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Experimental Observations of Natural Circulation Flow in the NSTF at Steady-State Conditions

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Abstract – *A ½ scale test facility has been constructed at Argonne National Laboratory (ANL) to study the heat removal performance and natural circulation flow patterns in a Reactor Cavity Cooling System (RCCS). Our test facility, the Natural convection Shutdown heat removal Test Facility (NSTF), supports the broader goal of developing an inherently safe and fully passive ex-vessel decay heat removal for advanced reactor designs. The project, initiated in 2010 to support the Advanced Reactor Concepts (ARC), Small Modular Reactor (SMR), and Next Generation Nuclear Plant (NGNP) programs, has been conducting experimental operations since early 2014. The following paper provides a summary of some primary design features of the 26-m tall test facility along with a description of the data acquisition suite that guides our experimental practices. Specifics of the distributed fiber optic temperature measurements will be discussed, which introduces an unparalleled level of data density that has never before been implemented in a large scale natural circulation test facility. Results from our first test series will then be presented, which provide insight into the thermal hydraulic behavior at steady-state conditions for varying heat flux levels and exhaust chimney configuration states.*

I. INTRODUCTION

There is a recognized need to address the safety requirements of advanced future nuclear reactors. Recent events have focused part of this effort on developing fully passive and inherently safe decay heat removal systems. One concept under consideration, the Reactor Cavity Cooling System (RCCS), is geared towards the latest generation of high temperature gas cooled reactors and provides an entirely ex-vessel means to reject decay heat to the environment without the need for pumps, diesel generators, or human intervention.

Relying primarily on radiative heat transfer from the walls of the reactor pressure vessel (RPV), the design philosophy for the RCCS is centered on natural circulation driven flow to successfully remove decay heat. The inherently sensitivity of these buoyancy driven systems, augmented by multiple parallel flow paths, introduces certain complexities that are often difficult to predict with computational models alone. The onset of flow instabilities may be triggered by minor perturbations and result in undesirable behavior or reduced performance. Thus, there is value in experimental validation, for which the Natural convection Shutdown heat removal Test Facility (NSTF) at Argonne National Laboratory (ANL) aims to address.

II. FULL SCALE DESIGN CONCEPT

The focus of this paper will be a scaled experimental investigation onto one specific design concept by General Atomics (GA) for their Modular High Temperature Gas cooled Reactor (MHTGR). Developed in the United States, this reactor design uses prismatic fuel elements within a hexagonal core, helium as the primary coolant, and is proposed via four unit plants and two steam turbines for a total power output of approximately 540 MW_e [1].

For each reactor within the four-unit plant, the design by GA proposes separate air-cooled RCCS networks that are integrated into each containment building. Serving as the primary means of decay heat removal, their RCCS comprises a series of ductwork (risers, plenums) and chimneys. The risers line the reactor containment and surround the RPV circumferentially and are joined via plenums to intake and exhaust chimney circuits, Fig. 1. The rectangular riser ducts, 227 in total number and each 5-cm by 25-cm in cross sectional area [2] span the full height of the concrete containment and serve also to protect the delicate concrete from heat induced degradation.

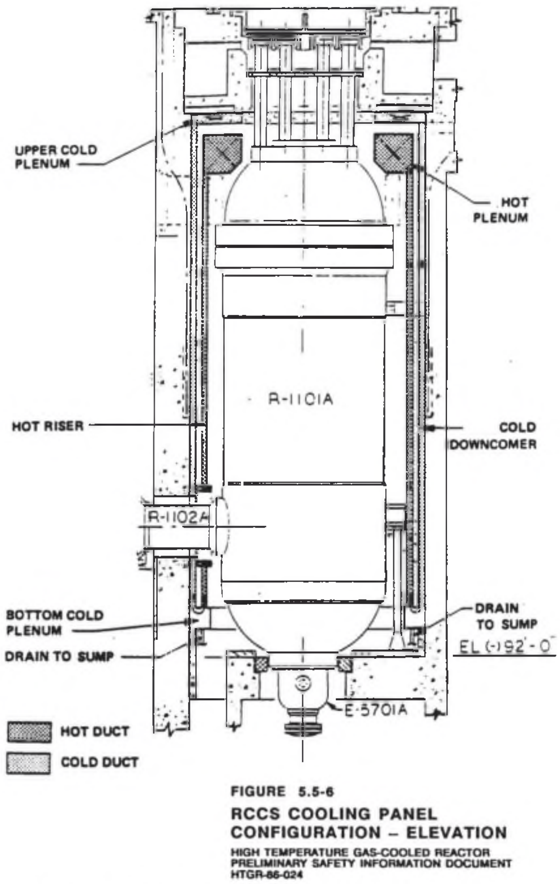

Fig. 1: GA-MHTGR RCCS concept [2]

III. EXPERIMENT DESCRIPTION

An air-based test facility has been constructed at ANL to investigate this design concept for passive decay heat removal. Modeled after the full scale RCCS design by GA described above, the NSTF contains 12 riser ducts (19.03° sector slice) at a reduced ½ scale, however still stands an impressive 26-m in overall height. Previous works by the authors have outlined the scaling studies that were performed to ensure the preservation of key thermal hydraulic phenomena, similarity among scales, and validity among the generated data sets [3].

The test facility features a single inlet downcomer, an inlet plenum, twelve riser ducts within a heated cavity that serve as the test section, an outlet plenum, and dual symmetric exhaust ducts, Fig. 2. Operator driven flexibility has been integrated into the test facility and includes controls for zoning of the heated test section, variations on heated surface – riser duct spacing, inlet and outlet ductwork configurations, and varying chimney roles.

Thus the proposed test series spans an exhaustive parameter set that includes investigations onto these variables; however the focus of our presented results will be on the integral power and resulting behavior with varying chimney roles.

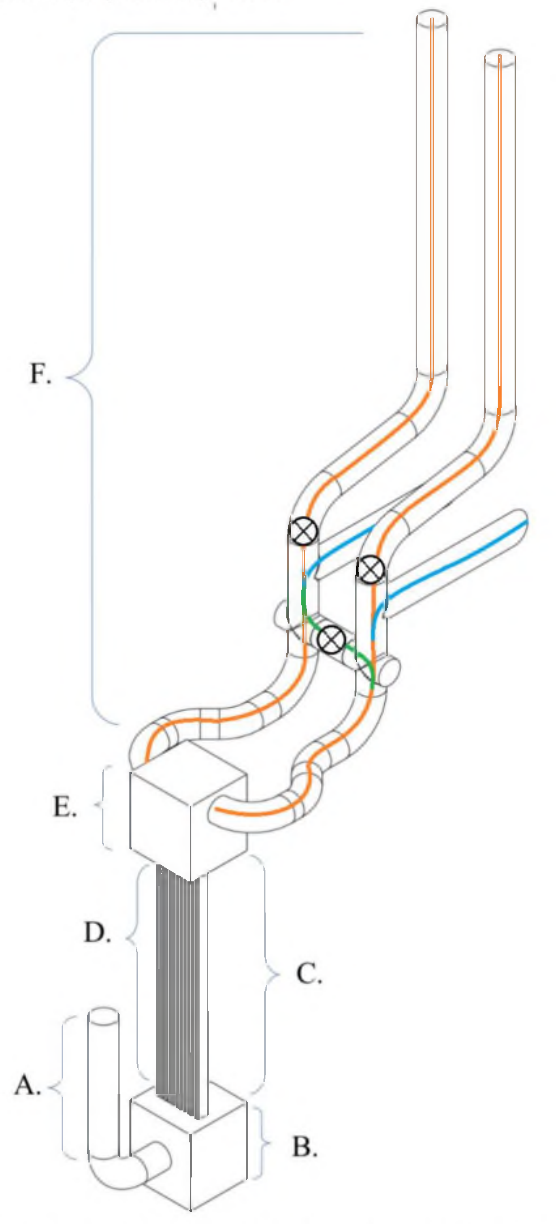

Figure 2: Simplified model of ½ scale NSTF. A. inlet downcomer, B. inlet plenum, C. heated cavity, D. riser tubes, E. outlet plenum, F. chimney. Flow paths for varying chimney roles: Baseline (orange), reduced discharge (blue), single chimney (green). Crossed circles represent manual valves.

A suite of more than 400 data acquisition channels guide test operations and serves to monitor key thermal hydraulic phenomena. Measurements of system mass flow rates, differential pressure drop, surface and gas temperatures, among others, are included in this suite. A summary is provided in Table 1, with additional details such as the heater configuration and insulation properties are provided in earlier works by the authors [4,5]

Table 1: NSTF instrumentation summary

Instrument	**Location**	**#**	**Range**
Flow rate[1]	Inlet	x1	0 – 1 kg/s
ΔP_{heated}[2]	Risers	x8	± 62.2 Pa
$\Delta P_{adiabatic}$[3]	Chimney	x2	± 24.8 Pa
Humidity[4]	Inlet	x1	3-95% RH
Heat flux[5]	Risers	x16	0-300 kW/m^2
Temperature[6]	*various*	x368	Type-K
Wind speed	Roof	x1	1 – 80 m/s
Wind direction	Roof	x1	0 - 360°
Humidity	Roof	x1	1-100% RH
Ambient temp.	Roof	x1	-40-60°C

[1]: ± 1% + 0.3 kg/min, [2] ± 1%, [3] ± 0.5%
[4]: ± 2%, [5]: ± 5%, [6]: ± 2.2 °C or 0.75%

While it is expected that radiation will be the primary mode of heat transfer, the heated cavity (essentially an internal enclosure environment) allows natural circulation cells to develop and grow. Similar to the concrete containment in a full scale design, contributions from convection aid in the overall heat transfer from the RPV to the riser ducts.

To quantify this split in heat transfer modes, specialty heat flux sensors have been installed in pairs along the duct walls in the NSTF. Each pair consists of one sensor that has a black, matte surface ($\varepsilon \approx 1$), while the other sensor has a shiny, reflective surface ($\varepsilon << 1$), Fig. 3. The black surface will absorb both radiation and convection portions of heat transfer, while the shiny will reflect the majority of radiation and instead measure those contributions solely from convection.

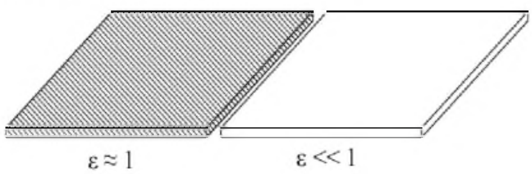

Fig. 3: Heat flux sensor pairs. Black matte (left), shiny reflective (right)

IV. EXPERIMENTAL PROCEDURE

Testing operations began with verifying cold-start, zero-flow conditions. A period of no less than 5 days was allowed to ensure any residual heat was dissipated from the massive steel structures and that the facility was allowed to reach ambient temperatures. Inlet and outlet ductwork were closed and zero-flow values were confirmed for the hydraulic instrumentation, and thermocouples were compared to ensure nominal values (natural gradients existed due to the 26-m height of the facility).

Test operations and active heating began by supplying a 3-hour power ramp to 56 kW_e, allowing the facility to stabilize for 24 hours, and then initiating a 2nd power ramp to 78 kW_e, Fig. 4. The 2nd and final power ramp allowed the test to approach the desired 56 kW_t test section power, and was held for a minimum duration of 12 hours to allowed averaged steady-state values to be measured. The test was concluded by a 4 hour power ramp to 0 kW_e and dampening of the outlet valves to allow for a gradual cool down and ensure no thermal shock was experienced by the ceramic heaters or heated plate.

The power ramps were employed to prevent thermal shock to the steel structure, minimize thermal gradient along the massive 2,000 kg heated steel plate, and ensure that the delicate ceramic heaters were not damaged by a sharp temperature excursion. The two power levels were selected first based on an electric equivalent of the desired thermal power, allowing the operator to determine the nominal heat losses. The second power level was determined by an estimated electric power that would provide the desired thermal power.

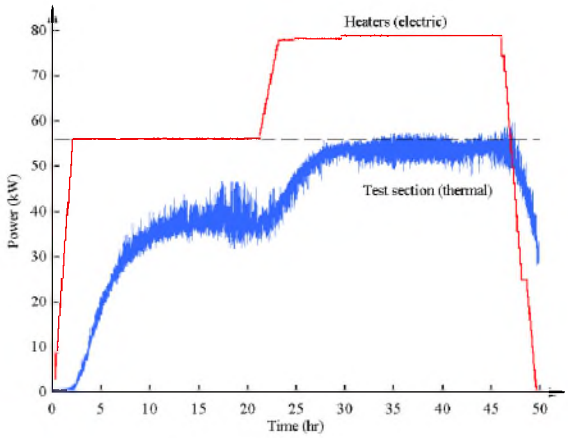

Fig. 4: Electric and thermal powers for baseline test case, dual vertical chimney exhaust

V. EXPERIMENTAL RESULTS

The baseline test case for experimental operations in the NSTF defined 56 kW_t within the test section, which was achieved by supplying a nominal 78 kW_e in a linear, uniform profile to the zoned electric heater banks. The outlet gases were vented through the vertical chimney stacks and the riser tube – heated plate spacing was kept constant at 71-cm.

V.A. Heat flux distribution

The split in heat flux distribution for the baseline test case is shown as a function of axial position in Fig. 5. The heat transfer off the heated plate is dominated by radiation, averaging 70% with the remaining 30% contribution from convection.

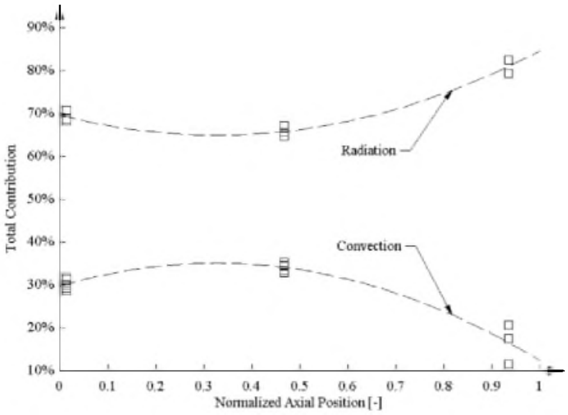

Fig. 5: Heat flux distribution from heated plate to front surface of riser ducts, baseline case

The downward trends of convection near the lower and upper cavity extents can be attributed to the natural circulation patterns near the corners of the heated enclosure. Along the bulk length the hot air is able to build momentum and increase its effectiveness, whereas nearest the corners it experiences a reduction in velocity and thus reduced convection coefficient.

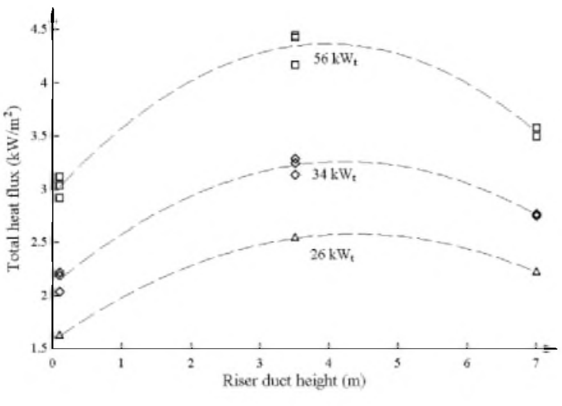

Fig. 6: Heat flux (hot riser face) for varying powers

Measured values of the heat flux varied widely along the length of the riser ducts, Fig. 6. The highest values during baseline conditions measured 4.4 kW/m^2 along heated side nearest the mid-plane of the ducts. Lowest values were recorded near 1.5 kW/m^2, which occurred at lower elevations of the duct walls facing the adiabatic (cold) wall.

V.B. Heated plate profile

The heated plate within the NSFT, mimicking the walls of a RPV, received a uniform heat flux for all the test cases presented. However, due to natural circulation convection cells both within the heated cavity and convection within the riser ducts themselves, a natural temperature gradient exists along the length of the plate. Fig. 7 shows the temperature distribution of the front surface of the heater plate with 78 kW$_e$ of supplied power, and is representative of the remaining test cases presented.

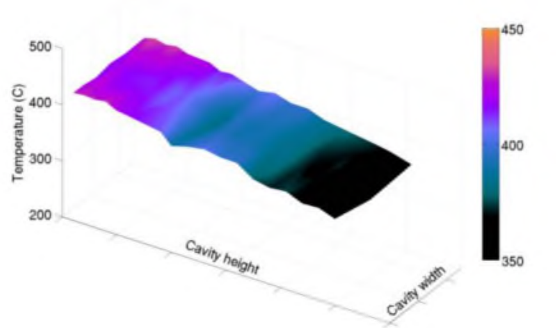

Fig. 7: Heated plate temperature profile, baseline

V.C. Differential pressure drop

The differential pressure drop across the heated test section (physically measured across the inlet and outlet of each riser duct) is a combined effect from both gravitational and frictional losses. Fig. 8 shows the relation between measured pressure drop and system mass flow rate for the baseline case at varying levels of supplied heater power.

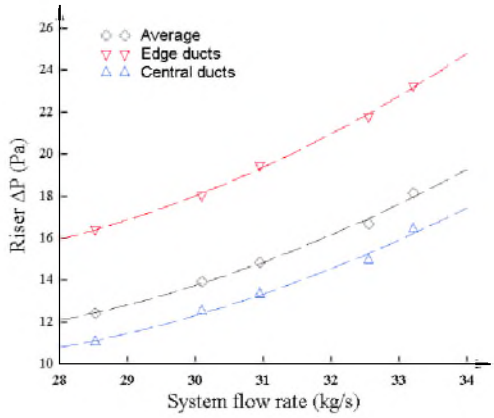

Fig. 8: Riser ΔP vs. system mass flow, baseline configuration at varying integral powers

Readily apparent is a difference among the edge and central riser ducts. However, thermocouple measurements of the inlet and outlet air flow show that the temperatures across all twelve ducts are similar within the bounds of experimental error. This suggests that the influences from gravitational effects may be considered uniform across the row of risers and that the variation can be attributed to differences in frictional losses or flow velocities. Considering that we have imposed a uniform heat flux, this finding is of great interest and will be examined in the future by additional velocity sensors in each duct.

VI. STARTUP AND METEOROLOGICAL SENSITIVITY

Characteristic to natural circulation loops, the NSTF exhibits certain sensitivities to ambient meteorological conditions. These influences manifest themselves throughout the full duration of test operations, and are especially prevalent during start-up transients. A weather station, mounted on the roof of the building nearest the exhaust stacks, provides this critical time synced weather data.

VI.A. Off-normal chimney roles

When exhausting through both vertical chimney stacks (orange flow paths in Fig. 2), a common occurrence is an abrupt shift in wind patterns that will perturb the chimney roles and flow directions.

Fig. 9 shows a scenario during start-up of the NSTF where shift in either wind direction and/or speed created a disturbance in the pressure at the outlet of the chimneys. Given the low total pressure differential across both chimney ducts (nominally 5 – 9 Pa for frictional losses) this disturbance will create an unequal split in flow distribution. Originating as an oscillating pattern, if left unmitigated the result is one chimney becoming a fresh air inlet and the other an outlet for both the newly formed inlet and heated exhaust gases from the riser ducts.

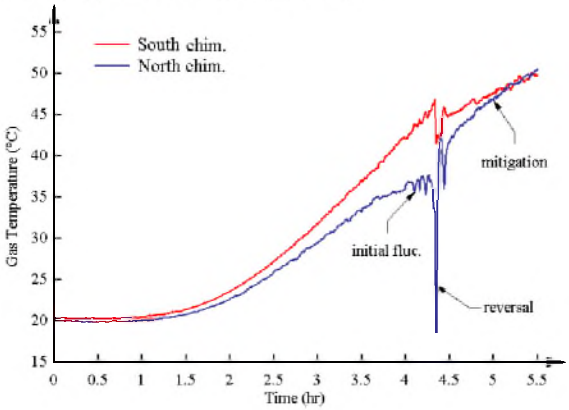

Fig. 9: Start-up instability, baseline case

This scenario in specific was mitigated by dampening the south chimney valve, which created constriction on the flow in the south chimney. This flow reduction allowed a buildup in the heated gravitational head that then began to travel out of the lower resistance north chimney network. Once this heated air succeeded in traveling the full length of the north network it began to heat up the metal ducts and revitalized the self-sustaining natural circulation flow path.

VI.B. Full system flow reversals

Another behavior that has been observed is a full system reversal during the start-up transient in a reduced chimney discharge height (blue flow path in Fig. 2). The reduction in exit elevation trends towards a U-loop versus a chimney column and thus is especially sensitive to flow reversals.

Fig. 10 shows the startup behavior where such a condition was observed. Between hours 1 and 2.5 the riser inlet temperature exhibited a temperature rise while the riser outlet gas temperatures (not shown) remain constant and equal to the outside ambient temperature. This scenario was mitigated by artificially dampening the valves near the chimney exhausts, allowing the system to build up head pressure and prime the metal ductwork, and re-opening the valves once the gravitational driving force was sufficiently tailored to resume the as-intended flow direction.

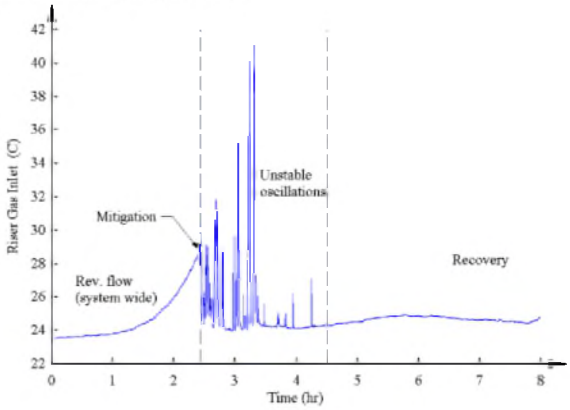

Fig. 10: Starting instability, reduced height

These valves, or dampers, installed in the NSFT are placed to facility experimental operations and guide test practices. Their use is instrumental in establishing zero-flow conditions, creating single or dual chimney configurations, and playing an active role in mitigating weather induced flow reversals. However, they do not represent the inherently safe and fully passive philosophy of the full scale RCCS design. The instabilities observed in the experimental test facility raise important questions on the engineering controls and real world implementation of such a safety system, and is an area requiring additional considerations.

VII. GENERAL SYSTEM TRENDS

The test series thus far have examined a range of supplied integral heater power for both single and dual chimney configurations. Each of these tests followed a similar procedure to the baseline test case, and was allowed to reach steady-state conditions across the range of thermal powers. Time-averaged thermal hydraulic parameters of interest are provided in tabulated form in Table 2, which were measured during a 12 hour steady-state period.

Table 2: Steady-state averages for baseline test

System Parameter	Steady-state Value
Heater power[1]	78.67 kW_e
Thermal power[2]	53.81 kW_t
Front plate[3]	667 K
Ceramic heaters	852 K
Riser duct wall	172.2 °C
Cold (unheated) wall	148.3 °C
Riser gas outlet	109.9 °C
Mass flow rate	0.548 kg/s
ΔP_{heated}	17.42 Pa

[1]Electric supplied power [2]$mC_p\Delta T$ [3]Representative of RPV

The system behavior at the baseline configuration for varying heater powers is shown in Fig. 10, and the effect of single vs. dual chimney roles in Fig. 11.

A linear relation can be observed for the riser outlet gas temperatures with increasing thermal power, however those specific to heated surface temperatures exhibit a non-linear trend by a reduced slope with increasing power. As the power increases, surface temperatures of the riser ducts, un-heated back cavity, and heated surfaces tape tapper off which can be expected for the T^4 relation of radiative heat transfer, and also in part by an increase in parasitic losses to the surroundings.

VIII. LUNA FIBER OPTIC

Unique to the NSTF is the installation of fiber optics for high density temperature measurements. This distributed sensing system, developed by Luna Technologies, has the ability to provide the necessary data density for validation of CFD tools. This technology is relatively new and has never before been utilized in a large scale thermal hydraulic test facility.

Based upon distributed strain sensing, the system leverages Rayleigh scattering losses from structural inhomogeneities in conventional (off the shelf) fiber cables [6]. The fibers, made from 155 µm polyimide-coated single mode commercial telecom fibers, are able to generate temperature measurements every 10mm at 1 Hz for a total of 9,750 data point/s along each of the 7.5-m fibers installed in the NSTF. Installed at eleven locations within a single central duct in the NSTF, five are within the gas space and the remaining six along the walls, Fig. 12.

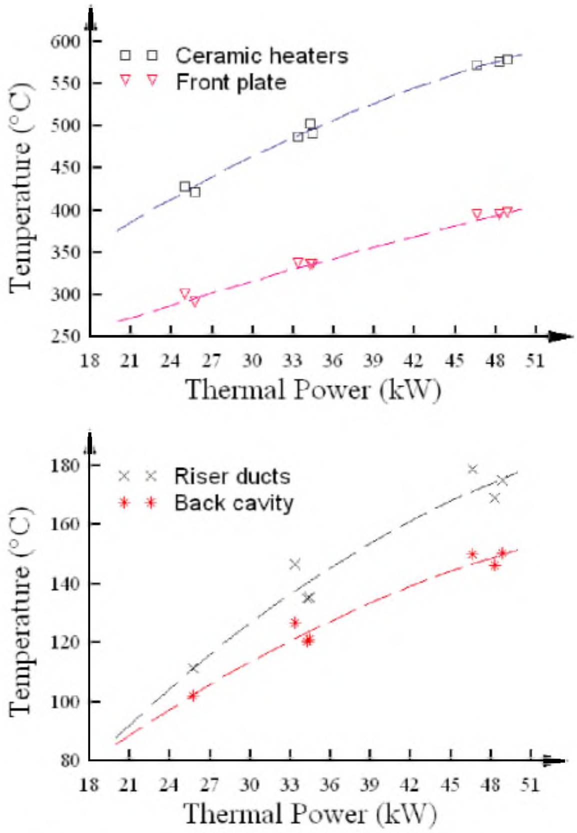

Fig. 10: Select temperatures for baseline case

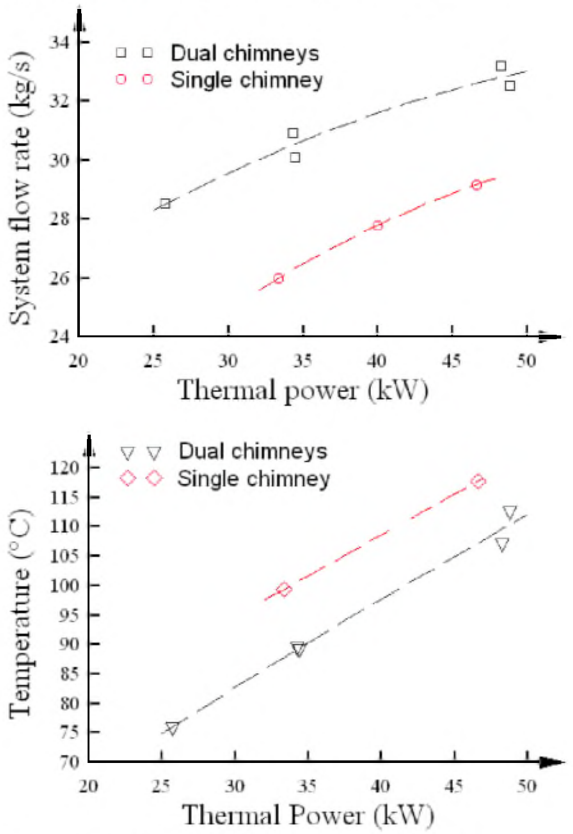

Fig. 11. System parameter trends for varying chimney configurations.

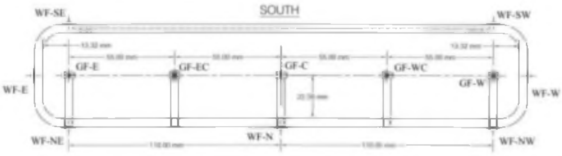

Fig. 12: Position of LUNA fibers in NSTF

Initial data collected from these fibers has been promising and is expected to serve the requirements of CFD grade data for verification and validation purposes. However, considerations have been identified for the influences of humidity on the measurements and data collected. It has been discovered that changes in relative humidity induce swelling (strain) in the hydrophilic polyimide coating of the fibers, which translate to artificial or unphysical temperature changes. The influence, which has been quantified in separate effects testing, is estimated to be on the order of 0.15°C/%RH. A sample of the one collected data set (acquired during winter months with relatively stable humidity swings) is shown below in Fig. 13.

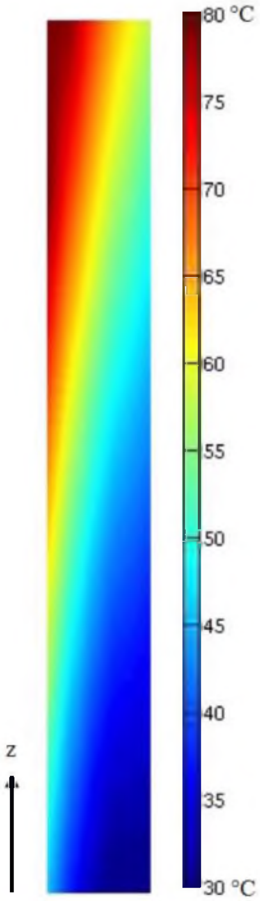

Fig. 13: 2D contour map of gas space temperatures, generated from five LUNA fiber cables along full length of riser duct at baseline test conditions

IX. PATH FORWARD

Active testing on the NSTF has been in progress since early 2014 and will reach a milestone by fall of this year. The test matrix entails a multi-parameter study that began with scaling, integral power, and chimney role studies. A multi-day test is expected to be performed near the half-way mark, which will simulate an accident scenario for the GA MHTGR during depressurized cool down conditions. The experimental conditions will begin with reaching steady-state operation at the steady heat load during normal operation (700 kW_t at full scale), at which point a reactor trip will be simulated and begin a transient coast through the typical power-time history of the decay heat profile. The peak power at full scale, 1.5 MW_t, is anticipated to occur at the 120 hour mark and will be included in the scaled test procedure.

ACKNOWLEDGMENTS

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