ANL-GenIV-058

Topical Report: Natural Convection Shutdown Heat Removal Test Facility (NSTF) Evaluation for Generating Additional Reactor Cavity Cooling System (RCCS) Data

Nuclear Engineering Division

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Topical Report: Natural Convection Shutdown Heat Removal Test Facility (NSTF) Evaluation for Generating Additional Reactor Cavity Cooling System (RCCS) Data

by
M. T. Farmer, D. J. Kilsdonk, C. P. Tzanos, S. Lomperski, R. W. Aeschlimann, D. Pointer
Nuclear Engineering Division, Argonne National Laboratory

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1.0 INTRODUCTION

1.1 Background

As part of the Department of Energy (DOE) Generation IV roadmapping activity, the Very High Temperature gas cooled Reactor (VHTR) has been selected as the principal concept for hydrogen production and other process-heat applications such as district heating and potable water production. On this basis, the DOE has selected the VHTR for additional R&D with the ultimate goal of demonstrating emission-free electricity and hydrogen production with this advanced reactor concept.

One of the key passive safety features of the VHTR is the potential for decay heat removal by natural circulation of air in a Reactor Cavity Cooling System (RCCS). The air-cooled RCCS concept is notably similar to the Reactor Vessel Auxiliary Cooling System (RVACS) that was developed for the General Electric PRISM sodium-cooled fast reactor. As part of the DOE R&D program that supported the development of this fast reactor concept, the Natural Convection Shutdown Heat Removal Test Facility (NSTF) was developed at ANL to provide proof-of-concept data for the RVACS under prototypic natural convection flow, temperature, and heat flux conditions. Due to the similarity between RVACS and the RCCS, current VHTR R&D plans call for the utilization of the NSTF to provide RCCS model development and validation data, in addition to supporting design validation and optimization activities. Both air-cooled and water-cooled RCCS designs are to be included.

In support of this effort, ANL has been tasked with the development of an engineering plan for mechanical and instrumentation modifications to NSTF to ensure that sufficiently detailed temperature, heat flux, velocity and turbulence profiles are obtained to adequately qualify the codes under the expected range of air-cooled RCCS flow conditions. Next year, similar work will be carried out for the alternative option of a water-cooled RCCS design. Analysis activities[1] carried out in support of this experiment planning task have shown that: (a) in the RCCS, strong 3-D effects result in large heat flux, temperature, and heat transfer variations around the tube wall; (b) there is a large difference in the heat transfer coefficient predicted by turbulence models and heat transfer correlations, and this underscores the need of experimental work to validate the thermal performance of the RCCS; and (c) tests at the NSTF would embody all important fluid flow and heat transfer phenomena in the RCCS, in addition to covering the entire parameter ranges that characterize these phenomena. Additional supporting scaling study results are available in Reference 2.

1.2 Objectives and Approach

The purpose of this work is to develop a high-level engineering plan for mechanical and instrumentation modifications to NSTF in order to meet the following two technical objectives:

1. provide CFD and system-level code development and validation data for the RCCS under prototypic (full-scale) natural convection flow conditions, and

2. support RCCS design validation and optimization.

As background for this work, the report begins by providing a summary of the original NSTF design and operational capabilities. Since the facility has not been actively utilized since the early 1990's, the next step is to assess the current facility status. With this background material in place, the data needs and requirements for the facility are then defined on the basis of supporting analysis activities.[1] With the requirements for the facility established, appropriate mechanical and instrumentation modifications to NSTF are then developed in order to meet the overall project objectives. A cost and schedule for modifying the facility to satisfy the RCCS data needs is then provided.

2.0 ORIGINAL NSTF DESIGN AND OPERATIONAL CAPABILITIES

2.1 Mission

The Natural Convection Shutdown Heat Removal Test Facility (NSTF) is a large-scale test facility located in Bldg. 310 on the Argonne National Laboratory site. An overview photograph of the building where the facility is located is shown in Figure 2.1. The facility was originally developed to provide confirmatory data for the GE PRISM RVACS design. A schematic diagram showing key elements of the PRISM RVACS is provided in Figure 2.2. The NSTF mocked up the air-flow path formed by the reactor guard vessel (heated wall) and the outer duct wall surrounding the guard vessel.

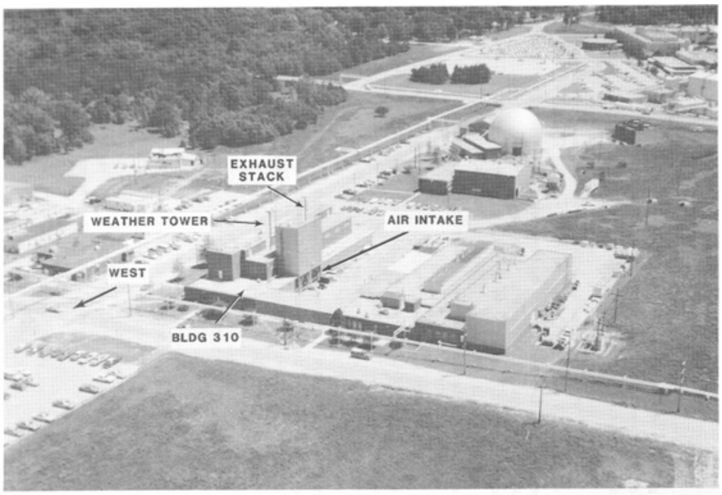


Figure 2.1. Aerial View of the Building Housing NSTF.

2.2 Overall Facility Design

Principal components of the facility consisted of the structural module, electric heaters, instrumentation, insulation, and a computerized data acquisition and control system. A schematic overview of the facility that illustrates key components is provided in Figure 2.3, while a summary of the facility design and operating parameters is provided in Table 2.1.

As is evident from Figure 2.3, the key features of the structural module consisted of an inlet plenum, a heated zone that mocked up the exterior of the reactor guard vessel, and an unheated stack or chimney. All sections, with the exception of the inlet plenum, were thermally

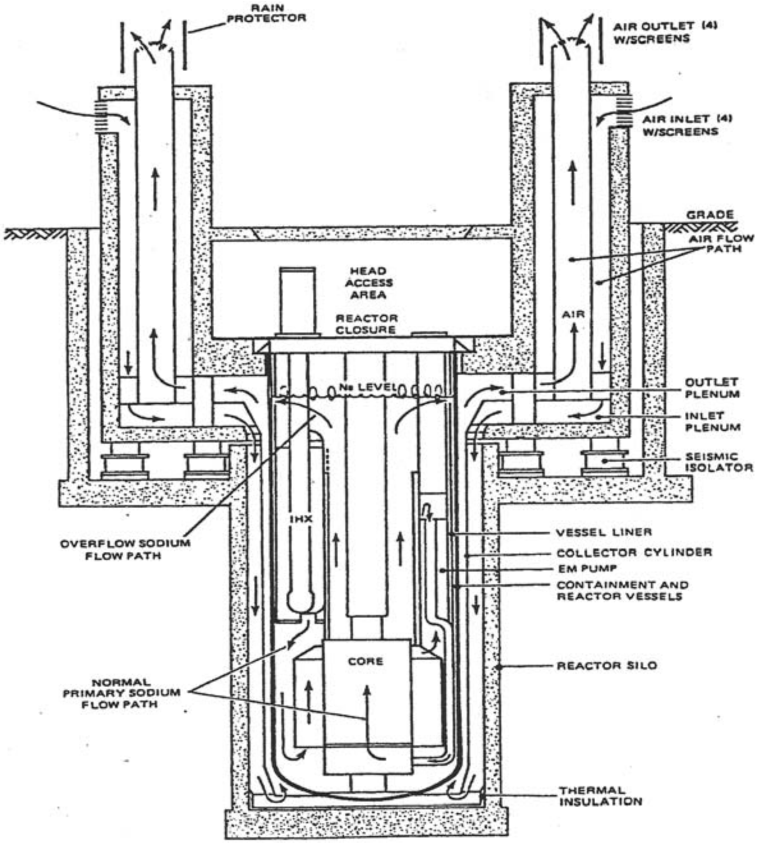


Figure 2.2. Schematic of GE PRISM RVACS Concept.

insulated to minimize parasitic heat losses to the environment. The heated channel width was 1.32 m. As originally designed, the channel width could be adjusted anywhere from 30.4 cm to 45.6 cm. A cross-section through the heated section of the structure is provided in Figure 2.4. The surfaces that simulate the guard vessel wall (heated wall) and the outer duct wall were smooth, 2.54 cm thick carbon steel plates. Within the heated zone, fins or ribs could be installed on the inner walls of the air channel to enhance turbulence and heat transfer. A photograph showing the heated test section walls during installation is provided in Figure 2.5. Note that there is sufficient space within the high bay where the facility is located to increase the channel width to as much as 150 cm if the need arises. However, this would require modification of the mechanical framework that supports the heated and unheated walls that simulate the guard vessel and outer duct wall. In addition, transition ductwork would need to be provided to mate the modified heated section to the existing stack.

In terms of simulating the thermal boundary conditions on the outside surface of the PRISM reactor guard vessel, the facility was capable of operation in one of two thermal modes: (1) constant (uniform) guard vessel wall temperature at up to 677 °C, or (2) constant (uniform) heat flux at levels ranging up to 21.5 kW/m^2. Alternatively, step-wise variation of these two boundary conditions was possible, either singly, or in any arbitrary combination. A total of 10

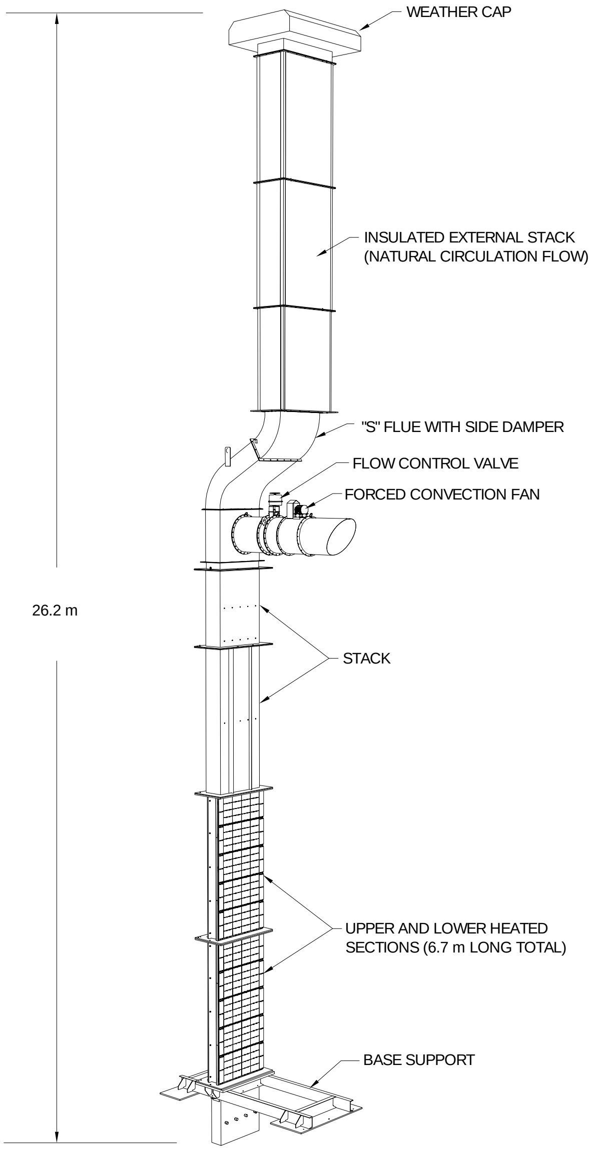


Figure 2.3. Schematic Overview of NSTF.

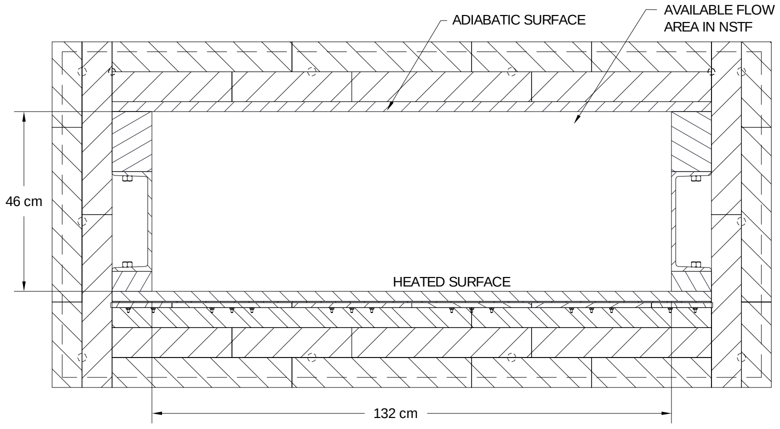


Figure 2.4. Cross-Section Through the Test Assembly.

Table 2.1. Original NSTF Design and Operating Parameters.

Parameter	Value	Notes
General	Natural convection air-flow T-H test facility	The case of water-cooled RCCS tubes can be readily addressed in the facility
Overall Facility Height	26.2 m (86 ft.)	-
Flow operating modes	Natural or forced convection	Facility includes fan loft
Heated Section Flow Area	Rectangular, 46 cm x 132 cm	Expandable to 150+ cm x 132 cm
Heated Section Length	6.7 m	-
Heating Distribution	One long side heated; other 3 sides adiabatic	-
Heated Section Operating Modes	1. Constant heat flux (limit: 21.5 kW/m^2) 2. Constant temperature (limit: 680 ˚C) 3. Arbitrary combination of 1 & 2	Heater limits: 23.7 kW/ m^2 and 1200˚C. Structure strength/thermal expansion tolerances are being re-examined for possible higher temperature operation.
Total Input Power	220 kW	-
Resolution of Axial Heat Flux/Temperature Control	10-67 cm axial segments	Resolution can be reduced to as little as 16 cm axial increments
Inlet Section Area	Rectangular, 46 cm x 132 cm	Expandable to 150+ cm x 132 cm
Inlet Section Length	1.5 m	-
Chimney Height	18.0 m	-
Chimney Area	Rectangular, 46 cm x 132 cm	-
Total head loss coefficient	1.5 to 20	Referenced to inlet flow velocity. Adjusted with fixed area dampers

heater zones spanned the 6.7 m heated length of the NSTF; each bank was independently controlled. Thus, the axial resolution in heat flux and/or temperature control corresponded to 67 cm.

The heat input to the guard vessel was provided by an assembly of ceramic electrical heaters that were fastened to 3.2 mm thick stainless steel mounting plates. Heat was transferred through the plates and then conducted across a small gap to the guard vessel surface. Power to the heaters was feedback-controlled based on readings from thermocouples attached to the surface between the mounting plate and the heaters. A photograph showing a heater mounting plate prior to installation on the test section is shown in Figure 2.6. As shown in Table 2.1, the total input power that could be provided by the 10 banks of plate heaters was 220 kW.

Above the heated zone the flow channel expanded to a cross section of 1.32 m by 45.6 cm. Two flow paths were provided. The main path for the experiments was upward through an "S" curve and then vertically through the building roof. This provided a stack for natural convection measuring nearly 15.2 m in vertical length. As shown in Figures 2.1 and 2.3, the top of the stack extended 6.1 m above the roof. The second flow path consisted of a fan with a variable motor speed and a damper. This feature was provided for forced convection tests, when a controlled air flow rate was desired.

2.3 Instrumentation, Data Acquisition, and Control

The data acquisition system (DAS) for the original system was capable of sampling 300 channels. The large majority of these instruments consisted of

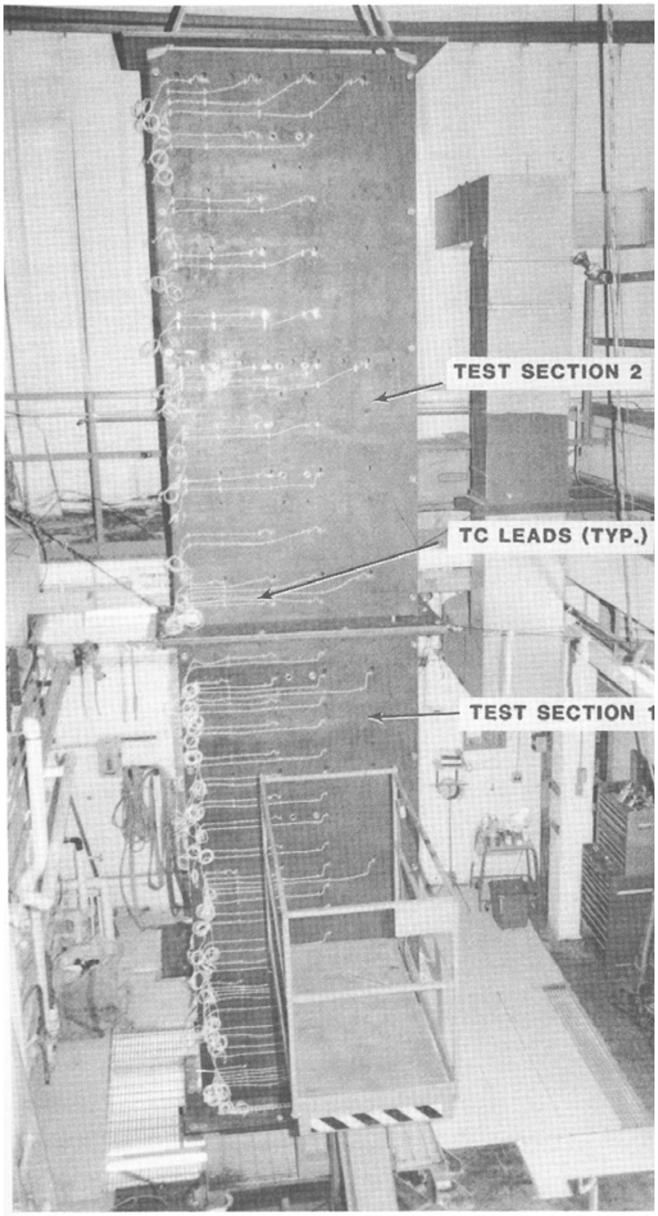


Figure 2.5. Heated Test Section Assemblies.

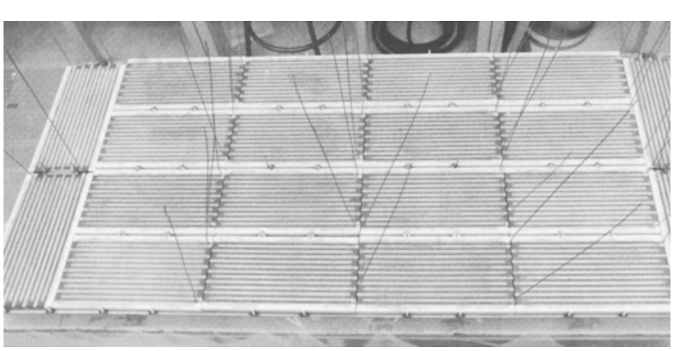


Figure 2.6. Typical Heater Plate Assembly.

thermocouples that were dedicated to monitoring temperatures in the heated zone of the assembly. The DAS stored the data on disk; selected channels were displayed at the operator's console to help guide test operations. The DAS computer was also used to compute system parameters for real-time display. As discussed in Section 5, the heater power control and DAS systems will be completely renovated as part of the current work to satisfy the RCCS data needs.

The NSTF was heavily instrumented to help guide experiment operations, and also evaluate the heat removal performance for particular configurations under both natural convection and forced flow conditions. A summary of the overall instrumentation approach is provided in Table 2.2. As shown in the table, instruments were provided to measure local surface temperatures, local bulk air temperatures, local and bulk air velocities, air volumetric and mass flow rates, total normal radiation heat flux, and electrical power supplied to the duct wall heaters. The instrumentation consisted of thermocouples, pitot-static traversing probes, a pitot-static air flow rake, differential pressure transducers, radiation flux transducers, anemometers, and air pressure and humidity gages. The primary measurement objective was to determine the local heat fluxes and the associated heat transfer coefficients, as well as the bulk (or integral) heat removal rate of the system. To achieve this objective, both the heated and unheated walls of the facility were heavily instrumented with flush-mount thermocouples for accurate measurement of surface temperatures while not disrupting the flow field. A drawing that illustrates the surface thermocouple installation technique is provided in Figure 2.7, while schematics that show all thermocouple locations on the heated and unheated walls of the facility are provided in Figures 2.8 and 2.9, respectively.

2.4 Operational Capabilities

The various facility operating approaches and limitations have already been summarized as part of the overall facility description (e.g., see Table 2.1). During testing at NSTF in support of the GE PRISM RVACS design, flow velocity and temperature measurements were made for both smooth and finned channel walls. In addition, some measurements were made with a blocked flow channel configuration. Operationally, these measurements covered a range of natural convection flow conditions at Reynolds numbers above 40,000. Thus, this data is not directly applicable to the VHTR air RCCS, since the Reynolds number range for this system is not expected to exceed 20,000.[1]

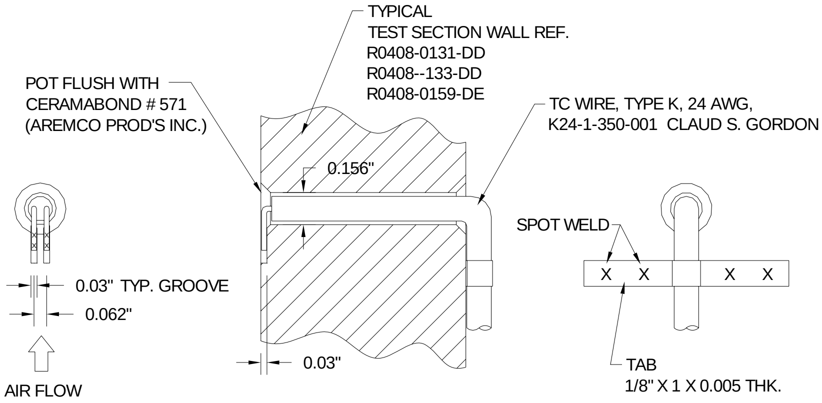


Figure 2.7. Surface Temperature Thermocouple Installation.

Table 2.2. Summary of NSTF Instrumentation Approach.

Measurement	Instrument	Purpose/Location
Temperature	Thermocouples	1. Heater Over-temperature/control 2. Guard vessel wall: ~ 60 on lower section at ~ 25 cm axial intervals, ~ 44 on upper section at ~ 50 cm intervals. 3. Duct wall: ~ 48 on lower section at ~ 25 cm axial intervals, ~28 on upper section at ~ 50 cm intervals. 4. Side walls: ~ 50 cm intervals. 5. Heated section inlet: 4 radiation-shielded 6. Heated section exit: 4 radiation-shielded
Flow velocity distributions	Pitot-static, anemometer, rotameter	1. Fixed pitot-static rakes at heated section inlet and exit (4 transverse locations each). 2. Access ports for movable pitot-static tubes and/or anemometers at 1.2 m axial increments; 4 transverse access ports at each axial elevation. 3. Rotameter for air velocity/direction measurement at stack exit.
Pressure	Strain-gauge transducers	1. Inlet static 2. Test section differentials
Radiation heat flux	Radiation sensor	Four used in NSTF; can be placed in selected access ports at 1.2 m axial increments; 4 transverse access ports at each axial elevation
Surface emissivity	Radiation sensor	″
Heater AC Power Distribution	Voltmeter and Halltipliers	Measure axial power distribution at 10 axial elevations

Figure 2.8. NSTF Surface Temperature and Heater Control Thermocouples on Heated Walls.

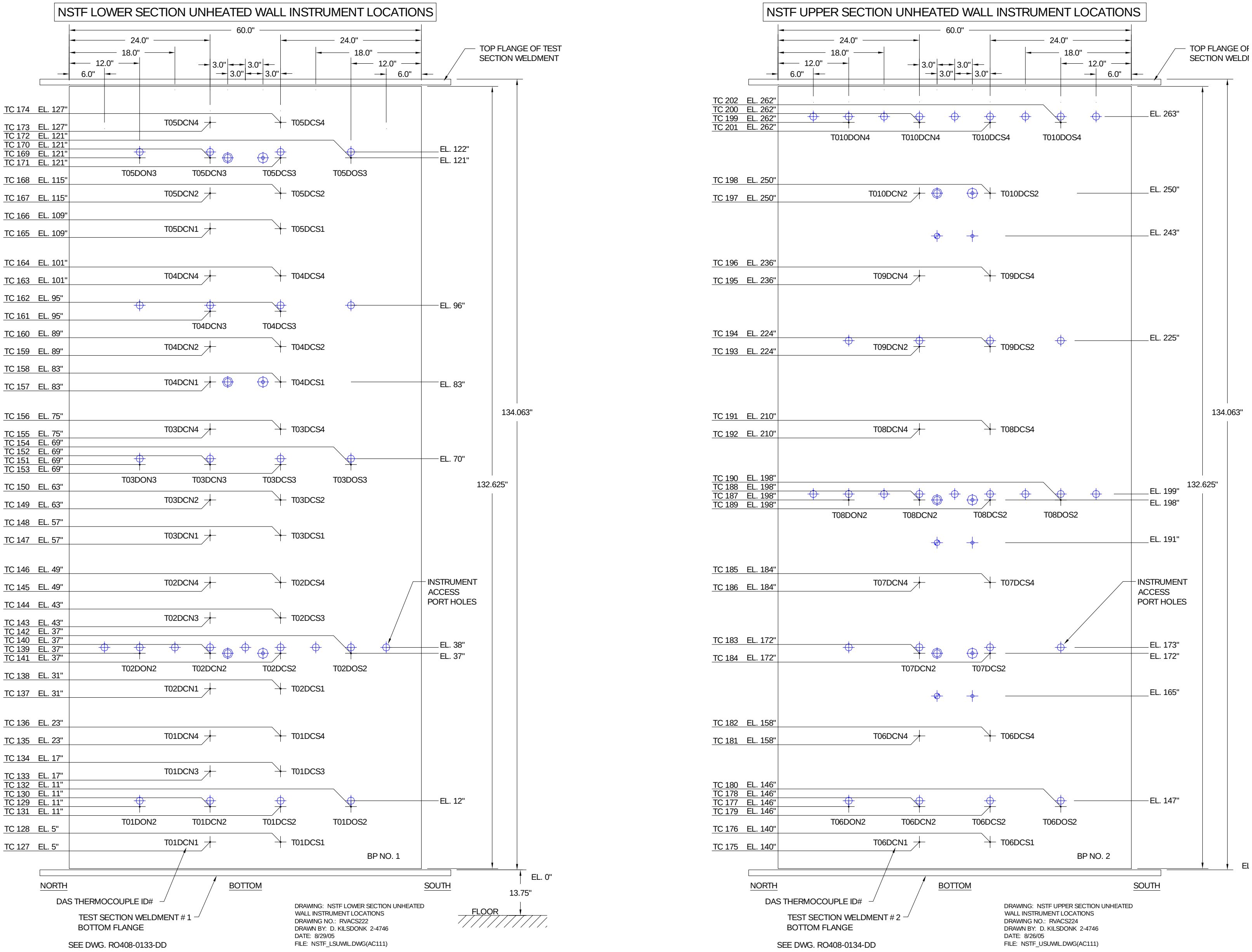


Figure 2.9. NSTF Surface Temperature Thermocouples on Unheated Walls.

3.0 ASSESSMENT OF CURRENT FACILITY STATUS

Testing at NSTF in support of the GE-PRISM RVACS design was carried out from the mid 1980's to the early 1990's. Once testing was completed, the facility was placed in a standby status where it has remained until now. As part of the present workscope, the facility was inspected to determine the status of the electrical and mechanical systems. This inspection provided the necessary background for assessing the hardware upgrades that would be required to initiate testing for the VHTR RCCS. The objective of this section is to summarize the findings from this assessment.

Over the course of two days, the facility was examined by a team that consisted of three staff experimentalists, two test engineers (one specializing in mechanical design, and the second specializing in electrical and instrumentation systems), two laboratory chief technicians, and the local ES&H coordinator. The team was selected to provide a solid background for evaluating not only the current facility status, but also to identify any other major physical or administrative issues (based on current DOE ES&H rules and regulations) that could significantly impede rehabilitation of the facility. The walkdown was initiated on January 20, 2005.

A summary of the findings from the facility assessment is provided in Table 3.1. In general, the facility appears to be sound shape; no structural, mechanical, electrical, or instrumentation issues were identified during the assessment that would impede facility modifications for RCCS testing. Additional details of the assessment are provided below.

3.1 Workspace

The facility workspaces consist of a control room, the high bay housing the test structure, and an adjacent laboratory preparation area. The control room was cleaned out and vacated following RVACS testing. Aside from general housekeeping, this area will require floor and ceiling repairs before beginning equipment installation. The high bay structure is in sound shape. Aside from cleaning, a few surplus items will need to be removed and the area will be painted as a precursor to initiating work. Lighting in the upper loft area needs to be upgraded. The ladders need to be brought up to current OHSA standards.

3.2 Test Structure

Overall, the test section is in excellent mechanical shape. The inlet plenum is heavily rusted, but this component will be replaced for RCCS testing anyway. Both the heated and unheated duct walls appear to be in good shape; i.e., no mechanical distortion from RVACS testing was discernable. All components of the chimney are present and are also in good mechanical shape. The fan also appears to be in working order, but this component could not be tested without rewiring of the power feed. The chimney extension above the high bay roof also appears to be in good shape, but the exterior surface needs to be painted.

3.3 Electrical Heaters

Insulation was removed in several places on the heated wall to examine the ceramic plate heaters. This inspection indicates that the plate heaters are in good shape. Several heaters were randomly checked for continuity; the resistances were within the heater specifications. The mechanical mounting plates also seemed to be in good order.

Table 3.1. Summary of Findings from the NSTF Facility Assessment.

Area/Component	Status
Working Areas	Control Room: Completely cleaned out following RVACS testing. Needs general housekeeping. Floor tile and ceiling repairs are needed. High Bay: Building structure is in sound shape. Needs cleaning, removal of a few surplus items, and painting. Lighting in the upper loft area needs upgrading to facilitate the work. Ladders need to be brought up to current OHSA standards.
Structural Module	Overall, the test section is in excellent mechanical shape. The inlet plenum is rusted, but this component will be replaced for RCCS testing anyway. Both the heated and unheated duct walls appear to be in good shape; i.e., no mechanical distortion from RVACS testing was discernable. All components of the chimney are present and are also in good mechanical shape. The fan also appears to be in working order, but this component could not be tested without rewiring of the power feed. The chimney extension above the high bay roof also appears to be in good shape, but the exterior surface needs to be painted.
Electric Heaters	Insulation was removed in several places to examine the ceramic plate heaters. This inspection indicates that the plate heaters are in good shape. Several heaters were randomly checked for continuity; the resistances were within the heater specifications. The mechanical mounting plates also seemed to be in good order.
Heater Control System	The heater controllers were removed for utilization on other programs at completion of RVACS testing. The control system will be replaced according to current electrical standards for RCCS testing.
Instrumentation	The key facility instrumentation that will be utilized for RCCS testing consists of the large array of thermocouples used for monitoring of the heated and unheated duct wall temperature distributions; see Figures 2.8-2.9. The inspection indicates that these thermocouples are still intact. Several were tested for junction continuity and all were found to be functional. The junction labeling is still intact; all junctions are easily traceable to the installation locations.
Data Acquisition System	The DAQ was removed for utilization on other programs at completion of RVACS testing. This system will be replaced with a modern LABView-based DAQ/control system for RCCS testing.
Infrastructure	The main power feeds for the electrical heaters into the high bay are intact and functional. Water service to the high bay exists: capacity is estimated at 25 gpm. However, water is not required for air-cooled RCCS testing.

3.4 Heater Control System

The heater controllers were removed for utilization on other programs at completion of RVACS testing. The control system will be replaced according to current electrical standards for RCCS testing, as described in Section 5.0.

3.5 Instrumentation and Data Acquisition

The key facility instrumentation that will be needed to successfully carry out the RCCS testing consists of the large array of thermocouples used for monitoring of the heated and unheated duct wall temperature distributions; see Figures 2.8-2.9. The inspection indicates that these thermocouples are still intact. Several were tested for junction continuity and all were found to be functional. The junction labeling is still intact; all junctions are easily traceable to the installation locations, which will allow the labeling to be rechecked before testing is initiated.

The DAQ was removed for utilization on other programs at completion of RVACS testing. This system will be replaced with a modern LABView-based DAQ/control system for RCCS testing, as described in Section 5.0.

3.6 Infrastructure

The main power feeds for the electrical heaters into the high bay are intact and functional. Water service to the high bay exists: capacity is estimated at 25 gpm. However, water is not required for air-cooled RCCS testing.

4.0 REQUIREMENTS FOR RCCS TEST FACILITY

Supporting analyses have been carried out by Tzanos[1] to provide the technical basis for identifying required mechanical and instrumentation modifications to NSTF to meet key air RCCS data needs. The principal findings from this work[1] that directly impact the facility planning process are summarized below.

4.1 Scoping Calculations

Analysis of the air RCCS design requires some knowledge of the system geometry. Although design details of the VHTR RCCS have not yet been established, the design may be similar to the GA GT-MHR RCCS.[3] This particular design consists of 292 rectangular ducts (tubes) arranged around the reactor vessel. Each tube is manufactured from standard structural steel with cross-sectional dimensions of 5.05 cm x 25.4 cm, and a wall thickness of 4.8 mm. Air at 43 ºC, driven by natural convection, enters the inlet plenum above the downcomer, and then flows through the downcomer to the bottom of the reactor compartment, where it is distributed to the RCCS tubes. The hot air leaving the tubes is collected in an exhaust plenum, and from there it is discharged to the atmosphere through chimneys that exit the reactor confinement building. Heat is transferred from the reactor vessel to the tubes mainly by radiation, but also by convection.

To evaluate the ability of NSTF to reproduce the expected flow behavior in the prototype RCCS, CFD analyses of both the prototype and of the modified facility were carried out. The objective of these calculations were to determine if all significant fluid flow and heat transfer phenomena in the RCCS could be simulated, and that the tests could cover the whole parameter range describing these important phenomena.

As described in the next section, NSTF can accommodate up to twelve RCCS tubes with full scale cross-section. Thus, this geometry was assumed for the calculations. In the GT-MHR design, the distance between the outer surface of the reactor vessel and the front side of the RCCS tubes is ~77 cm. However, in NSTF this distance would need to be reduced to ~10 cm to preserve the tube full-scale cross-section. This will have an effect on the radiation view factors between the reactor vessel and the RCCS tubes. The height of the heated section in the facility is 6.7 m, with room to extend the heated zone by ~ 1 m if needed. The height of the tubes in the GT-MHR design is ~ 20 m. Because the air flowrate is a function of not only the tube heated length but also of the pressure drop along the complicated flow path (i.e., tube, downcomer, upper and lower plena, and exhaust chimney), CFD analyses were needed to verify that prototypic flowrates could be established in the facility for a tube height in the range of 7 to 8 m. If this could be established, then the facility would be able to provide an essentially full scale simulation of the RCCS.

In general, the results of the calculations identified important fluid flow and heat transfer phenomena in the RCCS. Specifically, strong buoyancy effects reduce turbulence and thermal mixing and the overall heat transfer coefficient. The heat transfer coefficient is a strong function of radial position around the tube wall. Radiation between the RCCS tube walls leads to a significant redistribution of the heat flux. These 3-D effects cannot be captured by 1-D models, and by codes that do not use turbulence models. The analyses further indicate that there are large differences in the predicted heat transfer coefficients by turbulence models and heat transfer correlations.

Aside from these phenomenological findings, a key result from these analyses is that prototypic flowrates can be established in the available 6.7 m heated test section length of NSTF. In addition, the analyses further indicate that experiment distortions due to the reduced setback distance between the heated wall and the front side of the RCCS tube in the facility are minimal. Thus, the principal conclusion of this study[1] is that NSTF is able to provide essentially a full scale simulation of the RCCS.

4.2 Data Needs for Code Verification and Validation

Based on the above analyses, high level design requirements for the NSTF were established. These requirements are summarized in Table 4.1. The first requirement is to mock up the actual geometry of the RCCS to the greatest extent possible. This will ensure that the prototypic natural convection flow patterns will be established during the tests. The remaining four requirements are data-related. Namely, measurements of the axial and radial temperature and heat flux distributions on the tube walls are required, as well as the heated and non-heated duct walls. In addition, data on the tube interior gas velocity and temperature distributions are needed. This collection of measurements will provide the necessary data to evaluate the heat transfer coefficient variation not only axially along the tube length, but also radially around the extent of the tube walls. Finally, turbulence measurements are needed at several axial elevations to reduce the uncertainty in the appropriate form of the turbulence models required to accurately compute the flow and heat transfer behavior in the RCCS.

This information forms the basis for the facility modification plan that is provided in the next section.

Table 4.1. Summary of NSTF Requirements to Provide Code V&V Data.

No.	Requirement
1	Mock-Up Air RCCS Geometry under prototypic flow conditions.
2	Obtain data on the RCCS tube and channel axial temperature distributions under prototypic flow conditions.
3	Obtain data on the RCCS tube heat flux distributions at prototypic RCCS flow conditions.
4	Obtain data on the RCCS tube interior bulk gas velocity and temperature distributions.
5	Obtain turbulence data as a function of axial position within RCCS tubes.

5.0 NSTF MODIFICATIONS TO SATISFY RCCS DATA NEEDS

Overall RCCS data needs for code verification and validation were described in the previous section. The objective of this section is to outline a high-level plan for modifying NSTF to meet these data needs.

5.1 Overall Approach

A summary of the experiment approach for satisfying key data needs is provided in Table 5.1. The first requirement is to mock up the actual geometry of the RCCS to the greatest extent possible to ensure that the prototypic natural convection flow patterns will be established during the tests. To meet this requirement, the approach is to strive for geometric similitude between the experiment and prototype to the greatest extent possible.

As shown in Table 5.1, the balance of the requirements for NSTF are data-related. In particular, to obtain data on the tube and channel wall axial and radial temperature and heat flux distributions, three of the center tubes and the channel walls are heavily instrumented with thermocouples to measure surface temperatures and local heat fluxes at 29 axial positions along the heated test section length. The requirement to obtain data on the RCCS tube interior and exterior gas velocity and temperature distributions will be met by utilizing insertable, hot-wire anemometers with co-located, radiation-shielded thermocouples. Finally, the requirement to obtain turbulence data as a function of axial position within the RCCS tubes will be met by providing quartz viewports through cavity and tube walls at ~ 1 meter axial increments so that turbulence measurements can be obtained with LDV under prototypic RCCS flow conditions.

Additional details regarding the experiment approach for satisfying RCCS data needs are provided in the balance of this section.

5.2 Mechanical Modifications to Mock Up RCCS Flow Geometry

As noted above, the approach for mocking up the RCCS geometry is to try to match the prototype geometry to the greatest extent possible. This is accomplished by installing twelve tubes of prototypic cross-section (based on the GA GT-MHR design[3], wall thickness, and pitch in the heated section of NSTF. The tube fabrication details are shown in Figure 5.1, while the tube mounting technique is illustrated in Figure 5.2. The overall tube length is 7.39 m, which provides sufficient material to mechanically attach the tubes at the top of the heated portion of the facility, pass through the entire 6.7 m long heated test section length, and penetrate through the bottom of the base support weldment with sufficient clearance to mechanically support and instrument the tubes to measure inlet flow conditions. As shown in Figure 5.1, the top flange of the upper heated section will be modified to receive a support plate for the twelve RCCS tubes. The tubes will be suspended (hung) from this support plate. The support plate also seals off the available space exterior to the RCCS tubes, thereby providing a stagnant air environment that is consistent with the GA GT-MHR RCCS design.[2] An alignment plate (Figure 5.3) is used to ensure proper positioning of the twelve tubes within the opening at the lower heated section inlet. The alignment plate also seals off the bottom of the section to produce the proper boundary condition for the RCCS tube enclosure. The alignment plate is not rigidly attached to the tubes, so that it can accommodate tube thermal expansion (< 2 cm) during the tests. A lower expansion

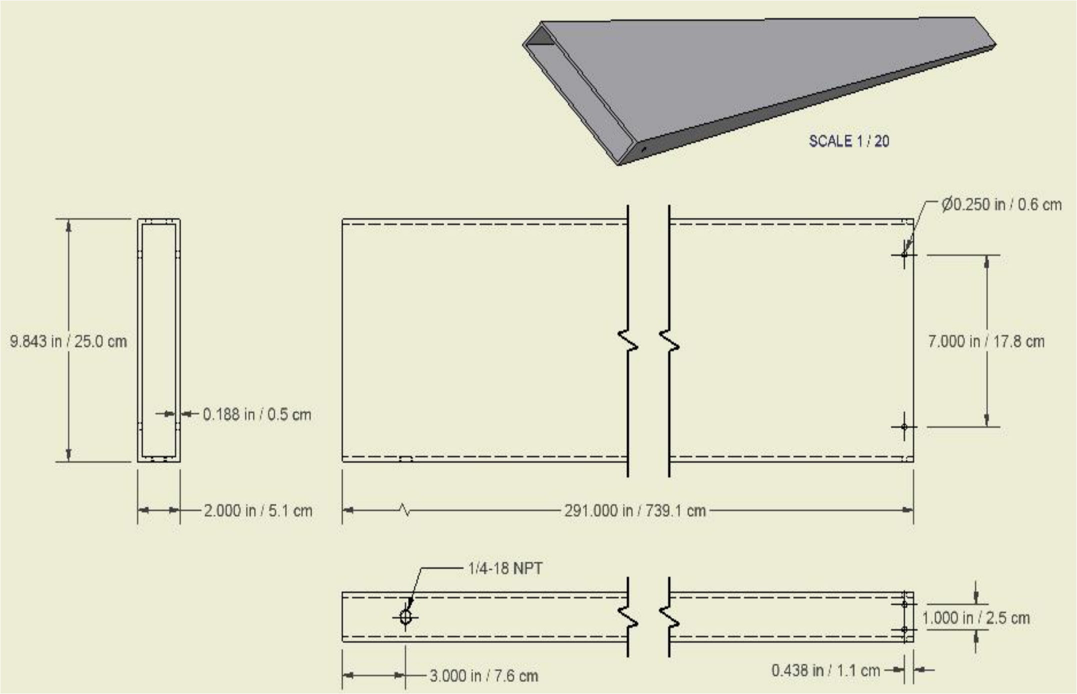


Figure 5.1. RCCS Tube Fabrication Details.

joint assembly (Figure 5.4) is provided at the tube inlets to accommodate thermal expansion while maintain a well-defined flow geometry at the inlet. As shown in the figure, all the tube inlets are rounded to minimize entrance loss effects.

The inlet plenum duct will be replaced as part of the workscope since the existing duct is for the 30.5 cm wide flow channel option, and RCCS testing for the VHTR will be carried out using the expanded channel width of 46 cm (see Table 2.1). Fabrication of a new inlet duct will also provide the opportunity to add additional instruments to better characterize the inlet flow conditions. Fabrication and installation details of the inlet duct are provided in Figure 5.5. Instrumentation details are provided later in this section.

As is evident from Figure 5.1, the RCCS tubes are long, slender objects that will provide a challenge to install in the existing NSTF apparatus. The method by which this will be accomplished is illustrated in Figure 5.6. The test section base support spans an 8 m deep pit beneath the test facility, which provides sufficient space to stand the RCCS tubes up beneath the test section after the inlet duct and expansion joint assembly have been removed. As part of the installation procedure, the 'S-flue' will be removed to provide access to the interior of the test section; see Figure 2.3. Through this access, the crane (with appropriate rigging) will be used to hoist each RCCS tube up through the interior of the test section so that the tubes can be attached to the top support plate (see Figure 5.2). To gain access for the installation of the support plate, a doorway will be installed in the first non-heated stack section immediately above the top heated test section. The doorway will also provide access for attaching the tubes to the plate as they are raised into position. Once the tubes are installed, the doorway will be closed and sealed to return the facility to a test-ready status. This overall approach will allow tubes that span the entire 6.7 m heated length to be installed in the NSTF.

Table 5.1. Approach for Satisfying Key RCCS Data Needs.

	Requirement	Approach	Notes
1	Mock-Up Air RCCS Geometry under prototypic flow conditions	Twelve (12) 6.7 m long tubes with prototypic cross-section (5 cm x 25 cm), wall thickness (4.8 mm), and pitch (10 cm) installed in heated section of NSTF. Peripheral area around tubes sealed at top and bottom to achieve prototypic flow geometry. Apply prototypic surface temperature and/or heat flux boundary conditions to achieve prototypic flow patterns.	Tube dimensions based on the GA GT-MHR RCCS design, but other designs can be accommodated, including water-cooled tubes.
2	Obtain data on the RCCS tube and channel axial temperature distributions under prototypic flow conditions.	Highly instrument the three center tubes and channel walls to measure channel surface and tube internal and external surfaces temperatures at 29 axial positions along the heated length. Obtain measurements on the heated, unheated, and side walls of the tubes.	1. Key information for CFD code V&V under prototypic VHTR air RCCS flow conditions. 2. Data from 2-4 provides information needed to evaluate heat transfer coefficients vs. axial position in tubes.
3	Obtain data on the RCCS tube heat flux distributions at prototypic RCCS flow conditions.	Using Req. No. 2 measurements, evaluate tube axial heat flux distributions at 29 axial positions using inverse heat conduction technique. Include heat flux meters for measurement diversity.	
4	Obtain data on the RCCS tube bulk gas velocity and temperature distributions.	Utilize insertable hot wire anemometers with co-located, radiation-shielded, thermocouples to measure bulk gas velocity and gas temperature distributions at ~ 1 meter axial increments.	
5	Obtain turbulence data as a function of axial position within RCCS tubes	Provide quartz window viewports through cavity and tube walls at ~ 1 meter axial increments so that turbulence measurements can be obtained with LDV under prototypic RCCS flow conditions.	

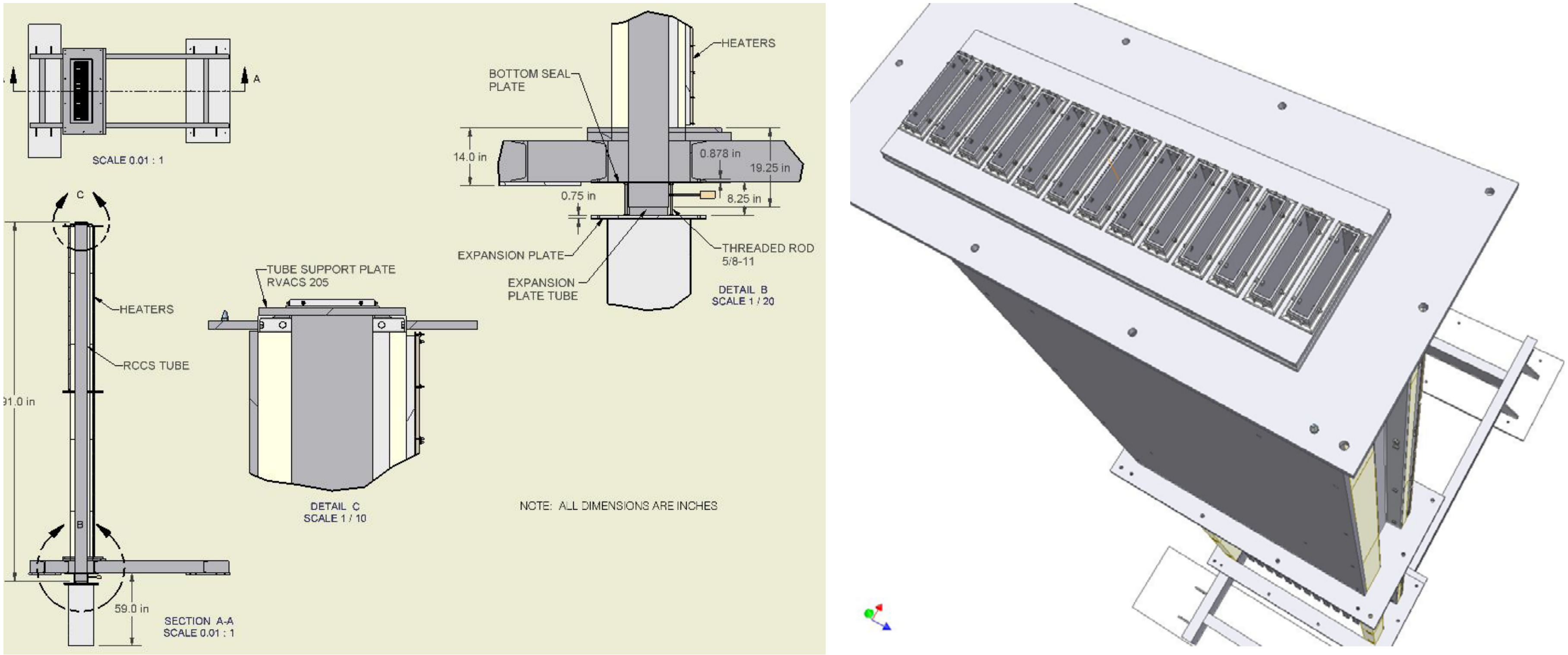


Figure 5.2. RCCS Tube Installation Procedure for NSTF.

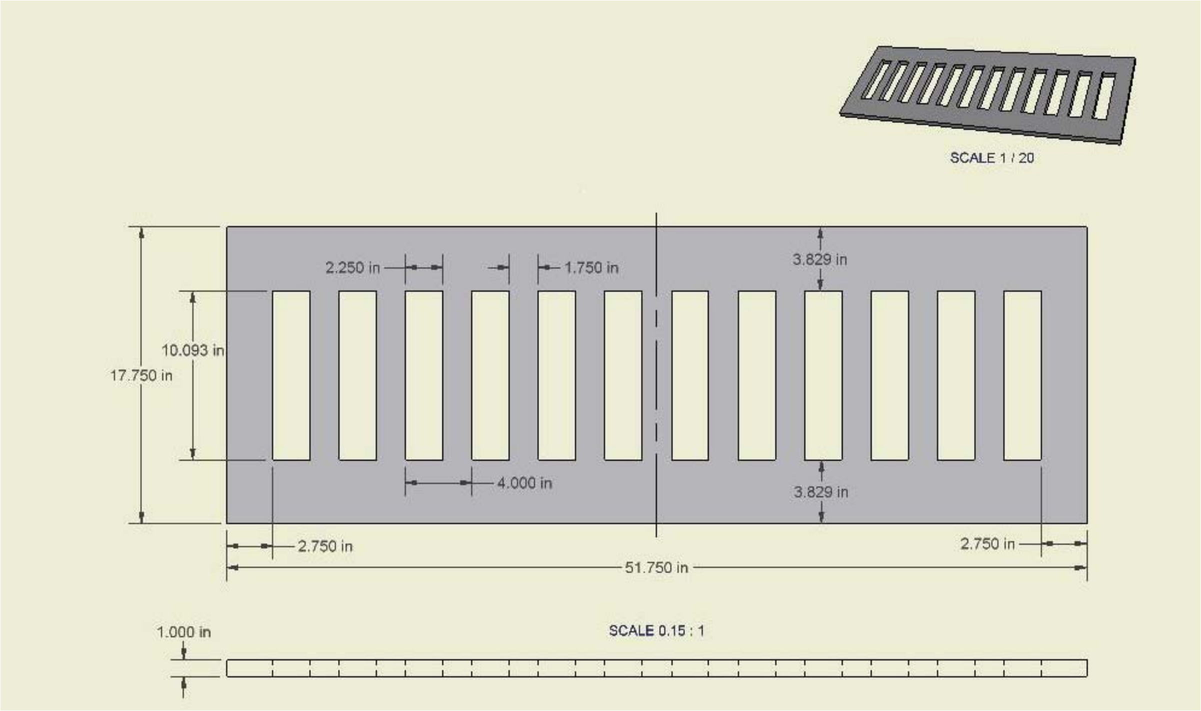


Figure 5.3. RCCS Tube Bottom Alignment Plate.

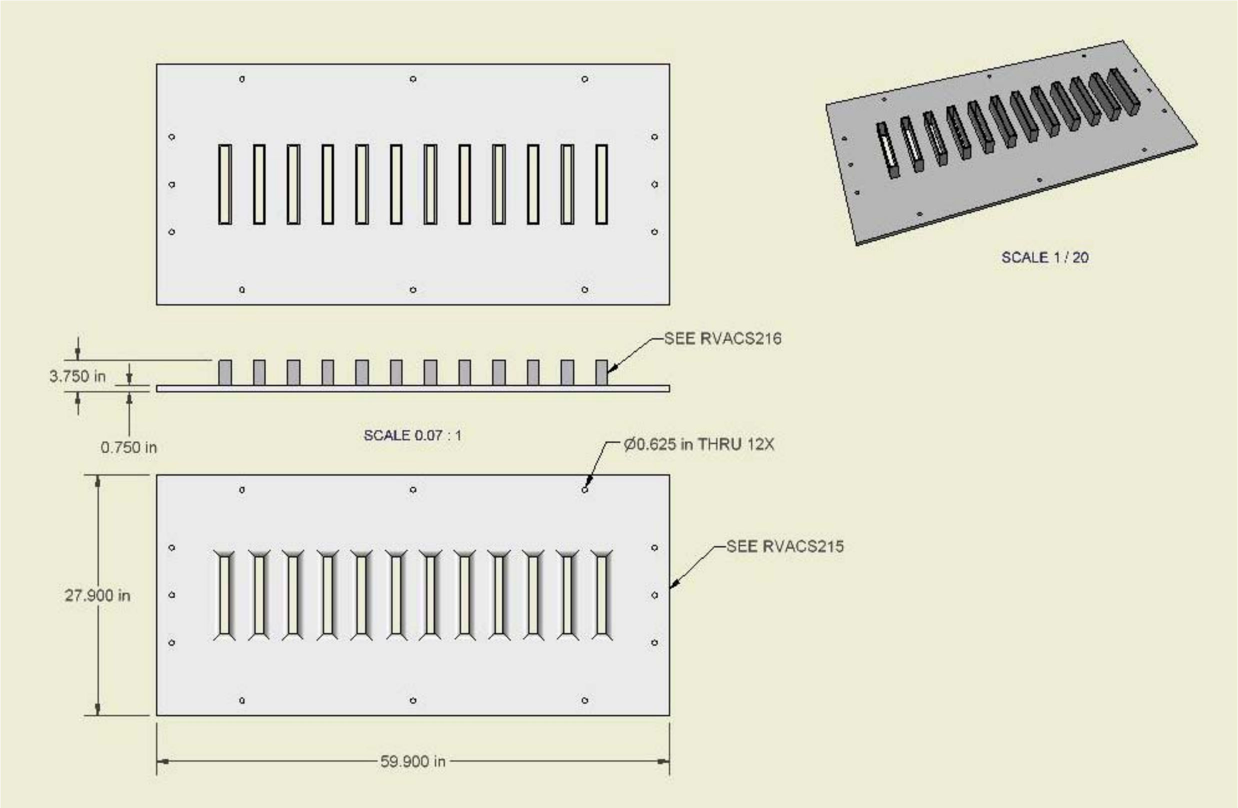
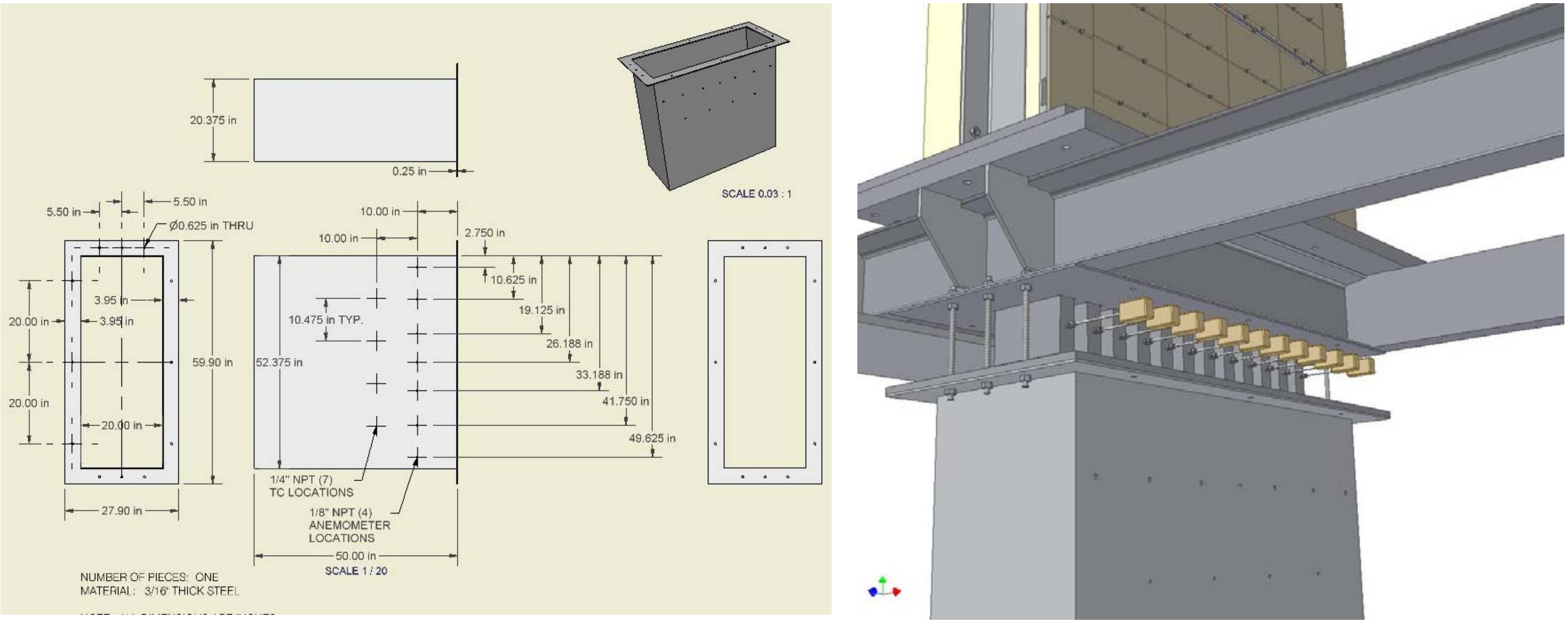


Figure 5.4. RCCS Tube Expansion Joint Assembly.



(a) (b)

Figure 5.5. (a) Fabrication Details of the Inlet Duct, and (b) 3-D Model Showing the Duct Mated to the Tube Expansion Joint.

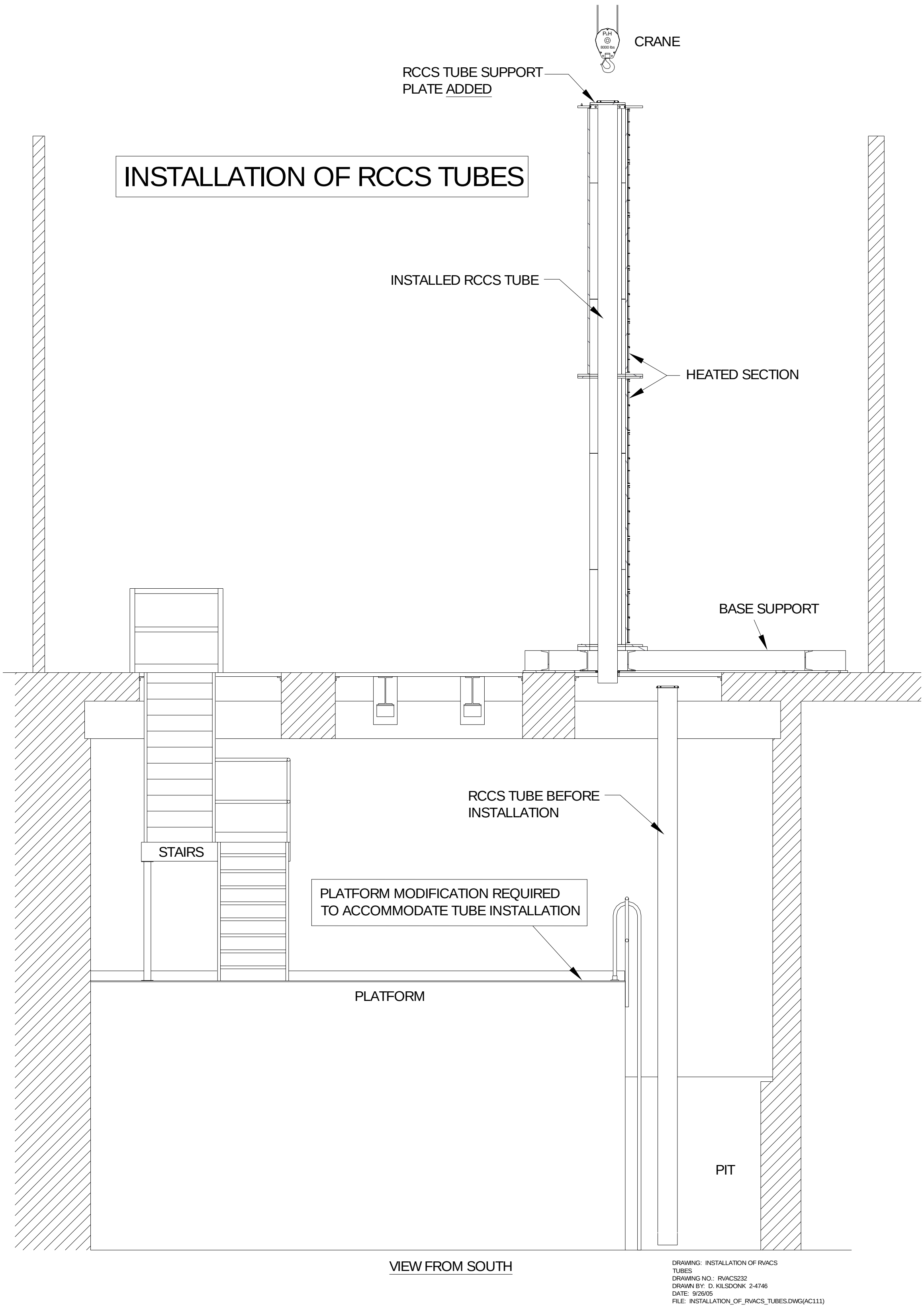


Figure 5.6. Approach for Installing RCCS Tubes in NSTF.

5.3 Heater Control System

The heater power control system will consist of 10 independent control units, one for each of the 10 axial heating zones of the heated test section length (see Table 2.1). As shown in Figure 5.7, power to each heater bank will be controlled using a single phase SCR power controller with phase angle firing. All controllers will be capable of providing soft starts, in addition to heater diagnostics and internal fusing for short circuit protection. The power controllers will receive commands from a PID (Proportional, Integral, Differential) loop controller than can follow either a time-based or a ramp-based program. Each PID controller will utilize a thermocouple as a reference device for temperature feedback control. The 10 PID controllers will be programmed and monitored using the DAS computer system. Heater voltage and current will be monitored at the power control unit; this data will be communicated back to the DAS computer.

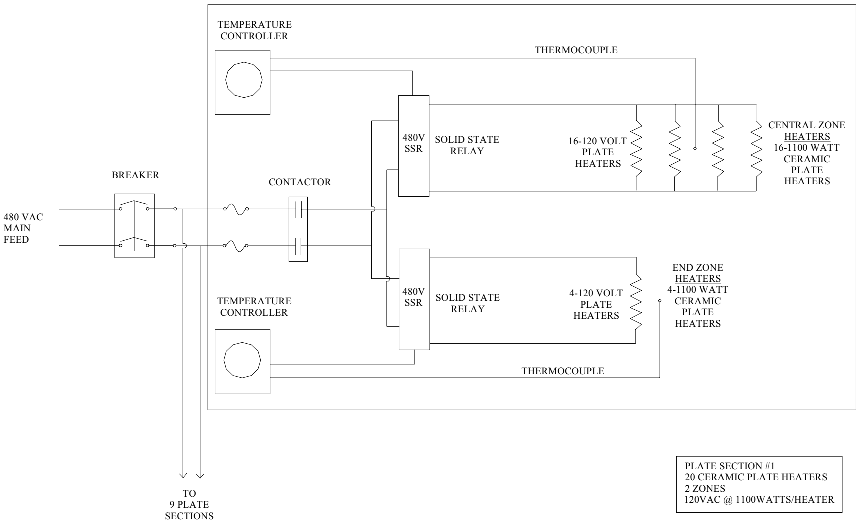


Figure 5.7. Schematic of Heater Power Control System.

5.5 Data Acquisition and Control

All data acquisition and process control tasks will be managed by a PC executing LabVIEW under a Windows operating environment. The computer will be linked to an SCXI chassis (National Instruments) that holds modules for signal conditioning, analogue to digital conversion, and switching. The first chassis slot will contain a 16-bit analogue to digital converter (ADC) with a maximum sampling rate of 200 kS/s and ability to multiplex up to 352 input channels. The unit has an input signal range of ±10 V. The ADC module controls the signal conditioning and switching modules within the chassis. The chassis will be located in the control room near the test section to minimize the length of instrument cabling and control signal noise. If required, a USB port will provide a digital link between the chassis and the computer if the separation distance exceeds 50 m, but this is unlikely.

Instrument output signals will be connected to SCXI-1102C signal conditioning modules. Each module has 32 input channels and provides cold-junction compensation for thermocouples. Each channel has a programmable gain amplifier and low-pass filter with a cutoff frequency of 10 kHz. For 4-20 mA signals, load resistors across the terminal block inputs are used to convert the current output to a voltage signal for the ADC. The input signal range for the SCXI-1102C is ±10 V.

A selected number of electrical devices will be controlled from the console using relay switches operated by LabVIEW. The relay modules have 16 SPDT electromechanical relays that can switch up to 2 A at 250 VAC. They are controlled by clicking on switches located on a process diagram created with LabVIEW. The relays are latched and so they maintain their state when the SCXI chassis is switched off or if there is loss of power in the control room.

5.4 Instrumentation

The approach for satisfying key RCCS data needs is summarized in Table 5.1. As is evident from the table, one of the most important requirements is to obtain data on the tube and channel wall axial and radial temperature distributions under prototypic flow conditions. As shown in Figures 2.8 and 2.9, both the heated and unheated channel walls of the test section are already highly instrumented to measure surface temperature distributions. By virtue of the heater power control system, the heat flux distribution on the heated wall will also be known. Finally, the test section is heavily insulated, so the unheated channel wall will essentially be adiabatic.

Aside from the channel walls, accurate knowledge of the RCCS tube surface temperature distributions is equally as important, since this information feeds directly into the evaluation of the local heat transfer coefficients, which is key information for code verification and validation. As shown in Figure 5.8, a central tube in the tube bank will be extensively instrumented to measure both the inner and outer surface temperatures on tube surfaces facing both the heated and unheated channel walls. As is evident by comparing Figure 5.8 with Figures 2.8 and 2.9, the elevations of the surface temperature thermocouples on the tube walls vertically align with the surface temperature measurement locations on both the heated and unheated channel walls. Moreover, the instrumented tube will be located such that the thermocouples are laterally aligned with one of the vertical arrays of thermocouples on the heated and unheated channel walls (i.e., at ± 15.2 cm from the channel vertical centerline; see Figures 2.8 and 2.9). Thus, at each axial elevation where thermocouples are located, the radial temperature profile across the channel will be completely known. This simplifies the evaluation of the convective heat transfer coefficient as a function of axial position.

The supporting analyses (see Section 4.0) indicate that it is also important to quantify surface temperature and heat flux distributions on tube surfaces that are perpendicular to the heated and unheated channel walls. As shown in Figure 5.8, the interior surfaces of the tube walls are similarly instrumented to measure surface temperatures at ~ 1 m axial increments. Tubes on both sides of the central, highly instrumented specimen are instrumented to check for reproducibility in the surface temperature data.

As is evident from Figure 5.8, the thermocouple layout for the central tube requires the measurement of inner and outer tube surface temperatures at 29 axial elevations on the tube surfaces facing both the heated and unheated channel walls. Thus, a total of 116 thermocouples must be installed in this critical component without significantly influencing the flow field. The approach for the installation procedure is illustrated in Figures 5.9 and 5.10. As is evident from these figures, the individual thermocouples are brought into the tube to their respective installation locations through small sheet metal conduits that are spot-welded in the four interior corners of the tube. The thermocouples are grounded junction, coaxial Type K units with a

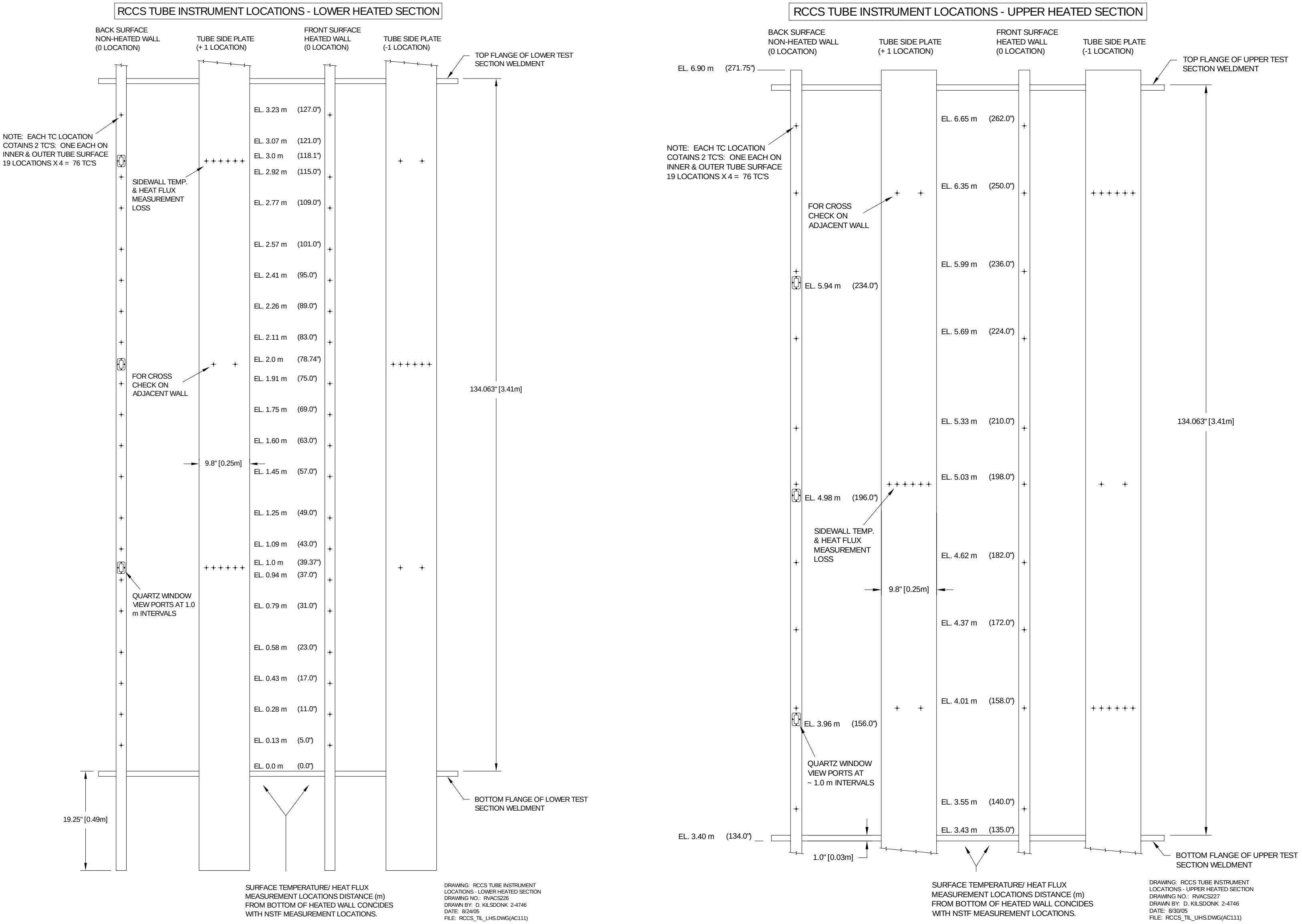
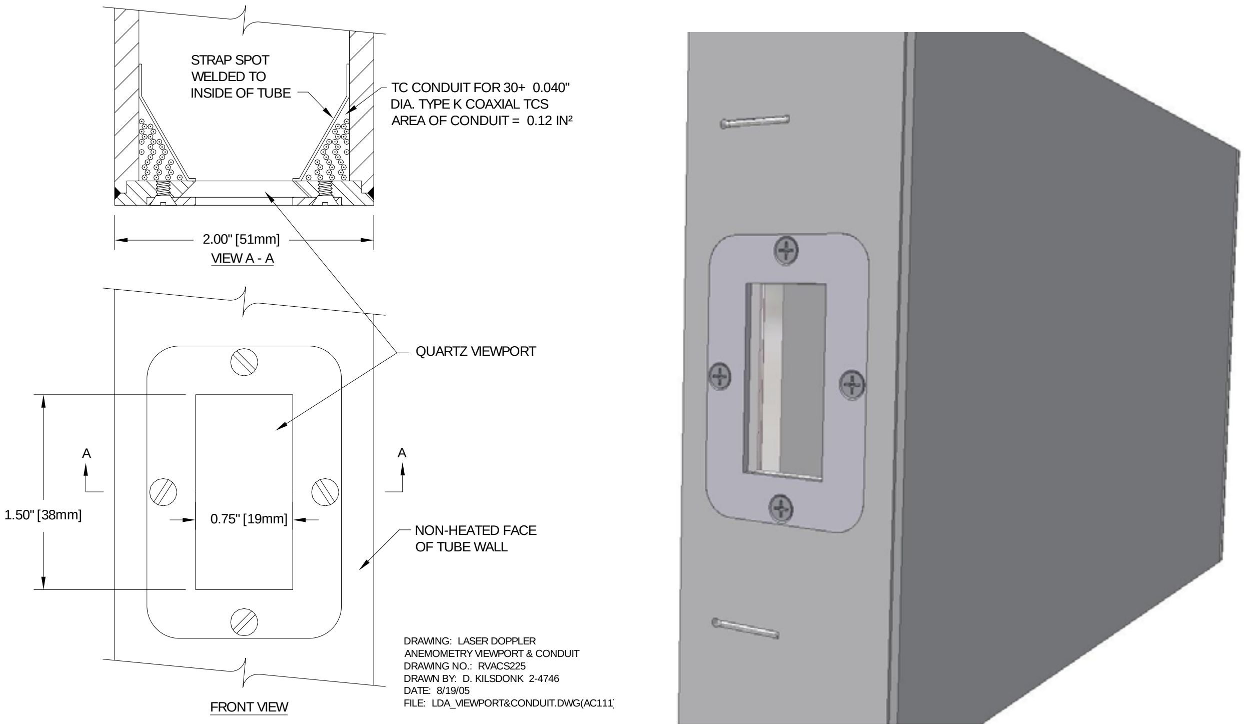


Figure 5.8. Tube Lower and Upper Section Thermocouple Locations.



(a) **(b)**

Figure 5.9. (a) Fabrication Details of the Thermocouple Conduit and LDA Viewports, and (b) 3-D Rendering Showing the Exterior View of the Viewport.

Figure 5.10. Tube Interior View Showing Thermocouple and Viewport Installation Details.

sheath diameter of no more than 1.0 mm. As indicated in the figure, the thermocouples are flush-mounted with the tube surface by placing them within a 1.05 mm wide by 1.05 mm deep recessements that are milled into the tube surface. Once the thermocouples are installed (i.e., spot-welded) into the recessments, the openings are back-filled flush with the tube surface with a high temperature potting cement. The thermocouple conduit sizes shown in Figures 5.9 and 5.10 can comfortably accommodate the 116 - 1.0 mm diameter thermocouples. Should this project move forward, then a few specimens will be fabricated to ensure that the installation procedure is viable, and also to explore the possibility of utilizing small diameter thermocouples for the surface temperature measurements. If the latter testing is successful, then the conduit size shown in Figures 5.9 and 5.10 could be reduced even further in the actual test specimen.

As shown in Table 5.1, the third key data requirement for the experiments is to obtain surface heat flux measurements at various points along the tube surface under prototypic RCCS flow conditions. As indicated earlier, measurements of both the interior and exterior surface temperatures will be obtained at each thermocouple location shown in Figure 5.9. With this data, local surface heat fluxes can also be estimated using standard inverse heat conduction techniques. However, the tube wall thickness (based on the GA GT-MHR design[3]) is only 4.8 mm. Thus, the 1.0 mm thermocouple diameter constitutes a significant fraction (viz. ~ 21 %) of the junction separation distance. Thus, the uncertainty in the heat flux measurements will be large due to the close proximity of the thermocouple junctions. As a result, a specialized calibration technique will need to be developed to measure the local thermal conductance (i.e., k/δ) at each two-unit junction location. Although the details remain to be worked out, it is envisioned that the calibration technique would consist of applying a surface heat flux at the thermocouple location with a plate heater, and measuring the actual heat flux with a heat flux meter with NIST-traceable calibration. Given the known heat flux and the measured temperature gradient, the effective conductance at the TC location can then be evaluated. This effective conductance would then be used to evaluate the actual surface heat flux from the temperature gradient data obtained during the tests.

As shown in Table 5.1, the fourth key data requirement is to obtain data on the tube bulk gas velocity and temperature distributions under prototypic RCCS flow conditions. The planned approach for satisfying this need is to utilize insertable hot wire anemometers with co-located, radiation-shielded, thermocouples to measure bulk gas velocity and gas temperature distributions at ~ 1 meter axial increments along the heated tube length. However, initial contacts with reputable vendors for these types of probes (e.g., Dantec) indicate that the large temperature gradient across the radial extent of the tubes (a few hundred ˚C) will introduce large measurement uncertainties in the gas velocity measurements. Although it may be possible to develop a temperature compensation system for these probes, it is not clear at the current time that anemometry will work for measuring velocity distributions across the tube. Thus, the backup instrument for this measurement is an insertable Pitot-static tube with a co-located, radiation-shielded thermocouple for measurement of the bulk gas temperature distribution.

As shown in Table 5.1, the fifth key data requirement is to obtain turbulence data as a function of axial position within RCCS tubes. The approach for producing this data is to provide viewports through the channel and tube walls at 1 meter axial increments so that turbulence measurements can be obtained using visualization techniques. The specific objectives of this difficult task are as follows:

1. Utilize Laser Doppler Anemometry (LDA) to obtain distributions of instantaneous velocity profiles at various axial elevations within tubes that have been added to the NSTF to mock up the RCCS air coolant tubes.
2. From the instantaneous velocity profile data, develop distributions of mean velocities and Reynolds shear stresses that are required to validate the CFD turbulence models.

As shown in Figures 5.8 through 5.10, the LDA measurements will be made through specially designed co-axial quartz windows that provide visual access inside the RCCS tubes at a total of six axial elevations while the NSTF is at operational conditions. At each axial elevation, two quartz windows will be provided; one through the non-heated guard vessel wall of NSTF, and a second mounted on the RCCS tube. These windows will be designed with the objective that the LDA will be able to obtain transverse measurements of the instantaneous velocity distributions with the surface target distance being ~ 1y+.

Aside from the above instruments that are intended to directly address the key data needs, other instruments will be provided to fully document the test conditions and help guide experiment operations. Total air flowrate through the test section will be evaluated from a total of seven transverse velocity measurements across the inlet duct using the standard log-linear method (accuracy: ± 3%). General purpose anemometers will be used for the purposes of this measurement. In addition, the inlet air velocity will be measured at the centerline of each of the twelve RCCS tubes to verify that the flow distribution across the tube bank is uniform (see Figure 5.5 (b)).

Bulk gas temperatures at the duct inlet and at the heated section exit will be measured using four radiation shielded thermocouples at each location. Thus, the integral heat removal by the RCCS tubes can be determined by the overall air mass flowrate measurement (described above) and the bulk gas temperature rise measured across the heated test section length. Static pressure at the duct inlet will be measured using an absolute pressure transducer, while pressure drop across various sections of the apparatus will be measured with differential pressure transducers. Tube displacement at elevated temperatures will be measured at each LDA viewport location using Linear Voltage Displacement Transducers (LVDTs). Atmospheric conditions that may affect system integral heat removal rate (i.e., humidity, wind direction, and speed) will be monitored during the course of each test.

6.0 COST AND SCHEDULE FOR FACILITY MODIFICATIONS

In the previous sections of this report, an overall high-level plan has been developed for mechanical, electrical, instrumentation, data acquisition, and control system modifications to NSTF in order to supply the data needed to adequately qualify both CFD and system-level codes for application to the VHTR air RCCS under both PCC and DCC event sequences. The purpose of this section is to provide a cost and schedule for carrying out this work. These estimates factor in the design and planning work that has already be accomplished and documented in this report. Note that these estimates are laboratory related; i.e., they do not cover companion code validation and analysis activities that will be carried out in tandem with this work. Cost and schedule estimates for the analysis tasks are documented elsewhere.

A summary of key tasks associated with modification of NSTF to meet the VHTR air RCCS data needs is provided in Table 6.1, along with a timeline for completion of each task. For reference, an outline of the overall workscope that provides additional details is provided in Appendix A.

As shown in Table 6.1, the first task is to obtain the necessary laboratory ES&H approvals to initiate the work. This includes preparation and submittal of National Environmental Protection Act (NEPA) documentation, as well as a safety plan for covering the laboratory efforts. The key deliverables from this task are DOE and laboratory approvals to initiate testing in the facility.

Task 2 consists of preparation of a Quality Assurance (QA) plan for the program. This plan will be developed in close collaboration with INL to ensure that the results produced by the project will meet the end-user needs and requirements. The key deliverable from this stage of the work will be a Program QA Plan that is approved by both INL and ANL laboratory and project management.

Task 3 consists of development of a facility test plan. This work covers the development of final designs for the facility mechanical, electrical, instrumentation, data acquisition, and control systems, as well as the supporting fabrication drawings and equipment specifications that are required for procurement. From the mechanical viewpoint, this includes the fabrication of the both the instrumented and dummy RCCS tubes, as well as the tube support and bracing structure within NSTF. The instrumentation plan for measuring flowrates, temperatures, pressures, surface emissivities, and turbulence characteristics at key locations throughout the system will be finalized. Design and specifications for the electrical system for controlling and monitoring of the duct wall heaters will also be completed. Finally, general operating procedures for the facility will be developed, from cold shakedown testing to hot startup. The key deliverable from this stage of the work will be an approved facility test plan.

Task 4 covers the key area of experiment planning. Laboratory personnel will collaborate with analysts and data end-users at INL, ANL, and industry to identify key RCCS conditions and data ranges expected during both PCC and DCC event sequences for potential VHTR air-RCCS designs. Based on this input, a test matrix and test operating procedures will be developed that will generate the data needed for code verification and validation. The key deliverable from this stage of the work will be an experiment test matrix planning report.

Table 6.1. Schedule for Completion of Key Tasks.

No.	Task	Time from Project Initiation																							
		Year 1												Year 2											
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	Obtain ES&H Approvals to Initiate Laboratory Work	├	─	─	─	◆																			
2	Develop Program QA Plan	├	─	◆																					
3	Develop Facility Test Plan	├	─	─	─	─	◆																		
4	Develop Test Matrix			├	─	─	─	─	─	◆															
5	Prepare Test Area	├	─	─	◆																				
6	Acquire Key Equipment and Services for Facility Modifications	├	─	─	─	─	─	─	─	─	─	─	─	─	◆										
7	Prepare Test Facility				├	─	─	─	─	─	─	─	─	─	─	─	─	─	◆						
8	Conduct Facility Shakedown Testing																├	─	─	─	◆				
9	Initiate Testing According to Task 4 Plan																				├	─	─	─	◆

The balance of the tasks shown in Table 6.1 cover the laboratory efforts required to bring the facility up to an operational stage and to begin the conduct of tests identified under Task 4. Progress during these various stages of work will be documented in the form of monthly progress reports to the sponsor. Task 5 covers preparation of the laboratory space where the facility resides. The high bay area will be cleaned and surplus items will be disposed of. The lighting in the upper loft area will be upgraded to facilitate the work. The lab space will be painted to make it presentable. Ladders will be brought up to current OHSA standards. Similar cleaning and repair activities will be conducted in the facility control room.

Once the lab space is updated, modifications to the facility will be initiated. This includes the procurement of services and equipment for conducting the work (Task 6), as well as the revisions to the facility itself (Task 7). The key steps in the mechanical modifications to the facility consist of:

a) removal of insulation from the two heated test sections to facilitate work,
b) removal and disposal of the existing (30 cm) inlet plenum,
c) removal of test section non-heated duct wall plates,
d) machining of the non-heated plates to receive new instruments for flow characterization (LDA viewports, and anemometer, emissivity, and displacement transducer access ports),
e) machining modifications to test assembly to gain access and to attach the tube upper support plate,
f) manufacture and instrumenting the RCCS tubes,
g) installation of tubes in the test assembly,
h) installation of stud extenders and insulation to expand channel width to 46 cm,
i) installation of the modified non-heated duct wall plates,
j) checkout of all thermocouples and heaters after reassembly,
k) installation of the lower tube guide plate, and finally
l) installation of the new inlet plenum ductwork.

With these steps completed, instruments will be installed and wired into the Data Acquisition System (DAS) according to the Test Plan.

In parallel with this work, the test section heaters will be wired to the heater temperature controllers, relays, and contactors. The associated power monitoring instruments will be wired into the DAS. This work will include rewiring the heater power feeds from the control room into the relay racks in the high bay.

With these steps completed, Task 8 (facility shakedown testing) will be initiated. This work will include checkout of the controllers and heaters for proper operations under low-power conditions (heater temperatures < 150 ˚C). Flow measurement devices will be checked out at room temperature using the fan loft to provide test section ΔP. After these steps are completed, the facility will be brought up to conduct initial low power testing (heater temperatures ~150 ˚C) to verify proper integral operation.

With these steps completed, actual data generation will be initiated according to the test matrix developed under Task 4 of the overall workscope.

A summary of the overall costs associated with carrying out this work is provided in Table 6.2. In terms of staff, the project is assumed to consist of a Principal Investigator who is in charge of the overseeing the overall workscope, reporting, and for developing the project documentation shown in Tasks 1-4. The PI is assumed to be covered at a level of 50 % on the project. In addition, there will be a Lead Experimenter who is in charge of overall laboratory activities. The Lead Experimenter must be covered full time on this project. In addition, two Test Engineers are required to carry out the workscope: one in charge of the mechanical systems, and the other in charge of electrical/instrumentation systems. Both Test Engineers are assumed to be covered at a level of 75 % on the project. Thus, the overall staff effort required to carry out the work is estimated to be 3.5 Full Time Equivalents (FTEs). Aside from staff, laboratory technicians are needed at a level equivalent to 1.5 FTEs. One effort-intensive element of this work is to set up and carry out the LDA turbulence measurements that are deemed to be very important insofar as providing CFD code qualification data. To minimize the impact on project costs, it is assumed for budgeting purposes that a PhD graduate student will take the lead on this aspect of the work, under the direct supervision of the Lead Experimenter.

Costs associated with the effort described above are shown in Table 6.2. The effort rates are based on those within the Nuclear Engineering (NE) division at ANL. The rates are those projected for FY07-08 based on current rates within the division assuming a 4% rate of inflation. Aside from effort, Materials and Services (M&S) are required to carry out the work at the level shown in Table 6.2. These estimates include all laboratory overhead and taxes. The detailed breakdown of the M&S distribution is provided in Appendix A.

The total cost to modify the facility and to begin generating prototypic code qualification data for the VHTR air RCCS is estimated as 3070 K$. Of this total estimate, the estimate for conducting shakedown testing and performing experiments for the first six month period after startup is included as ~ 700 K$. Note that this is cost is for fully instrumented high-fidelity experiments. The overall cost could of the work could be reduced by ~ 300 K$ if the LDA turbulence measurements are omitted from the overall workscope.

Table 6.2. Estimated Costs for the Proposed Workscope.

Project Year	**Staff Effort**		**Tech Effort**		**M&S (K$)**	**Total (K$)**
	FTE	**Cost (K$)**	**FTE**	**Cost (K$)**		
1	3.0	920	1.5	340	400.0	1660
2	3.0	960	1.5	350	100.0	1410
Total		1880		690	500	3070

7.0 SUMMARY AND CONCLUSIONS

An engineering plan for mechanical and instrumentation modifications to the Natural Convection Shutdown Heat Removal Test Facility (NSTF) at Argonne National Laboratory has been developed to meet key VHTR air RCCS data needs. The specific objectives of the experiment planning process were as follows:

1. provide CFD and system-level code development and validation data for the VHTR RCCS under prototypic (full-scale) natural convection flow conditions, and

2. support RCCS design validation and optimization activities.

Companion analysis activities carried out to support the experiment planning indicate that: (a) strong 3-D effects in the RCCS result in large heat flux, temperature, and heat transfer variations around the tube wall; (b) there is a large difference in the heat transfer coefficient predicted by turbulence models and heat transfer correlations, which underscores the need for experimental work to validate the thermal performance of the RCCS; and (c) tests at the NSTF would embody all important fluid flow and heat transfer phenomena in the RCCS, in addition to covering the entire parameter ranges that characterize these phenomena.

8.0 REFERENCES

1. C. P. Tzanos, “CFD Analysis for the Applicability of the Natural Convection Shutdown Heat Removal Test Facility (NSTF) for the Simulation of the VHTR RCCS,” ANL-Gen IV-055, September 2005.

2. R. B. Vilim and E. E. Feldman, “Scalability of the Natural Convection Shutdown Heat Removal Test Facility (NSTF) Data for VHTR RCCS Designs,” ANL-Gen IV-049, June 2005.

3. Gas Turbine-Modular Helium Reactor (GT-MHR) Conceptual Design Description Report, Rev. 1, GA Project No 7658, General Atomics, San Diego, CA (1996).

APPENDIX A
NSTF FACILITY MODIFICATION PLAN

1. **Obtain Laboratory and DOE ES&H Approvals:**

   a. Prepare and submit National Environmental Protection Act (NEPA) documentation.

   b. Prepare and submit Laboratory Activity Data Document (LADD) and safety plan for Experiment Review Committee (ERC) review and approval.

   Deliverable(s): DOE/ANL approvals to initiate laboratory work

2. **QA Program Plan**

   a. Work collaboratively with INL to develop a QA program plan

   Deliverable(s): QA program plan

3. **Facility Test Plan**

   a. Finalize mechanical plan and develop supporting fabrication drawings for modifying NSTF to accommodate RCCS tubes, including tube support and bracing structure, as well as mechanical modifications required to install instruments.

   b. Develop detailed instrumentation plan for measuring flowrates, temperatures, pressures, surface emissivities, and turbulence characteristics at key locations throughout the system.

   c. Develop detailed electrical plan for operation, control, and monitoring of duct wall heaters.

   d. Develop detailed data acquisition and control strategy.

   e. Develop general operating procedures (cold shakedown testing and hot startup).

   Deliverable(s): Facility test plan report

4. **Experiment Planning**

   a. Collaborate with analysts and data end-users at INL and ANL to identify key RCCS conditions and data ranges expected during both PCC and DCC event sequences for potential VHTR air-RCCS designs.

   b. Develop a test matrix and companion facility operating procedures that will generate the data needed for code verification and validation.

   Deliverable(s): Experiment test matrix planning report

5. **Test Area Preparations:**

   Deliverable(s): Progress on test area preparations described below will be documented in the form of monthly progress reports to the sponsor.

   a. High bay area:

    - i. Remove and dispose of old equipment and surplus insulation from loft.
    - ii. Clean area thoroughly.
    - iii. Replace light bulbs in upper structure and have double-headed spot lights installed on railing to increase lighting level.
    - iv. Paint walls and structures as appropriate.
    - v. Have ladders brought up to OHSA standards (covered by PFS).
    - vi. Paint the exterior facility chimney extending above the building roof.
    - vii. Fix exterior wall insulation that is falling down in the upper areas of the bay.
- b. Control room:
    - i. Remove and store RF generator
    - ii. Remove existing floor tile
    - iii. Clean area thoroughly
    - iv. Paint walls and ceiling
    - v. Install new floor tile
    - vi. Have roof checked for leaks and patched accordingly by PFS

6. **Manufacture/Acquire Key Equipment and Services for Facility Modification**

- a. Machine Shop Services (136.5 K$)
    - i. Instrumented and dummy RCCS tubes (50 K$).
    - ii. Upper tube support structure plate, including *in-situ* modifications for attaching plate to test section (10K$).
    - iii. Lower tube guide plate (3K$).
    - iv. Inlet plenum ductwork (1.5 K$)
    - v. Machine upper and lower unheated duct walls to receive instruments (LDA, anemometer, and displacement potentiometer access ports). (12 K$)
    - vi. Miscellaneous machining, welding, and glass shop services (60 K$).
- b. Instrumentation (242.2 K$)
    - i. Thermocouples for instrumenting tube walls (10 K$).
    - ii. Procure LDA system, including dedicated PC, software, seeding equipment, and alignment hardware (150 K$).
    - iii. Pressure transducers (Rosemount; 5 @ 2 K$/ea. = 10 K$).

    iv. Anemometers for tube inlet velocity characterization and bulk flow velocity measurement (18 @ 0.8 K ea. 15 K$).
    v. Anemometers for tube transverse velocity/temperature measurement and turbulence characterization (8 @ 2 K ea. = 16 K$).
    vi. Traversing system for anemometers (15 K$)
    vii. Bench top NIST-traceable reference for anemometer calibration (10 K$).
    viii. Linear displacement potentiometers for measurement of RCCS tube radial location (6 @ 0.2 K$ ea. = 1.2 K$).
    ix. Power measurement instruments (5 K$)
    x. Miscellaneous (thermocouples; humidity, barometric pressure, wind direction sensors) (10 K$).

c. Data Acquisition and Control (19.5 K$)
    i. Dedicated PC for DAQ (2.0 K$).
    ii. DAQ cards, Multiplexers, SCXI chassis, switch modules (300 Channel capacity) (10.0 K$)
    iii. Dedicated LABView license for facility; professional version (2.5 K$)
    iv. Equipment console (3 bay) (5.0 K$)

d. Heater Power Control System (9.0 K$)
    i. Temperature controllers (11 @ 0.3 K$ = 3.3 K$)
    ii. 50 Amp solid state relays (SSRs) (11 @ 0.15 K$ = 1.6 K$)
    iii. Contactors (11 @ 0.1 K$ = 1.1 K$).
    iv. Relay Racks (3 K$)

e. Miscellaneous (61.0 K$)
    i. Waste disposal (3.0 K$)
    ii. Electrical (lighting & electric power services) (5.0 K$)
    iii. Painting services (8.0 K$)
    iv. Insulation removal/disposal (WMO) (15.0 K$)
    v. Scaffolding/lift for routine work on test assembly (20.0 K$)
    vi. Insulation for facility (10.0 K$)

7. Test Facility Preparations:

Deliverable(s): Progress on facility preparations described below will be documented in the form of monthly progress reports to the sponsor.

a. Remove insulation from the two heated test sections, and also on the unheated side of the transition duct to prepare for the access door for installation of the RCCS tubes (WMO contract).

b. Remove and dispose of the existing (12”) inlet plenum.

c. After insulation is removed, check out heated sidewalls as follows:

    i. Check heaters electrically (continuity, resistance) and verify that the mechanical attachments are still in good shape.

    ii. Check thermocouples for proper operation and installation.

d. Modify non-heated duct wall plates to receive instrumentation for RCCS testing:

    i. Label/roll back thermocouples to plate wall.

    ii. Remove the plates with cell crane (requires design and qualification of a lifting jig for removal of plates with support structure in place; design developed as part of Step 3.a.)

    iii. Transfer the plates to Central Shops for machining of instrument access ports.

    iv. Once the plates are received back from Central Shops, check thermocouples for proper operation.

e. Fabricate instrumented RCCS tubes in preparation for installation:

    i. Install and pot surface temperature thermocouples. Once the thermocouples are installed, weld the units together to produce the finalized RCCS tube configuration.

    ii. Evaluate the effective thermal conductance (k/δ) at each TC location to be used for local heat flux evaluation using an insulated plate heater and a traceable heat flux probe. Apply a known heat flux (~10 kW/m^2), measure the temperature gradient at the position, and from this data evaluate the conductance.

    iii. Install LDA viewports.

f. Install RCCS tube simulators in NSTF:

    i. Cut access door in transition duct to facilitate tube installation.

    ii. Machine blind holes in upper heated section flange for attaching the upper tube support plate.

    iii. Install and secure tube upper support plate.

    iv. Install and secure 12 RCCS tubes to upper support plate.

    v. Install lower tube guide plate.

    vi. Reinstall access door in transition duct.

g. Install inlet plenum ductwork.

h. Re-Install non-heated duct walls.

    i. Install stud extenders and insulation to expand channel width to 46 cm.

    ii. Reinstall and secure non-heated duct walls on the test section.

i. Re-insulate upper and lower test section components.

j. Heater power controllers:

    i. Install and wire up heater temperature controllers, relays, and contactors, and wire these units into the DAQ switching chassis.

    ii. Rewire power feeds from the control room into the relay racks in the high bay.

k. Instrumentation-Install instruments according to the test plan in the various locations and wire the instruments into the DAQ.

8. Conduct Facility Shakedown Testing.

Deliverable(s): Progress on shakedown testing will be documented in the form of monthly progress reports to the sponsor.

a. Checkout controllers/heaters for proper operations under low-power conditions (T < 150 ˚C).

b. Check instruments under room temperature conditions using fan loft to provide test section ΔP.

c. Conduct initial low power testing (heater temperatures ~150 ˚C) to verify proper facility integral operation.

9.0 Initiate Testing According to Plan Developed Under Step 4.0.

Argonne
NATIONAL LABORATORY

Nuclear Engineering Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 208
Argonne, IL 60439-4842

www.anl.gov

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