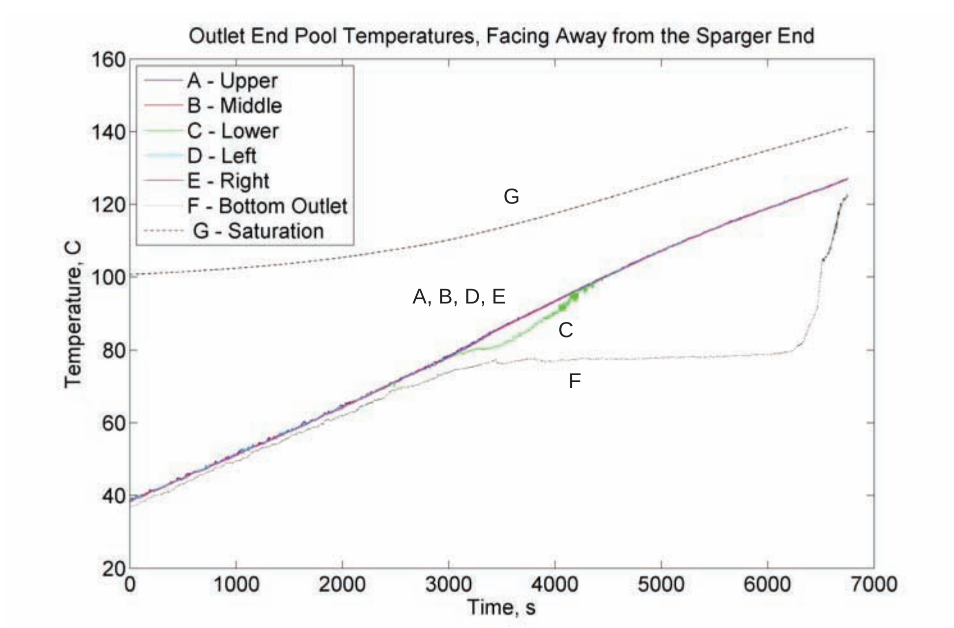

Figure 9. 157 kW Stratification Profile

The acoustic character at the beginning of the test was much the same as the other two RCIC alignment tests initially. And, as in the 107 kW test, there was an audible transition period. However, the transition seemed much quicker and there was less calming of the rapid condensation leading up to it; it seemed to come suddenly. It too seemed to align with the temperature and differential pressure transitions for the sparger, here seen in Figure 10.

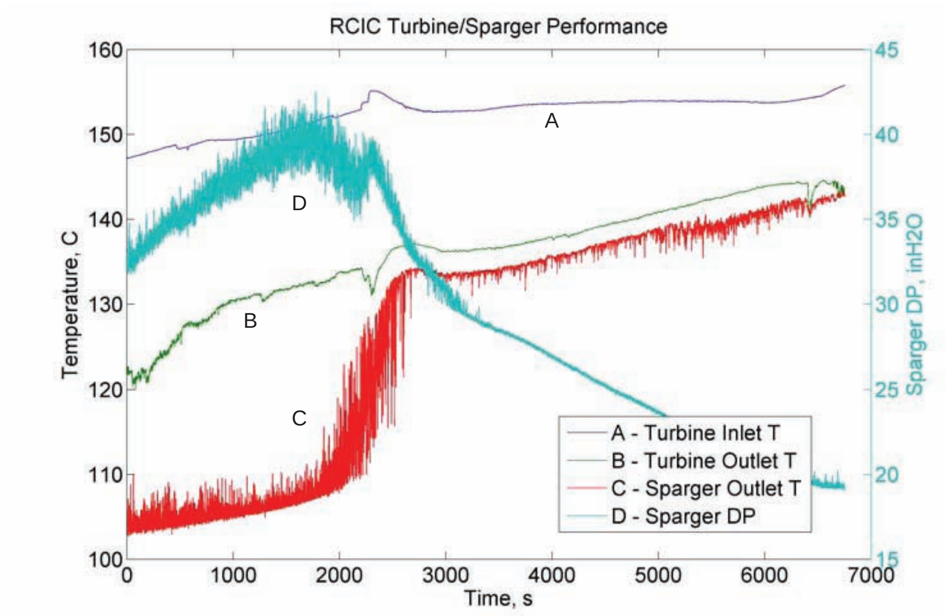

Figure 10. Turbine Analog Performance with Rapid Transition (157 kW)

2.3.4. SRV standard alignment at 157 kW

Instead of injecting steam into the Suppression Pool through the RCIC turbine and sparger analogs, steam was injected through an SRV ramshead analog. In this test, run at 157 kW, the pool maintained very uniform temperatures. Vertical temperature gradients were limited to near 5 °C for the entire test period. As with the other tests, the pool was initially at half the vessel's volume and pressure was allowed to accumulate.

Both steam and feedwater flow rates were maintained near 66 g/s. As shown in Figure 11, the pool appeared to be well mixed for the entire run.

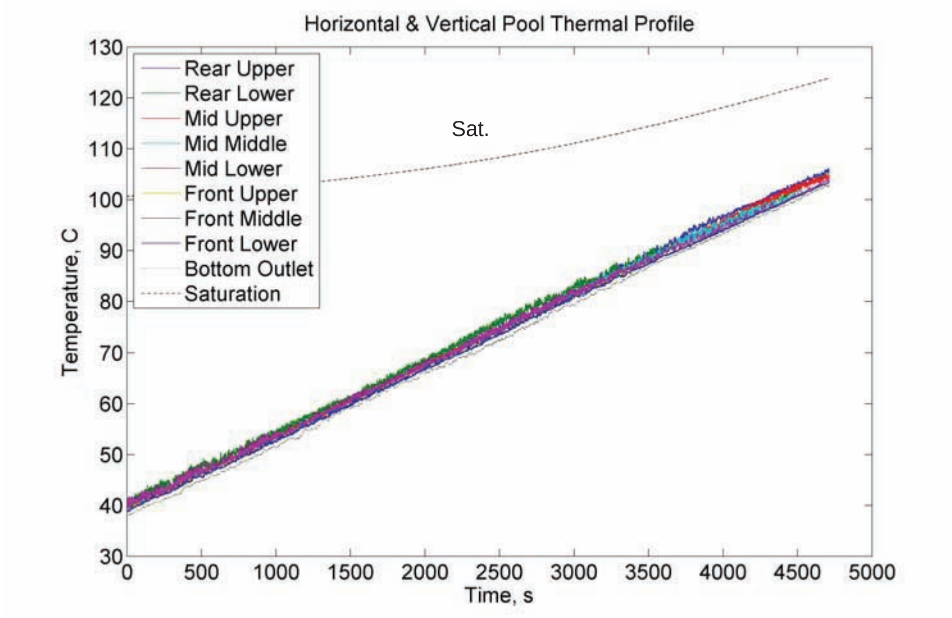

Figure 11. Non-Stratifying Thermal Profile

2.4. Discussion

Each of the RCIC analog tests performed and documented here developed a degree of thermal stratification in the Suppression Pool analog, and did so in a manner similar to [3-4]. No major horizontal distributions were noted, even though the Suppression Chamber in this facility is a straight cylindrical vessel. It is not a torus, but may behave in the manner of a single bay/segment of the full Torus in the BWR Mark I containment. As a result, while not observed here, lateral thermal stratification cannot be completely discounted.

The thermal stratification that appeared in these tests did not isolate the top of the pool from the middle. These regions, in which some limited stratification was observed, did not differ much even when exhibiting their largest temperature differences. Significant stratification did appear between the middle and lower regions, and even more so between the lower regions and the very bottom/outlet. While the most severe case, from the lower region to the bottom, developed a peak difference of 43 °C, the volume of water involved is less than that at higher pool elevations. The 21 °C difference appearing between the pool middle and lower regions may be cause for greater concern, as the volumes of water considered are large fractions of the total volume and represent a larger amount of thermal capacity that was not utilized.

It should be noted that, while stratification did occur, in each case it was limited. As the pool continued to condense steam, the stratification eventually disappeared – often suddenly. In addition, the particular design and position of the sparger clearly plays a role in the development of stratification; the ramshead-style sparger maintained a well-mixed pool.

The development and effects of such stratification as observed herein may be heavily dependent on plant-specific details. It is known that multiple RCIC turbine exhaust sparger designs are in use at different sites, which could lead to a variety of different pool thermal profiles when large fractions of the reactor's steam are deposited in the Suppression Pool through the RCIC sparger. The role that stratification would then play also depends on the elevation and specific location of the RCIC Pump's suction. At sufficient elevations, stratification could limit the long-term operation of the pump. In severe cases, large fractions of the pool could remain relatively cool (for example, 23 °C below the top), leading to premature pressurization of containment as the pool surface approaches saturation.

Complicating this would be the expected operation of not only the RCIC System but the occasional operation of SRV lines as well; the interplay between multiple spargers here has not been explored.

While most of the consequences of thermal stratification are expected to be negative, that may not be universal. In moderate cases, any pump drawing suction from the very bottom of the Suppression Pool will see cooler temperatures than it otherwise would. If pump inlet temperatures are major limiting factors, then such stratification would enhance pump operability.

3. CONCLUSIONS

An experimental facility constructed and operated at Texas A&M University for the investigation of long-term RCIC System operation in BWR plants has yielded its first set of results. It was observed that, in the middle to lower regions of a steam-condensing pool of water, thermal stratification could occur with differences of 21 °C. The very bottom of the pool could be even more separated: differences of more than 43 °C were observed from the lower regions to the bottom. In a BWR Suppression Pool, this can be expected to have implications for the operability of safety systems which make use of the pool. The major conclusions are threefold:

- The potential for significant thermal stratification in a BWR Mark I containment Suppression Pool has been demonstrated
- The design, placement, and operation of sparger systems are important to pool mixing
- The use of different designs may require separate analyses for each plant

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