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ENGINEERING SERVICES FOR THE NEXT GENERATION NUCLEAR PLANT (NGNP) WITH HYDROGEN PRODUCTION

Test Plan for the Reactor Cavity Cooling System

Prepared by General Atomics
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ACRONYMS AND ABBREVIATIONS

AFR	Advanced Fuel Research
ANL	Argonne National laboratory
CFD	Computational Fluid Dynamics
DAS	Data Acquisition System
DDN	Design Data Need
FT-IR	Fourier Transform - Infrared
GA	General Atomics
GE PRISM RVACS	General Electric PRISM Reactor Vessel Auxiliary Cooling System
GT-MHR	Gas Turbine – Modular Helium Reactor
NGNP	Next Generation Nuclear Plant
NSTF	Natural Convection Shutdown Heat Removal Facility
PCS	Primary Cooling System
RCCS	Reactor Cavity Cooling System
SCS	Shutdown Cooling System
TBD	To Be Determined
TRL	Technical Readiness Level

1 INTRODUCTION

The primary functions of the Reactor Cavity Cooling System (RCCS) are to protect the concrete structure surrounding the reactor vessel from overheating during all modes of operation and to provide alternate means of removing reactor heat when neither the Primary Cooling System (PCS) nor the Shutdown Cooling System (SCS) is available. In addition, the RCCS cooling panels form part of the barrier that separates the ambient atmosphere from the reactor cavity atmosphere. Figure 1 presents a schematic representation of the RCCS.

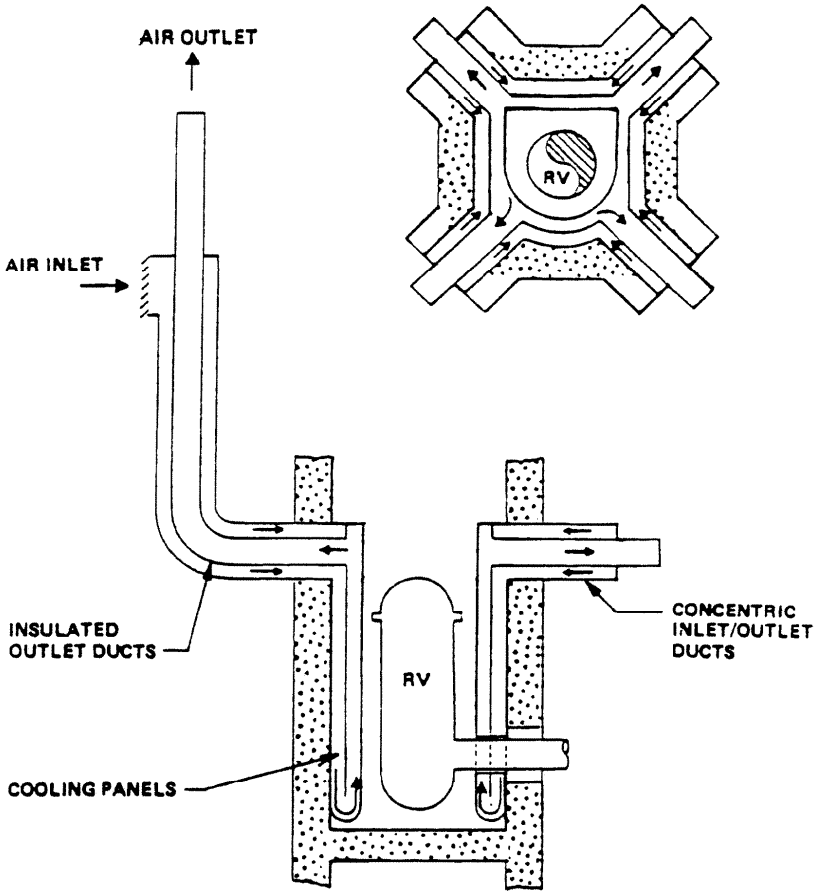

Figure 1. Schematic Representation of RCCS

1.1 Scope

The scope of the RCCS Test Plan is to address all technical issues that require developmental and confirmatory testing. The identified technical issues include:

1. Emissive testing for the RCCS vessel and wall cooling panels to confirm emissivity value assumptions and optimize heat transfer capability.

2. Wind tunnel testing of a scale model RCCS system/facility to verify acceptable natural draft stack performance and to determine acceptable height.

3. Determine heat transfer coefficient and friction factors for the RCCS cooling panel hot risers specific geometry and operating conditions.

4. A full-scale test of the RCCS system to demonstrate the RCCS passive cooling function.

1.2 Purpose

Develop a RCCS Test Plan that will address the identified technical issues. The test plan will address items 1: RCCS cooling panel emissivity raise this RCCS component from a Technical Readiness Level (TRL) 4 to a TRL 5. To address item 2, scale model wind tunnel testing will be completed to verify acceptable stack performance and raise the TRL from 5 to 6. Item 3, cooling panel heat transfer heat transfer coefficients and friction factors, will be completed to raise this subsystem of the RCCS from a TRL 6 to TRL 7. To address item 4, an integrated precommissioning test of the NGNP RCCS system may be completed during the startup and commissioning operations of the NGNP to raise the NGNP RCCS system from TRL 7 to TRL 8.

Action required to raise the TRL from 4 to 5 is as follows:

> Perform emissivity testing of vessel and wall cooling panel materials and complete detailed modeling of vessel wall and wall cooling panel elements.

TRL 5 is achieved for this system after all test data have been obtained and detailed modeling has been performed for the vessel and wall cooling panels, and wind tunnel testing of the RCCS I/O structure to satisfy DDNs C.16.00.01, and C.16.00.02.

Action required to raise the TRL from 5 to 6 is as follows:

> Perform wind tunnel testing and detailed computational fluid dynamics (CFD) modeling of the RCCS performance under the test conditions.

Actions required to raise the TRL from 6 to 7 are as follows:

1. Perform test to determine the heat transfer and friction factors for the RCCS cooling panel hot risers specific geometry and operating conditions.

2. Perform thermal and CFD analysis using the test data obtained in item 1, to verify RCCS performance under the test conditions.

TRL 7 is achieved for this system after all integral test data have been obtained and detailed modeling has been performed to satisfy DDNs C.16.01.04.

To raise the TRL from 7 to 8, instrumented tests shall be peformed as part of NGNP startup testing to confirm combined radiation and conduction within the graphite core, natural convection and circulation within the primary coolant loop, combined convection and radiation between the core barrel and reactor vessel and the combined radiation and natural convection in the reactor cavity between the reactor vessel. TRL 8 is achieved for this system after all integral test data have been obtained and detailed modeling has been performed to satisfy DDN C.16.00.03.

Table 1 summarizes the test objectives and cross references the test objectives with the Test Title, Test Section and GA, GT-MHR DDN which must be completed to attain the Test Objective.

Table 1. Test Objective Summary

Test Objective	Test Title	Test Section	GA, GT-MHR, DDN #
Raise the TRL from 4 to TRL 5	Emissivity of RCCS Panel Surfaces	3	C.16.00.01
Raise the TRL from 5 to TRL 6	Wind Tunnel Testing of Scale Model RCCS I/O Structure	4	C.16.00.02
Raise the TRL from 6 to TRL 7	RCCS Cooling Panel Heat Transfer and Friction Factor and Integrated Test	5	C.16.00.04 and C.16.00.03
Raise the TRL from 7 to TRL 8	Integrated RCCS Performance	6	C.16.00.03

1.3 Background

Thermal-hydraulic analysis of the RCCS has been performed through computer modeling of heat transport and natural circulation phenomena that drive the system operation. Several of the key physical processes and components that support the passive nature of the system require testing to confirm hardware performance or to extend an existing data base to the NGNP conditions to reduce uncertainty in the design.

Design basis calculations for the RCCS utilize an emissivity value of 0.8 for the RCCS tube surfaces when determining vessel cooling capability. The RCCS panel fabrication will yield a surface finish which will provide a higher emissivity value.

The current stack design is a concentric stack within a stack design with elevated intake and exhaust. This arrangement minimizes the effect of wind speeds and directions in stack performance by elevating the stack intake and exhausts above the point where the local site structures have a significant effect on the wind flow boundary layer. The stack height must be optimized to an acceptable minimum elevation.

The current integrated system performance is based upon calculated component and system performances and supplemented by component tests. The integrated system test allows testing of the system at the design basis heat load and conduction cooldown heat input prior to constructing the actual plant.

Initial emissivity testing can be completed at an independent laboratory. Wind tunnel testing may also be completed at an independent wind tunnel facility, either commercial or academic facility. To complete the heat transfer and friction factor testing as well as the integrated RCCS test, the Natural Convection Shutdown Heat Removal Facility (NSTF) located at Argonne

National Laboratory (ANL) provides an ideal testing facility. Additional emissivity testing may also be completed at the NSTF facility.

2 APPLICABLE DOCUMENTS

Preconceptual Engineering Services for the Next Generation Nuclear Plant (NGNP) With Hydrogen Production NGNP Umbrella Technology Development Plan, GA Project 30283, July 10, 2007, PC-000543 Revision 0, Subcontract 00060845

Topical Report: Natural Convection Cooling Shutdown Heat Removal Test Facility (NSTF) Evaluation for Generating Additional Reactor Cavity Cooling System (RCCS) Data, ANL-GenIV-058, September 2005

600 MW(t) Turbine-Modular Helium Reactor Design Data Needs DOE-GT-MHR-1000217 (Draft), July 1994, GA Project 6302, DOE Contract DE-AC03-89-SF17885

Design Data Needs Modular High Temperature Gas Cooled Reactor, DOE-HTGR-86025 Revision 4, October 1989, GA project 6300, DOE Contract DE-AC03-89SF17885

3 TRL 4 TO 5 THERMAL TRANSFER DATA TESTING

3.1 Emissivity of RCCS Panel Surfaces Test, DDN C.16.00.01

3.1.1 Test Objective

The cooling panel emissivity is a key parameter with respect to the RCCS decay heat removal. A predictable and reasonably uniform emissivity is necessary to support the decay heat removal analysis. Adequate panel emissivity is not available for candidate materials for the service conditions identified. Figure 2 below presents the layout of the RCCS cooling panel and downcomer within the reactor cavity.

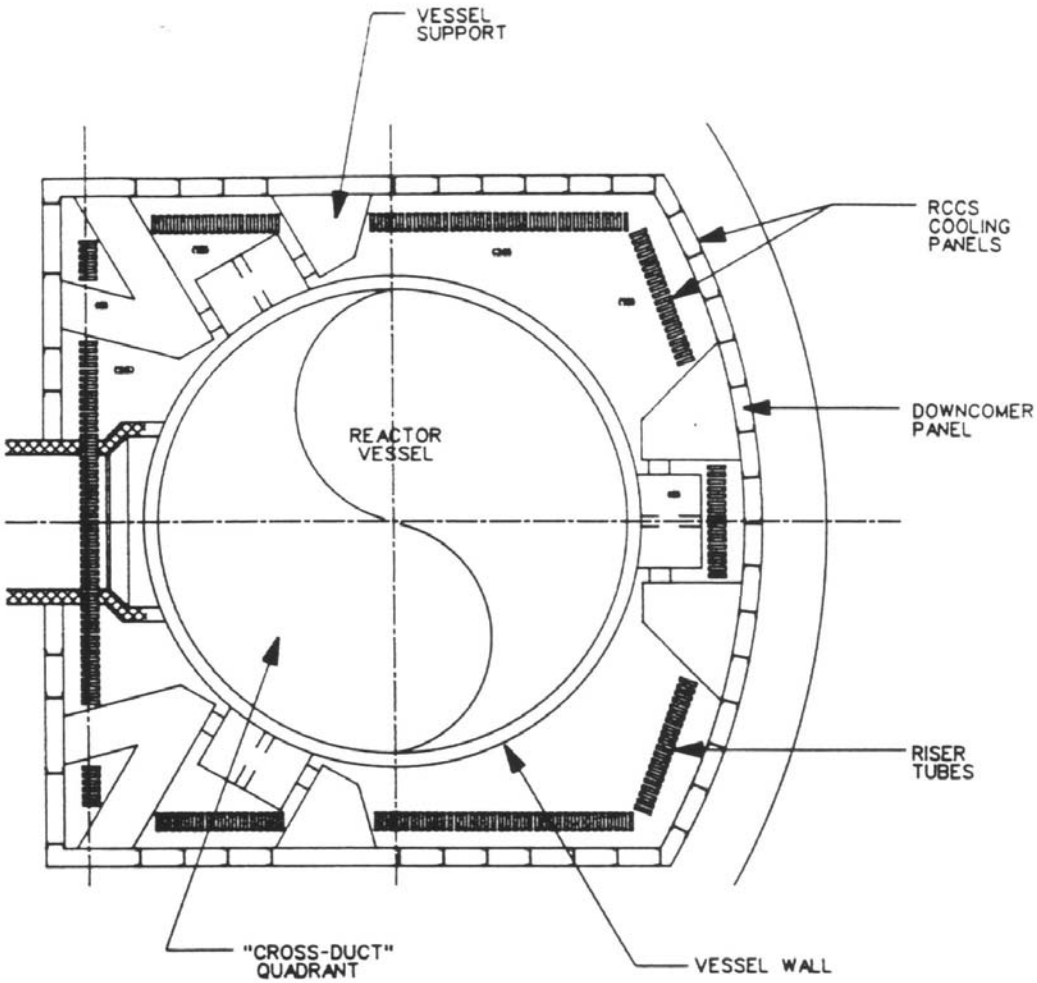

Figure 2. RCCS Panel Layout

To verify code the following data are required:

- The mean and variation of emissivity from one piece of material to the next.
- Variation of emissivity over a large surface
- Sensitivity of emissivity to various factors including manufacturing processes, operating service conditions and aging

3.1.2 Test Description

To determine the emissivity of candidate panel materials, the candidate materials must be identified and available. The sample material must have the material mechanical and physical properties as required by the design. The materials must also have the appropriate surface finish as required by the design. The sample material should be verified that it meets the above requirements.

Based upon the panel component size, statistical analysis should be applied to determine the appropriate number of sample and locations that they should be taken from a representative panel and from how many panels the samples should be taken from to yield a representative sampling of the panel material (i.e. over a large surface area, from panel to panel, lot to lot). Once the sampling plan is determined, samples would be taken from the panels and sent to an independent laboratory to conduct the emissivity testing.

3.1.3 Test Conditions

Service Life: 40 years

Service Temperatures:

Shutdown:	-45 to 110°F
Maximum accident:	430°F approximate
Normal operation:	220°F maximum
70°F Ambient Air :	180°F average

Relative Humidity 0 to 100%

3.1.4 Test Configuration/Set-up

Advanced Fuel Research (AFR), of East Hartford Connecticut has developed an emissometer to conduct high temperature emissivity testing. The AFR devise is an automated bench-top emissometer which measures spectral emissivity over a broad spectral range from the near to mid IR while simultaneously determining the surface temperature at the measurement location.

3.1.5 Measurements

The Model 205 NB and Model 205 WB Emissometers are Bench Top FT-IR based instruments designed specifically to facilitate simultaneous measurements of surface spectral emittance and temperature using optical techniques over the near and/or Mid-IR spectral range at temperatures ranging from 50 to 2000°C. This patented technology (U.S. patent # 5,239,488) can be used to measure radiative properties (emittance, reflectance, and transmittance) as a function of temperature.

The system can also provide measurements of radiance as well as directional-hemispherical reflection and transmission over a wide spectral range from 12,500 to 500 cm^{-1} (0.8 to 20 microns) for the Model 205 WB, and from 6,000 to 500 cm^{-1} (1.7 to 20 microns) for the Model 205 NB.

The Model 205 WB Emissometer has additional extended capabilities to operate as a stand-alone FT-IR spectrometer covering the Near and Mid-IR spectrum from 12,500 to 500 cm^{-1} with up to 1 cm^{-1} resolution. The Model 205 NB covers the Mid-IR spectrum from 6,000 to 500 cm^{-1}.

The Series 205 Emissometers significantly advance the state-of-the-art in emissivity measurements. Previous methods and instruments for measuring spectral emittance at elevated temperature required the precise knowledge of the sample temperature. The Model 205 overcomes these difficulties and provides all information necessary to simultaneously determine the precise temperature and emissivity for the same target spot on the sample.

3.1.6 Optics

The Emissometer is shown schematically in Figure 3. All optical components, including the FT-IR spectrometer, are mounted on a 3 foot x 4 foot optical bench. The hemi-ellipsoidal mirror enables the measurement of radiation in a hemispherical-directional mode. The sample can be heated with an oxy/acetylene torch, CO_2 laser, or other means. The FT-IR spectrometer is utilized in the emission mode and can accept radiation from either side of the sample by positioning the selector mirror. The design of the spectrometer's interferometer allows for the incoming beam to be modulated and split into two outgoing beams. In the Model 205 WB Emissometer, two separate detectors are utilized to measure near and mid-IR energy in these two beams simultaneously. A room temperature indium-gallium-arsenide detector is used for the Near-IR (12,500 to 6,000 cm^{-1}), and a liquid nitrogen cooled mercury-cadmium-telluride detector is used for Mid-IR (6,000 to 500 cm^{-1}). For the Model 205 NB Emissometer, only the MCT detector is required.

The hemi-ellipsoidal mirror has both foci inside the mirror. A near-blackbody source is located at one of the foci and the sample is located at the other focus. This mirror geometry, combined with the radiating characteristics of the near-blackbody source, provides a means of measuring

the hemispherical-directional reflectance of the front surface of the samples. Likewise, for transmissive samples, the hemispherical -directional transmittance can be measured from the back side.

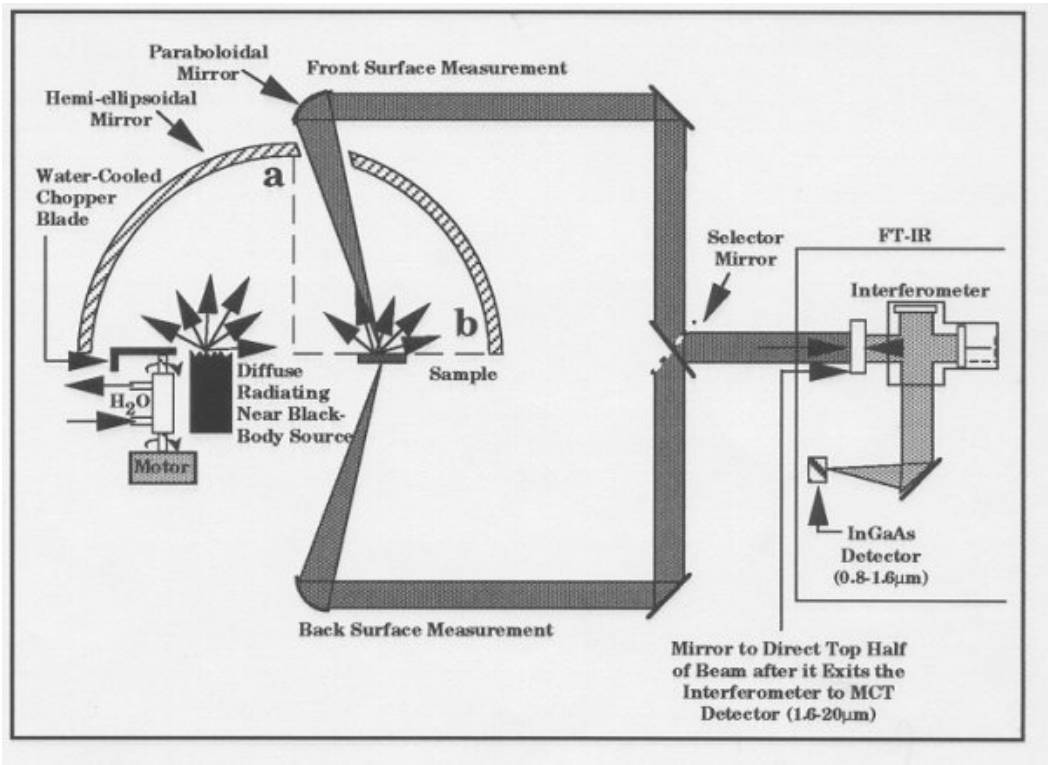

Figure 3. Schematic of Benchtop Emissometer

3.1.7 Operation

An integral part of the optical system is the rotating chopper system which moves either an aperture or a cold near-blackbody element in front of the source. The FT-IR data collection system is synchronized with these two states, and allows for the distinction of sample radiation from reflected/transmitted radiation as follows. For the reflectance measurement, the IR beam originates at the near-blackbody source at one focus of the hemi-ellipsoidal mirror. The radiation reflects from the hemi-ellipsoidal mirror and is focused onto the sample at the other focus where it is reflected (scattered) by the sample into the interferometer. The reflectance and the sample radiance are measured together when the aperture on the chopper rotor is in place over the source (chopper open condition). This is shown by the top curve in Figure 4. When a cold near-blackbody is substituted for the aperture over the source (chopper closed condition), it is the sample radiance alone which is measured (bottom curve in Figure 4). Both the radiance (r) and directional-hemispherical reflectance (R) can be obtained from these two spectra. Transmission measurements (T) are similarly obtained by repositioning the selector mirror.

The bidirectional scanning ability of the spectrometer's interferometer allows collection of sample radiance (chopper closed) in the "forward" scan, and sample radiance plus reflectance (chopper open) in the "reverse scan". At 32 cm^{-1} spectral resolution, a complete forward and reverse motion of the interferometer is accomplished in ~0.5 seconds, corresponding to a chopper rate of 2 Hz. Signal processing automatically separates forward motion scans from reverse motion scans and allows for signal averaging from sequential collection of data for each motion. Typically, a data set consists of 16 co-added scans of each component of the front surface measurement. For non-opaque samples, the selector mirror is flipped and 16 co-added scans of each component of the back surface are collected.

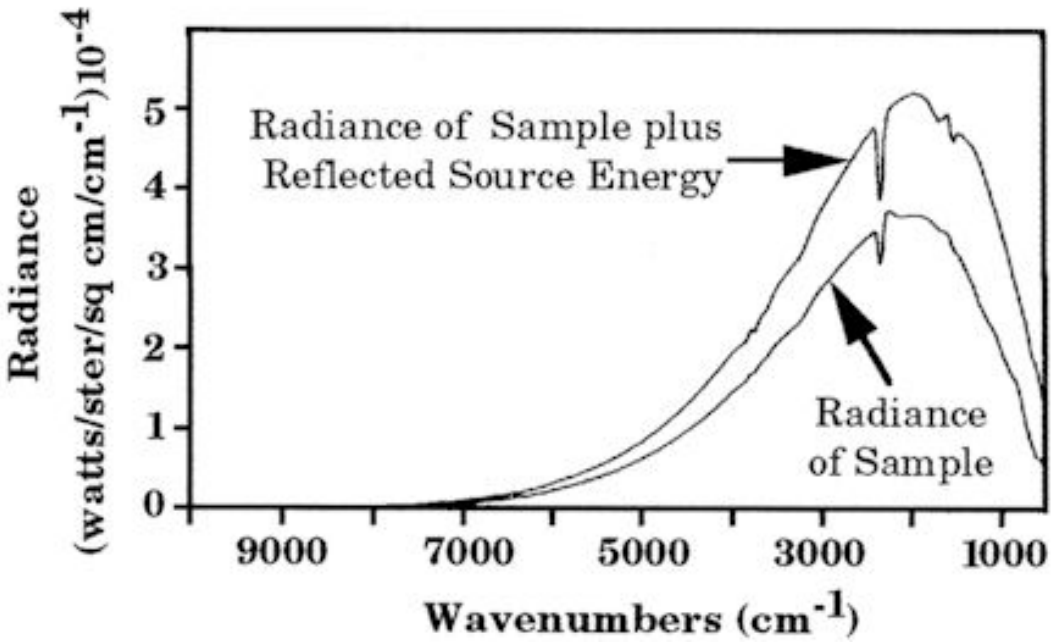

Figure 4. Spectral Measurements Performed with the Emissometer

Once the spectra are acquired, Spectral emittance (E) of the hot sample is determined by conservation of energy: E = 1 - R - T (Figure 3). The precise sample temperature is simultaneously determined by the Planck "Blackbody" (BB) relationship: r/E = BB. Hundreds of spectral data points or "colors" are used to match the shape and amplitude of the Planck temperature curve as shown in Figure 5. As shown in Figure 6, the emissometer can rapidly monitor spectral emittance as a function of temperature and time.

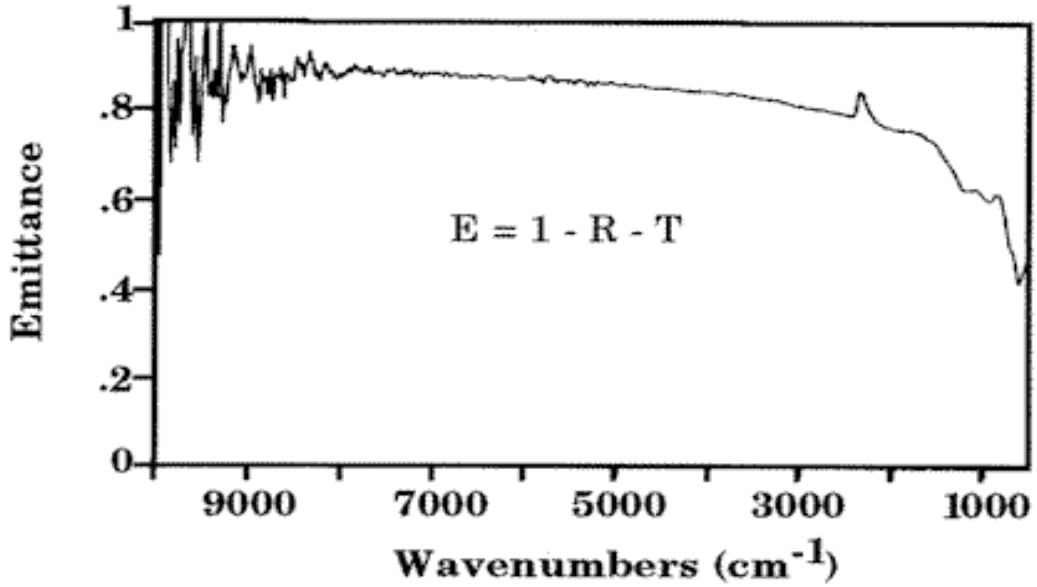

Figure 5. Determination of Spectral Emittance from Hemispherical Reflectance and Transmittance

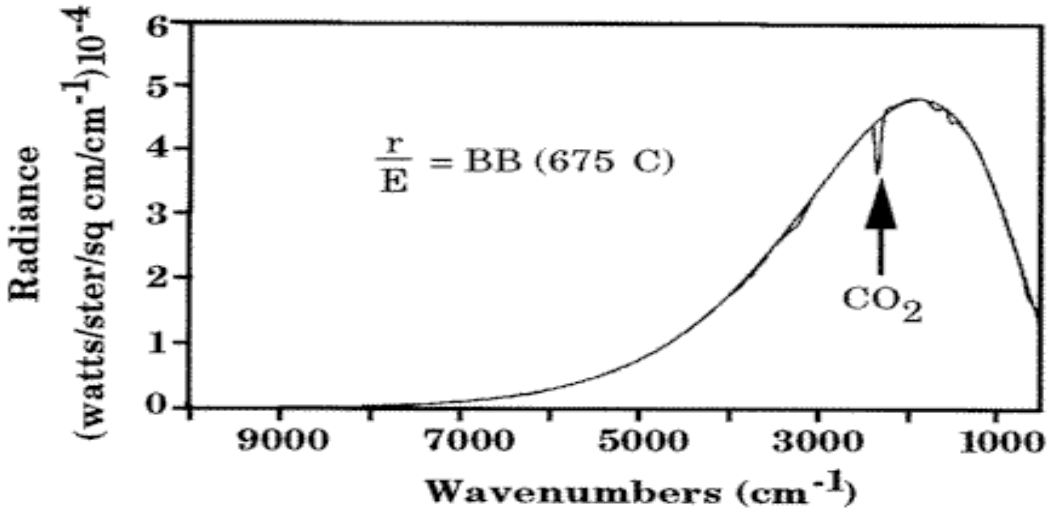

Figure 6. Determination of Temperature by Matching (r/E) with a Blackbody Curve

3.1.8 Samples

Samples are mounted into position with a clamping device which is arranged so as not to contribute extraneous radiation into the measurement. Three intersecting visible lasers beams are utilized to ensure correct positioning of the sample. Sample sizes on the order of 1 to 1-1/2 inches square or diameter are convenient, although samples as small as 1/4" square have been measured. The measurement spot on the sample is variable from 1 millimeter diameter to 3 millimeters in diameter. Samples have been heated by a variety of methods. These include: i) torch flames (propane, hydrogen, oxy/acetylene), ii) focused infrared radiation from high intensity lamps, and iii) infrared radiation from a CO_2 laser (25 W, continuous wave). Sample thickness of less than 1/4" is convenient for sample heating in order to achieve uniform sample surface temperatures when heating on the back surface. Torch heating allows the sample to be heated from the back, the front, or both surfaces. The influence on the measurements due to the radiation contributions from the combustion products of a torch flame is not a problem as it is limited to narrow spectral regions.

3.1.9 Specifications

Table 2. Emissometer Specifications

Emissometer Performance	Model 205 WB	Model 205 NB
Spectral Range	Near and Mid-IR	Mid-IR
Spectral Range	12,500 to 500 cm^{-1}	6,000 to 500 cm^{-1}
Emissivity Measurement Accuracy (typical)	± 3%	± 3%
Temperature Measurement Accuracy (typical)	± 5°C	± 5°C
Temperature Range	50 to 2000°C	50 to 2000°C
Sample Size	10 mm to 40 mm	10 mm to 40 mm
Measurement Spot Diameter	1 mm to 3 mm	1 mm to 3 mm
NEAR BLACKBODY SOURCE		
Source Surface Area	6.45 cm^{-1}	6.45 cm^{-1}
Surface Temperature Control	± 2°C	± 2°C
Surface Temperature Uniformity over Full Source	±10°C	± 10°C
Surface Temperature Uniformity over Measurement	± 2°C	± 2°C

Emissometer Performance	Model 205 WB	Model 205 NB
Spot Diameter		
Chopper Type	water-cooled rotating shutter	water-cooled rotating shutter
SAMPLE HEATING OPTIONS		
Oxy/Acetylene Torch and High Intensity Lamps	Standard	Standard
Propane, Hydrogen Torch and 25 W Continuous Wave CO2 Laser	Optional	Optional
STAND-ALONE FT-IR SPECTROMETER		
FT-IR Model	Bomem MB 155	Bomem MB 100
Spectral Range	12,500 to 500 cm^{-1}	6,000 to 500 cm^{-1}
Near IR Detector	InGaAs 12,500 to 6,000 cm^{-1}	
Mid-IR Detector	MCT 6,000 to 500 cm^{-1}	MCT 6,000 to 500 cm^{-1}
DATA SYSTEM		
Computer	Pentium PC	Pentium PC
PHYSICAL CHARACTERISTICS		
Optical Platform	4' x 3' x 1"	4' x 3' x 1"
Computer and Monitor Foot Print	17" x 17"	17" x 17"
Keyboard Foot Print	20" x 8"	20" x 8"
Input Voltage	120 VAC	120 VAC

3.1.10 Test Duration

Test Preparation: 6 months

Test Setup: 2 months

Testing: 4 months

Test Report: 3 months

Overall Duration: 15 months

3.1.11 Potential Test Location

Advanced Fuel Research, Inc.
87 Church Street
East Hartford, CT 06108
Phone: 860.528.9806 Fax: 860.528.0648

3.1.12 Measured Parameters

Sample temperature and corresponding emissivity

3.1.13 Data Requirements

Quality Assurance must be in accordance with the requirements for experimental data or validation testing which is safety related. All work performed to support the NGNP R&D Program will be in accordance with:

The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, “Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development.”

3.1.14 Test Evaluation Criteria

The emissivity and temperature data shall be determined to accuracy of +-3% and +-5°C respectively.

3.1.15 Test Deliverables

A final Test Report shall be provided which includes:

- Detailed discussion of test method
- Equipment employed
- Equipment calibration verification
- Detailed test procedures
- Original test data
- Summarized and reduced test data

- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing.

3.1.16 Cost

The estimated cost in 2008$ is $194,000.

3.1.17 Schedule

Experimental data to be 1 year before start of project final design.

3.1.18 Risk

Testing is necessary to validate the values used in the thermal analysis models. An improved understanding of the actors affecting emissivity will allow further optimization of the analysis with respect to emissivity. Optimization of emissivity values is required because the effectiveness of the RCCS influences the core power rating and/or vessel and internals performance requirements. Overly conservative emissivity data can contribute to over designing the system resulting in unnecessary cost of utilizing the existing design at less that full capability.

4 TRL 5 TO 6 WIND TUNNEL DATA TESTING

4.1 Wind Tunnel Testing of Scale Model RCCS I/O Structure, DDN C.16.00.02

4.1.1 Test Objective

The RCCS relies on the natural convection of air to remove heat from the reactor cavity. The air inlet/outlet (I/O) structures incorporate various features to minimize effects of varying wind conditions on the air flow. The designs of the RCCS inlet and outlet structures are unique to the NGNP (Figure 7). No experimental data on wind effects exist for this configuration. The design of the RCCS inlet and outlet structures require optimization and their performance under the design conditions need to be verified to validate the applicability of existing models.

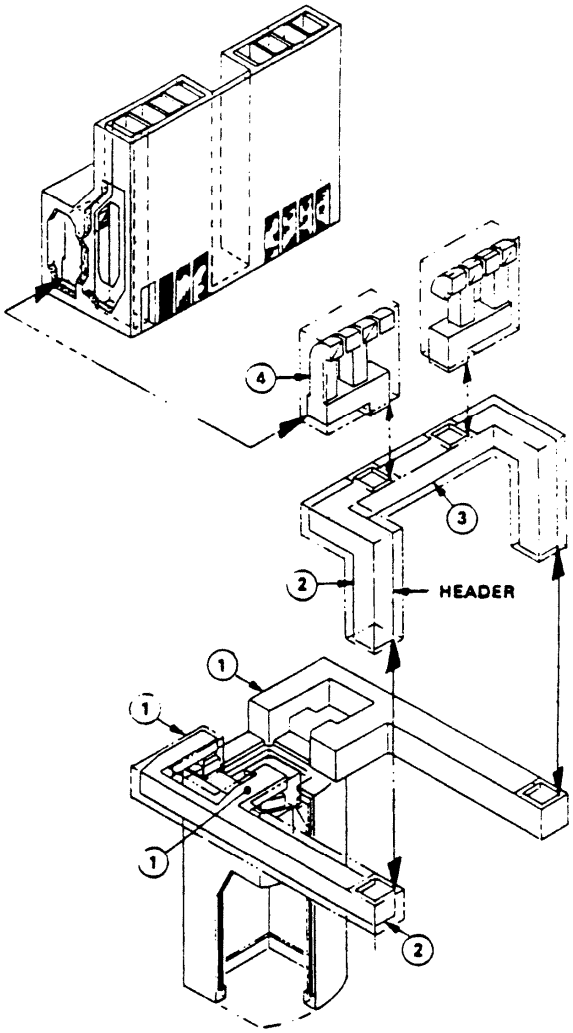

Figure 7. Inlet/Outlet Structure and Ductwork of the RCCS

4.1.2 Test Description

The Oran W. Nicks Low Speed Wind Tunnel, located at Texas A & M could be used to conduct scale model testing of the RCCS stacks as well as tests on a scale model (scale TBD) of the nuclear island with all facilities and potential site geographical features modeled. Scale models of the stacks and or scale model of the facility will be fabricated by the test facility. The wind tunnel and the models will be instrumented to yield the required data. Wind tunnel test runs will be made at the desired test conditions and repeated as required to verify experimental results.

4.1.3 Test Conditions

Maximum wind speed:	110 mph at a height of 33 ft above grade
Elevation:	Sea level to 6000 ft
Air temperature:	-45 to 110°F dry bulb
	82°F wet bulb

4.1.4 Test Configuration/Set-up

The Oran W. Nicks total wind tunnel circuit length at the centerline is 396 feet. From the power section at the exit of the diffuser around to the entrance of the contraction section, the tunnel cross section is circular and of steel plate construction. The maximum diameter of 30 feet occurs in the settling chamber. Turning vanes are installed at each corner of the circuit. A single screen is located at the settling chamber entrance and a double screen just upstream of the contraction section to improve dynamic pressure uniformity and to reduce flow turbulence level.

The contraction section which acts as a transition piece from circular to rectangular cross section is of reinforced concrete construction. Contraction ratio is 10.4 to 1 in a length of 30 feet. Diffusion takes place immediately downstream of the test section in a concrete diffuser which also returns the flow to a circular section. The horizontal expansion angle is 1.43 degrees and the vertical 3.38 degrees in an overall length of 46.5 feet.

The 12-1/2 foot diameter, four-blade Curtiss Electric propeller driven at a constant 900 RPM by a 1250 kVA synchronous electric motor provides the air flow in the wind tunnel. The propeller blades are from a standard B-29 airplane made of solid aluminum with the tips cut off about 1.5 feet. Blade tips are inset into the tunnel wall to minimize tip interference effects. Any desired test section dynamic pressure between zero and 100 pounds per square foot can be obtained by proper propeller blade pitch angle positioning. The propeller pitch angle is change using a 28 Volt DC electric drive. Motor starting is accomplished by an automatic motor control unit which allows synchronous speed to be achieved in about 10 seconds. Propeller pitch actuation and tunnel response are sufficiently rapid to allow setting of test section dynamic pressure within one minute.

The rectangular test section is 7 feet high, 10 feet wide and 16 feet long, fabricated of structural steel lined with marine plywood (Figure 8). The corners have 12 inch fillets which house fluorescent lamps to provide sufficient light to work and for photographic purposes. Cross sectional area of the test section is 68 square feet. Three inch wide vertical venting slots in the sidewalls at the test section exit maintain near atmospheric static pressure and the sidewalls diverging about 1-inch in 12-feet to account for boundary layer growth. A top door 8 feet wide by 10 feet long provides easy installation of assembled models while a 34 inch wide by 80 inch high side door aft of the test section allows access for personnel and smaller pieces of equipment. Sixty-five square feet of plated glass windows assure adequate visual access to a model undergoing testing and provide opportunity for model photography from many angles. A turntable seven feet in diameter built into the test section floor rotates with the external balance but is isolated from the balance and has a separate, but synchronous drive system.

To develop the required data the test facility the facility uses a PSI 8400 pressure system processor for electronic pressure scanners with a ±5 psi calibration unit and interface for up to 16 scanners. The PSI system has the advantage of obtaining pressure data with individual transducers at each port, therefore speeding up the data acquisition. At this time, the wind tunnel has 80 ports (2 scanners) with 1 psi transducers, 32 ports (1 scanner) with 20” H2O (0.72 psi) transducers and 160 ports (5 scanners) with 5 psi transducers. The system only adds a couple of seconds per data point to the data acquisition time.

Tunnel air flow is controlled and measured in terms of dynamic pressure (q) rather than in terms of velocity. Test section dynamic pressure is determined by a Druck pressure transducer which indicates tunnel set q in pounds per square foot using static pressures sensed by piezometer rings and carried to the transducer through pressure tubing. The high pressure piezometer ring is located in the settling chamber and the low pressure ring is just upstream of the test section entrance. The dynamic pressure resolution is pounds per square foot. The actual or calibrated dynamic pressure is obtained by using a previously obtained calibration between the set dynamic pressure and the dynamic pressure measured at the center of the empty test section.

Dynamic pressure is controlled by varying the propeller blade pitch angle and is infinitely variable between zero and 100 pounds per square foot. Except for very low dynamic pressures ($q<1$), tunnel q setting can generally be achieved and held steady in less than one minute from start.

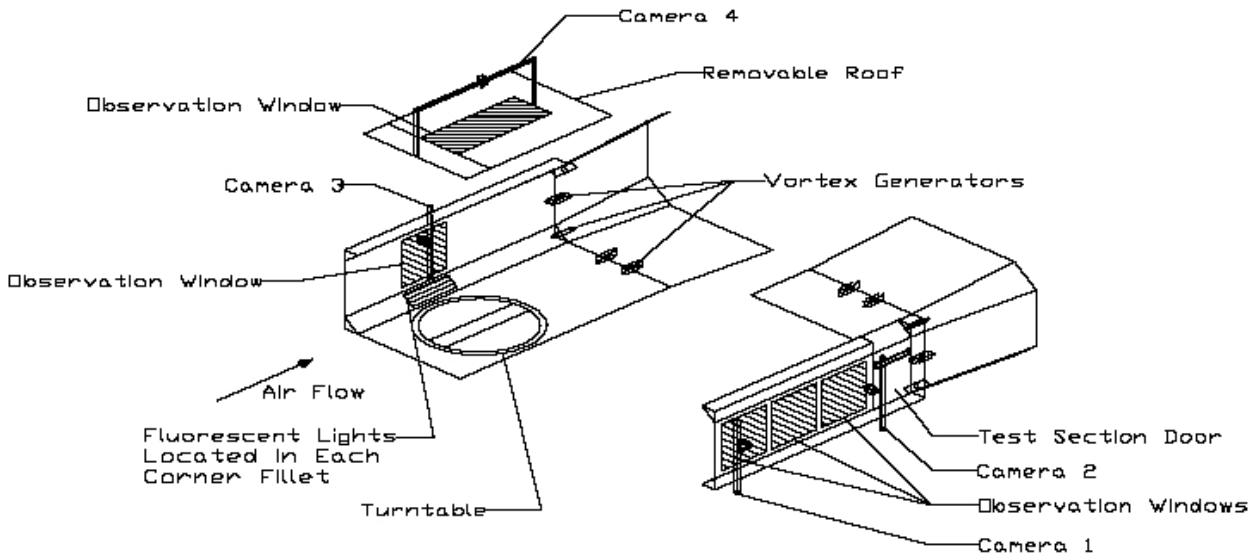

Figure 8. Oran W. Nicks Low Speed Wind Tunnel Test Section

A stand-alone data acquisition and analysis system is in use. The computer system is built around network of PC computers. The data acquisition system is built around a HP-75000 system with 16 A-D channels, 12 strain gage conditioner channels and 64 D-D channels, a PSI 8400 pressure system with a ±5 psi pressure calibration unit and the capability of taking data from up to 16 scanners. The data acquisition computer uses IEEE interface and all the programs and data are stored in the network drive, printers and graphic displays are connected directly to the computer for direct output and on-line monitoring of the data. The network server includes two 8 GB hard disks set up as mirroring for backup purposes, a tape backup system used for daily backup of the data throughout the test period and achieved purposes after every test.

4.1.5 Test Duration

Test Preparation:	8 months
Test Setup:	6 months
Testing:	4 months
Test Report:	3 months
Overall Duration:	21 months

4.1.6 Potential Test Location

Oran W. Nicks Low Speed Wind Tunnel
Texas A&M University
1775 George Bush Drive West
College Station, TX 77845
Phone: 979.845.1028 Fax: 979.845.8191

4.1.7 Measured Parameters

Pressure profiles inside and in the vicinity of the inlet and outlet structures for:

- Various locations along the length of the nuclear island
- Various wind directions and velocities

4.1.8 Data Requirements

Quality Assurance must be in accordance with the requirements for experimental data or validation testing which is safety related. All work performed to support the NGNP R&D Program will be in accordance with:

The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, “Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development.”

4.1.9 Test Evaluation Criteria

The conditions for successful completion of the test are: (1) the data identified in Section 4.1.7 has been obtained, (2) the test data satisfies the data quality requirements as defined in Section 4.1.8, and (3) the data is sufficient to verify (or permit modification) of the analytical models of the behavior of the RCCS inlet and outlet structures under all design conditions.

4.1.10 Test Deliverables

A final Test Report shall be provided which includes:

- Detailed discussion of Test method
- Equipment employed
- Equipment calibration verification
- Detailed test procedures
- Original test data
- Summarized and reduced test data
- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing

4.1.11 Costs

The estimated cost in 2008$ is $400,000.

4.1.12 Schedule

Experimental data must be available 1 year before start of NGNP final design.

4.1.13 Risk

Not completing preliminary scale model wind tunnel testing of the I/O structures would result in the as-built structures being tested with the prevailing wind conditions. This could cause delays in licensing and startup due to testing, wind conditions, and or design changes or modifications if required.

5 TRL 6 TO 7 INTEGRATED THERMAL TRANSFER DATA TESTING

5.1 Heat Transfer Coefficients, Friction Factors and Integrated RCCS Test, DDN C 16.00.03 and C 16.00.04

5.1.1 Test Objective

The first objective is to mock up the actual geometry of the GT-MHR 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 objectives are data-related. Namely, to take measurements of the axial and radial temperature and heat flux distributions on the tube walls as well as the heated and non-heated duct walls and also to take measurements of the tube interior gas velocity and temperature distributions. 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 must be taken 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.

5.1.2 Test Description

To complete RCCS testing the following steps are required:

- Mock up the existing NSTF facility to match the GA GT-MHR RCCS to the greatest extent possible.
- Measure the axial and radial temperature and heat flux distributions on the tube walls, and the heated and non-heated duct walls 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.
- Measure the tube interior gas velocity and temperature distributions.
- Measure turbulence 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.

5.1.3 Test Conditions

Riser surface temperature: 150 to 450°F

Riser surface heat flux:

Maximum accident:	10 kW/ft^2
100% power operation:	3 kW/ft^2
Low power operation:	0.5 kW/ft^2

Reynolds number:

Maximum accident:	approximately 10^5
100% power operation:	10^4 to 10^5
Low power operation:	10^3 to 10^4

5.1.4 Test Configuration/Set-up

The existing NSTF has been evaluated by ANL to determine if the facility could be utilized for the NGNP RCCS testing (Figure 9). ANL performed CFD analyses of both the prototype and of a modified facility. The objective of these calculations was 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. The facility was originally developed to provide confirmatory data for the GE PRISM Reactor Vessel Auxiliary Cooling System (RVACS) design. The NSTF mocked up the air-flowpath formed by the reactor guard vessel (heated wall) and the outer duct wall surrounding the guard vessel.

The facility consists of the structural module, electric heaters, instrumentation, insulation, and a computerized data acquisition and control system. The structural module consists 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, are thermally insulated to minimize parasitic heat losses to the environment. The heated channel width is 1.32 m. As originally designed, the channel width can be adjusted anywhere from 30.4 cm to 45.6 cm. The surfaces that simulate the guard vessel wall (heated wall) and the outer duct wall are 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. 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. The facility is 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.

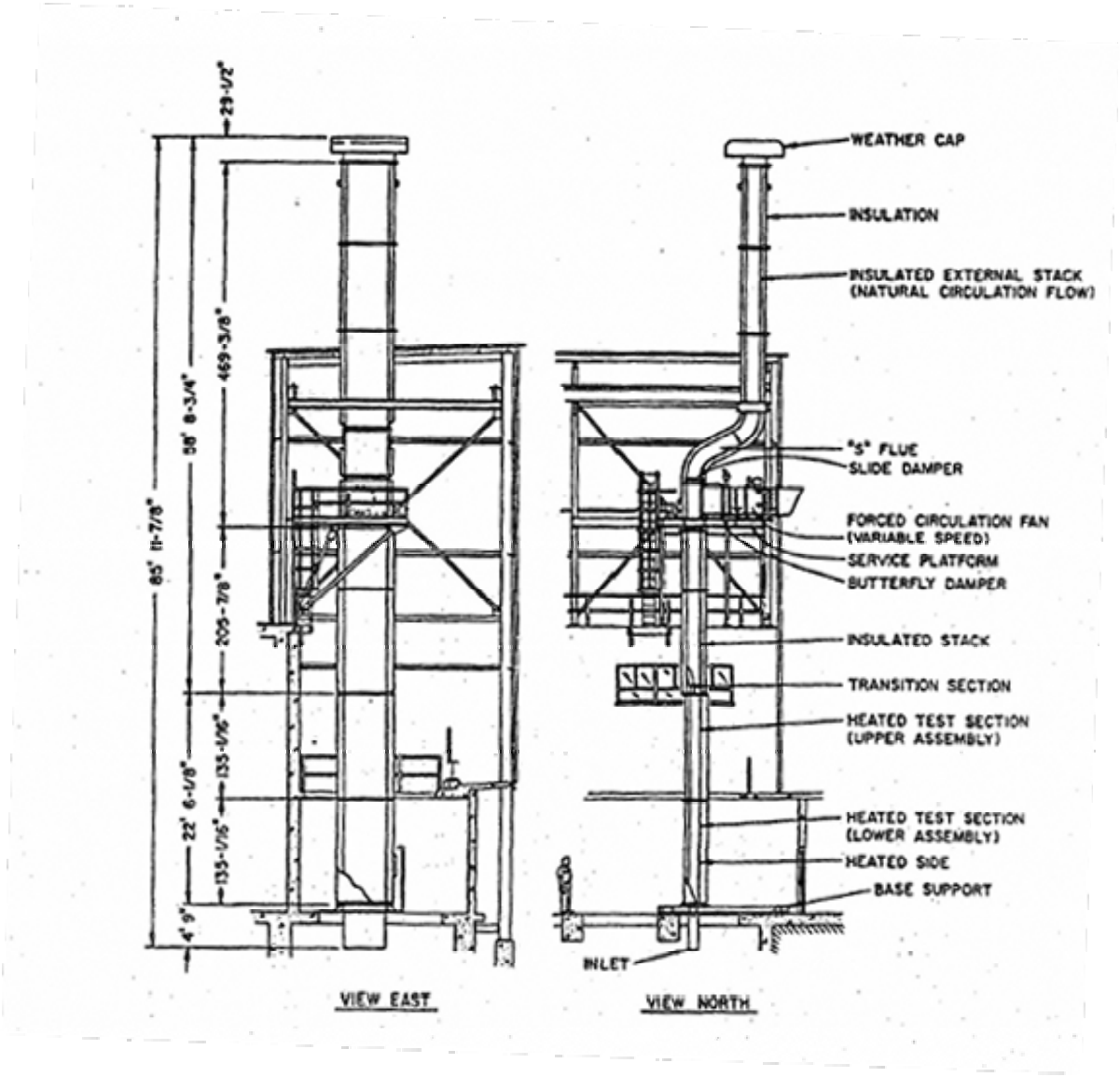

Figure 9. Natural Convection Shutdown Heat Removal Facility at ANL

The GA GT-MHR RCCS 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°C, 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.

ANL determined that the 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 neither by 1-D models nor 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 the ANL study is that NSTF is able to provide essentially a full scale simulation of the RCCS.

The original NTSF data acquisition system (DAS) was capable of sampling 300 channels. The DAS stored the data on disk and 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. 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. 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 pitotstatic air flow rake, differential pressure transducers, radiation flux transducers, anemometers, and air pressure and humidity gages.

The heater power control and DAS systems will be completely renovated by ANL as part of the current work to satisfy the RCCS data needs.

5.1.5 Test Duration

Test Preparation:	8 months
Test Setup:	20 months
Testing:	4 months
Test Report:	3 months
Overall Duration:	24 months

5.1.6 Potential Test Location

The Natural Convection Shutdown Heat Removal Test Facility (NSTF) located in Bldg. 310 on the Argonne National Laboratory site.

5.1.7 Measured Parameters

Measured parameters for the integrated RCCS are provided in Table 3.

Table 3. RCCS Measured Parameters

1	Mock up Air RCCS geometry under prototypical conditions.	Twelve 6.7 meter long tubes with prototypical cross section (5 cm x 25 cm), wall thickness (4.8) mm, and pitch (10 cm) installed in the heated section of the NSTF. Peripheral area around tubes sealed at top and bottom to achieve prototypical flow geometry. Apply prototypical surface temperatures and /or heat flux boundary conditions to achieve and demonstrate prototypical flow patterns.
2	Obtain data on the RCCS tube and channel axial temperature distribution under prototypical flow conditions.	Instrument the three center tubes and channel walls to measure channel surface and tube internal and external surfaces temperatures at multiple axial positions along the heated length. Obtain measurements on the heated, unheated, and side walls.
3	Obtain data on the RCCS tube heat flux distributions at prototypical RCCS flow conditions	Using the measurements from item 2, evaluate tube axial heat flux distributions 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 the bulk gas velocity and gas temperature distributions at approximately 1 meter intervals
5	Obtain turbulence data as a function of axial position within the RCCS tubes.	Provide quartz window viewports through cavity and tube walls at approximately 1 meter intervals so that turbulence measurements can be obtained with the LDV under prototypical RCCS flow conditions

5.1.8 Data Requirements

Quality Assurance must be in accordance with the requirements for experimental data or validation testing which is safety related. All work performed to support the NGNP R&D Program will be in accordance with:

The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, “Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development.”

5.1.9 Test Evaluation Criteria

The conditions for successful completion of the test are: (1) the data identified in Section 5.1.7 as needed to satisfy the test objectives stated in Section 5.1.1 has been obtained, and (2) the test data satisfies the data quality requirements as defined in Section 5.1.8.

5.1.10 Test Deliverables

The test report shall include a Report which includes the following:

- Detailed discussion of Test method
- Equipment employed
- Equipment calibration verification
- Detailed test procedures
- Original test data
- Summarized and reduced test data
- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing

5.1.11 Costs

The estimated cost in 2008$ is $3,450,000.

5.1.12 Schedule

Experimental data to be available before the end of the first year of final design.

5.1.13 Risk

Use of conservative heat transfer and friction factors values for safety analysis can result in overly conservative design.

6 TRL 7 TO 8 FULL SCALE INTEGRATED THERMAL TRANSFER DATA TESTING

6.1 Heat Transfer Coefficients, Friction Factors and Integrated Full Scale RCCS Test, DDN C 16.00.03 and C 16.00.04

6.1.1 Test Objective

The first objective is to test the as-built NGNP RCCS cooling system. The remaining four objectives are data-related. Namely, to take measurements of the axial and radial temperature and heat flux distributions on the tube walls as well as the heated and non-heated duct walls. Take measurements on the tube interior gas velocity and temperature distributions. 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 must be taken at several axial elevations to verify and demonstrate the RCCS design.

6.1.2 Test Description

To complete RCCS testing the following steps are required:

- Instrument the full scale, as built NGNP RCCS system to yield the design data used in scale and design phase testing.
- Measure the axial and radial temperature and heat flux distributions on the tube walls, and the heated and non-heated duct walls 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.
- Measure the tube interior gas velocity and temperature distributions.
- Measure turbulence 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 NGNP RCCS.

6.1.3 Test Conditions

Riser surface temperature: 150 to 450°F

Riser surface heat flux:

Maximum accident:	10 kW/ft^2
100% power operation:	3 kW/ft^2
Low power operation:	0.5 kW/ft^2

Reynolds number:

Maximum accident:	approximately 10^5
100% power operation:	10^4 to 10^5
Low power operation:	10^3 to 10^4

6.1.4 Test Configuration/Set-up

Assuming the GA GT-MHR RCCS design is used for the NGNP, the RCCS will consist of 292 rectangular 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°C, 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.

The NGNP RCCS would be instrumented to help guide experiment operations, and also evaluate the heat removal performance under both natural convection and forced flow conditions. Instruments required include instruments 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 shall consist of thermocouples, pitot-static traversing probes, a pitotstatic air flow rake, differential pressure transducers, radiation flux transducers, anemometers, and air pressure and humidity gages.

6.1.5 Test Duration

Test Preparation:	8 months
Test Setup:	20 months
Testing:	4 months
Test Report:	3 months
Overall Duration:	24 months

6.1.6 Potential Test Location

It is proposed to perform the test in the NGNP.

6.1.7 Measured Parameters

Measured parameters for the integrated RCCS are provided in Table 4.

Table 4. Full Scale Integrated RCCS Measured Parameters

1	NGNP air RCCS system under prototypical conditions.	Twelve or more full scale tubes with prototypical cross section (5 cm x 25 cm), wall thickness (4.8) mm, and pitch (10 cm). Apply test condition surface temperatures and /or heat flux boundary conditions to achieve and demonstrate actual flow patterns.
2	Obtain data on the RCCS tube and channel axial temperature distribution under prototypical flow conditions.	Instrument the three center tubes and channel walls to measure channel surface and tube internal and external surfaces temperatures at multiple axial positions along the heated length. Obtain measurements on the heated, unheated, and side walls.
3	Obtain data on the RCCS tube heat flux distributions at prototypical RCCS flow conditions	Using the measurements from item 2, evaluate tube axial heat flux distributions 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 the bulk gas velocity and gas temperature distributions at approximately 1 meter intervals
5	Obtain turbulence data as a function of axial position within the RCCS tubes.	Provide quartz window viewports through cavity and tube walls at approximately 1 meter intervals so that turbulence measurements can be obtained with the LDV under prototypical RCCS flow conditions

6.1.8 Data Requirements

Quality Assurance must be in accordance with the requirements for experimental data or validation testing which is safety related. All work performed to support the NGNP R&D Program will be in accordance with:

The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, “Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development.”

6.1.9 Test Evaluation Criteria

The conditions for successful completion of the test are: (1) the data identified in Section 6.1.7 as needed to satisfy the test objectives stated in Section 6.1.1 has been obtained, and (2) the test data satisfies the data quality requirements as defined in Section 6.1.8.

6.1.10 Test Deliverables

The test report shall include a Report which includes the following:

- Detailed discussion of Test method
- Equipment employed
- Equipment calibration verification
- Detailed test procedures
- Original test data
- Summarized and reduced test data
- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing

6.1.11 Costs

Costs are incorporated as part of startup commissioning tests for the NGNP.

6.1.12 Schedule

Testing performed as part of startup commissioning tests for the NGNP.

6.1.13 Risk

Not applicable

7 COST AND SCHEDULE SUMMARY

Figure 10 provides an integrated schedule for RCCS technology development and design, and a summary of the estimated costs.

		Estimated	Calendar Year												
TRL	Activity	Cost ($K)	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
	NGNP Schedule														
	Common Conceptual Design														
	Common Preliminary Design														
	NHSS Conceptual and Prelim. Design														
	Final Design														
	Site Work and Construction														
	Startup and Testing														
	RCCS Design, Fab, & Installation Schedule														
	Conceptual Design														
	Preliminary Design														
	Final Design														
	Fabricate and Install RCCS in NGNP														
	RCCS Technology Development														
4→5	Emissivity of RCCS Panel Surfaces Test	194													
5→6	Wind Tunnel Testing of RCCS I/O Structure	400													
6→7	Integrated RCCS Mockup Test	3450													
7→8	RCCS testing in NGNP	TBD													
	Total	3850													

Figure 10. Schedule and Cost Estimate for NGNP RCCS Development

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