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

Test Plan – Control Rods

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ACRONYMS

ASME	American Society of Mechanical Engineers
ASTM	American Society of Testing and Materials
C/C	Carbon/carbon
CCD	Conduction Cool Down (event)
CFD	Computational Fluid Dynamics
CR	Control Rod
CTF	Component Test Facility
DDN	Design Data Need
DOE	U.S. Department of Energy
FEA	Finite Element Analysis
FSV	Fort Saint Vrain
GA	General Atomics
GT-MHR	Gas Turbine Modular Helium Reactor
HTGR	High-Temperature, Gas-Cooled Reactor
HTTR	High Temperature Test Reactor
INL	Idaho National Laboratory
KAERI	Korea Atomic Energy Research Institute
NGNP	Next Generation Nuclear Plant
MHR	Modular Helium Reactor
MHTGR	Modular HTGR
NCA	Neutron Control Assembly
NP-MHTGR	New Production Modular HTGR
ORNL	Oak Ridge National Laboratory
TRL	Technology Readiness Level

1 INTRODUCTION

1.1 Purpose

This Test Plan provides a high-level description of a technology development program to support design, fabrication, and deployment of control rods for the Next Generation Nuclear Plant (NGNP). The technology development program must be well coordinated with a control rod design and fabrication schedule that supports an NGNP construction schedule consistent with NGNP startup in 2021.

This Test Plan is applicable to control rods for the plant configuration shown in Figure 1, which General Atomics (GA) has selected as the reference NGNP configuration for the NGNP technology development roadmapping effort under which this Test Plan has been prepared. This configuration is essentially the same as the preferred configuration that GA selected for the NGNP during the Phase A Conceptual Design Studies in early 2008 (GA Report 911120), except that the reactor outlet temperature has been increased from 900°C to 950°C to be consistent with the high-level NGNP Project requirement that the reactor be designed not to preclude operation at 950°C.[1]

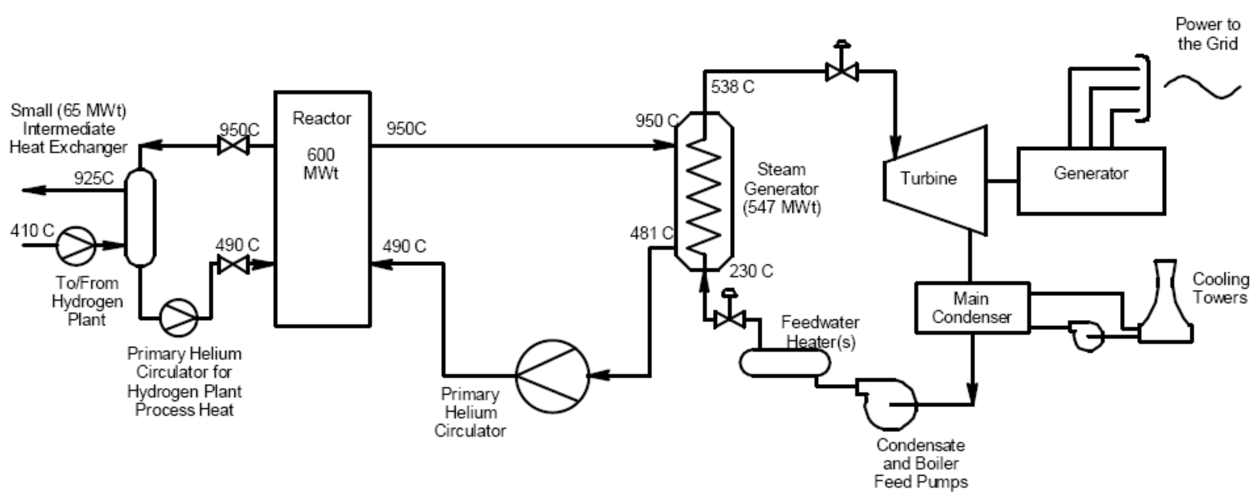

Figure 1. NGNP Configuration for Technology Development Roadmapping

[1] A decision has been made recently by the NGNP Project to reduce the nominal reactor outlet helium temperature for the NGNP from 950°C into the range of 750°C to 800°C with a corresponding reduction in the reactor inlet helium temperature. However, the technology roadmapping task was started and largely completed while the reactor outlet helium temperature objective for NGNP was still 950°C. Thus, the focus has been to define the technology development activities required for a reactor operating at that temperature. With respect to the control rods, it is not anticipated that the reduction of the reactor outlet (and inlet) helium temperatures will have a significant impact on the required technology development program because it will still be necessary to fabricate the control rod structural elements from a ceramic composite material.

Because the NGNP design process is at a very early stage, the design details needed to precisely define testing requirements are currently largely unavailable. Consequently, this Test Plan is intended primarily to identify the testing activities that are likely to be needed and to provide cost and schedule estimates, which are necessarily based on engineering judgment. It is assumed that this umbrella Test Plan will be updated periodically as the NGNP design progresses and that detailed test plans and test procedures will be prepared by the testing organizations for the specific tests that are actually conducted.

1.2 Scope

As part of the FY08-2 conceptual design studies, GA performed an evaluation to assess the need to use ceramic composite materials for reactor internals, including control rods, in the NGNP, and the R&D technical issues associated with the use of composites (GA Report 911125). This study was based on the same NGNP configuration as shown in Figure 1. A conclusion of this study was that it will be necessary to construct the control rods (as well as other reactor internals) from a ceramic composite material. Such composite materials are widely used in the aerospace industry, but little data is available on irradiation effects and corrosion in an impure helium environment. Consequently, although the design of the NGNP control rods is expected to be geometrically similar to that of the control rods in Fort St. Vrain (FSV), GA has assigned a technology readiness level (TRL) of 2 to the control rods because a suitable composite material and fabrication technique must be qualified before proof of concept (TRL 3) is achieved. The required technology development program to advance the TRL of the control rods from 2 to 8 is outlined in this Test Plan.

The program for developing and qualifying ceramic composite materials for use in the NGNP will be extensive and will require preparation of a comprehensive technical program plan similar to the technical program plans prepared for fuel and graphite. Such a plan, which is well beyond the scope of this document, will be prepared by the reactor designer working with the technology organizations that will perform the tests (e.g., INL and ORNL). The ceramic composites technical program plan will provide the details of the ceramic composites development program that is outlined in Sections 3 and 4 of this Test Plan.

While many standards, such as those embodied in the ASTM exist for composite materials, some property-specific standards are lacking and there is no nuclear-specific standard similar to that for nuclear graphite. Section 6 of GA Report 911125 addresses the codification issues associated with the use of ceramic composite materials for various reactor system components, including the control rods. Section 7 of GA Report 911125 provides a summary-level composites development schedule that includes development of ASTM/ASM material specifications and standard test methods, and ASME code rules for design of reactor components made from ceramic composite materials. These activities are important because it will be essential for composite materials to go through an extensive qualification process because these materials have never been approved for use in nuclear cores by regulatory authorities in the U.S. or in other countries.

In recognition of this need, a program for ceramic composites qualification is already underway. A major element of this program has been the initiation of an international collaboration to develop test standards. A task group to address the evaluation of fiber-reinforced ceramic matrix composite structures for a future generation of nuclear energy systems was established in ASTM International Subcommittee C28.07 on Ceramic Matrix composites in 2005. The task group is developing standard procedures for baseline mechanical properties for testing of tubular geometry components made of fiber-reinforced ceramic matrix composites, since the original scope was primarily for supporting the qualification of composite control rod sleeves. Also, an ASME composites design code development effort has recently been initiated to complement the effort previously undertaken by the international Gen IV graphite community. However, the effort to develop standardized test methods, particularly for tubes, must be completed as a prerequisite to developing the ASME code design rules. Because the composites material codification requirements have already been discussed in GA Report 911125 and are common to several reactor system components besides the control rods, the necessary codification activities are not addressed in this Test Plan. However, it should be noted that completion of these activities is considered a prerequisite to achieving a TRL of 5 for the control rods.

The efforts to develop codes and standards is likely critical to the ability to license an NGNP reactor design having a reactor outlet helium temperature in the vicinity of 950°C, but this activity, although underway, is not progressing fast enough to effectively support the composites technology development program. Thus, it will be necessary to develop composites technology in parallel with the composite materials codification effort, which increases the risk associated with the use of composite materials in NGNP. If ceramic composite control rods cannot be qualified in time to support NGNP startup by 2021, the fallback position will be to use metallic control rods such as were used in the FSV Reactor. The use of metal control rods will likely require certain limitations on control rod use and reactor operation, but initial operation of the NGNP reactor can be conducted safely with the metal control rods until composite control rods are available.

1.3 Background

The control rods are located in two general areas of the reactor core. There is a circle near the inner boundary of the fuel and central replaceable reflector elements (12 rods). There is another circle near the outer boundary between the fuel and outer replaceable reflector reflectors (18 rods) as shown in Figure 2.

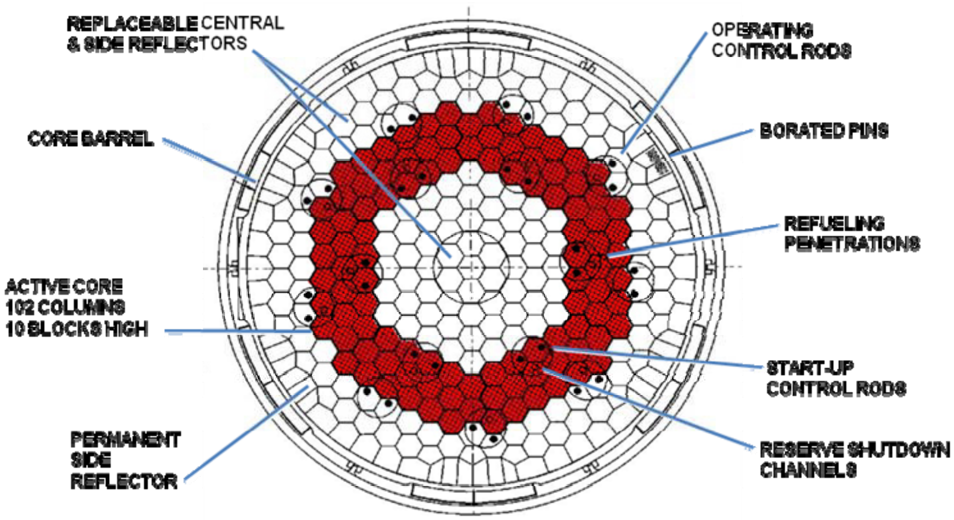

Figure 2. Cross-section of reactor core

The outer control rods are used to control the power in the core and are inserted during normal operation. The inner rods are withdrawn during normal operation and are only used to shut down the nuclear reaction. There are six inner and six outer reserve shutdown columns with a channel for insertion of boronated graphite pellets in the unlikely event that the control rods cannot be inserted.

Each control rod is a flexible assemblage of rigid links comprised of boronated graphite (B_4C) compacts within a cylindrical sleeve. Each of these rigid sections is approximately 50 cm in length. Flexibility of the control rod assembly is provided by the ball-joints that connect the rigid sections. The sleeves and joints are the structural elements that contain the nonstructural neutron absorbing B_4C compacts and transfer the operational loads to the control rod drive. All control rods are identical to accommodate interchangeability.

For the reference NGNP configuration shown in Figure 1, the maximum control rod temperature during normal operation is about 895°C and the maximum temperature during accident conditions (a de-pressurized conduction cool-down event) is about 1470°C. During a scram, all the control rods are inserted into the core. If, in addition to the scram, a loss of forced circulation of the primary coolant occurs, then the inserted control rods will increase in temperature during the conduction cool-down (CCD) event.

The neutron fluence that the control rods experience varies depending on the location in the reactor core. The outer control rods experience the largest fluence because they are inserted throughout power operation to control the reactor. The inner rods are only inserted during shutdown. However, the inner control rods experience the highest temperatures during a CCD event. All control rods are interchangeable, so they are designed to meet a combination of the worst conditions. The highest total neutron fluence is 3.2×10^{26} n/m^2, or 4.0 dpa. It takes 8 years of operation to accumulate this fluence. It is planned to replace the control rods at that time to refresh the B_4C compacts.

Metallic control rods may not be able to withstand the maximum neutron fluence, and they cannot withstand the temperatures in the inner circle positions during a CCD event. SiC/SiC composites can easily withstand the fast neutron fluence with a fast neutron fluence limit greater than the lifetime fluence for 60 years of reactor operation. However, SiC/SiC composites have a temperature limit of about 1400°C. Carbon/carbon (C/C) composites[2] will just meet the 8-year life of the control rods from the standpoint of the fast neutron fluence, but they can easily withstand the maximum design temperature because C/C composites have a temperature limit greater than 2000°C. Given the maximum expected fast neutron fluence and temperature, the best options appear to be that the control rod sleeves be manufactured from filament- or tape-wound fiber-reinforced carbon-based composites. The choice of fiber reinforcement and the degree of graphitization of the matrix are likely key to the ability of the composite material to withstand the neutron radiation.

No data was found in the study on corrosion of C/C composites in an impure helium environment; therefore, this is an issue that must be addressed in the technology development program. There is a need for corrosion data to validate the life of C/C composite materials in the NGNP reactor environment.

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2 Carbon/carbon (C/C) is a composite consisting of carbon fibers in a carbon matrix.

2 APPLICABLE DOCUMENTS

Table 1. Documents Applicable to Control Rod Technology Development

Document Number	Title	Date
GA Report 911120/0	NGNP Steam Generator Alternatives Study	April 2008
GA report 911125/0	NGNP Composites R&D Technical Issues Study	October 2008
GT-MHR DDN C.11.03.24	Properties of High Temperature Control Rod Materials	June 1994
GT-MHR DDN C.11.03.02	Control Rod Vibration Data	June 1994
GT-MHR DDN C.11.03.05	Control Rod Shock Absorber Data	June 1994
GT-MHR DDN C.11.03.06	Control Rod Structural Integrity Data	June 1994
GA-A16466	Safety-Related DV&S Programs for HTGRs	September 1981
PCV-000396	PC-MHR Engineering Development Plan	November 1995
HTR2008 Conference Paper HTR2008-58050	Ceramic Composites for Near Term Reactor Application	Sept 28 – Oct 1, 2008
GA Report 911133/0	Test Plan for NGNP Reactor Control Equipment	December 2008

3 TEST PLAN TO ADVANCE FROM TRL 2 TO TRL 3

A TRL of 3 is achieved when proof-of-concept is established. This requires that sufficient industrial experience or testing at laboratory scale provide proof of viability in anticipated service. A number of activities are required to advance the TRL of the control rods from 2 to 3. These include:

1. Define the control rod operating conditions and design requirements.

2. Develop the conceptual control rod design and perform structural and seismic analyses to calculate the mechanical loads (i.e., based on the dead weight of the control rod and the core pressure drop) and lateral earthquake loads for the control rod. Initiate development of the composite material models that will be needed to support control rod design.

3. Develop a composite architecture (i.e., fiber type and fiber architecture, type of matrix material, and processing conditions) for the control rod structural elements that is consistent with the control rod geometry and mechanical loads

4. Fabricate pieces that are representative of the candidate composite architecture(s) and cut specimens from these parts for testing.

5. Conduct basic physical and mechanical properties screening tests, irradiation tests, and corrosion tests in an environment representative of reactor helium on the test specimens from activity 3.

6. Make an initial selection of the composite material(s) to be used for the control rods based on the screening test results from activity 5.

These activities are discussed in the following sections. An overall schedule and cost estimate summary is provided in Section 9.

3.1 Develop Control Rod Design Requirements

3.1.1 Activity Description

Once the point design for the NGNP has been finalized, computational fluid dynamics (CFD) analyses similar to those performed by KAERI for the composites R&D technical issues study (GA Report 911125) will be performed to determine the operating temperatures and flow conditions for the control rods. Analyses will also be performed to confirm that the design helium coolant impurity levels in Table 2 are applicable to the NGNP and to estimate the expected impurity levels specific to the NGNP design and operating conditions[3]. The design requirements for the control rods will then be defined based on the results of these analyses.

Table 2. Design and Expected Levels of Primary Coolant Impurities

Impurity	Design Value	Expected Value*	Units
H_2O	2.0	0.5	ppmV
CO_2	2.0	1.0	ppmV
CO	5.0	2.0	ppmV
H_2	10.0	3.0	ppmV
CH_4	2.0	0.1	ppmV
N_2	10.0	2.0	ppmV
Particulates	10.0	1.0	lb/yr
* For GT-MHR operating at 100% power with Tin = 490°C and Tout = 850°C			

3.1.2 Test Requirements

This activity does not require any testing. The analyses will be performed by the reactor vendor (assumed to be GA) or GA's designated subcontractor(s) using computer codes that have been verified and validated in accordance with the applicable requirements of ASME NQA-1.

3.1.3 Schedule and Cost

The activities described in Section 3.1.1 will start early in conceptual design and will require about 6 months to complete. The cost is estimated to be about $350K.

3.2 Control Rod Design and Analysis

3.2.1 Activity Description

Several MHR control rod design concepts have been developed, but further analysis is required to select the concept for further design development and qualification. In the control rod design that is the leading candidate at this time, the rigid sections of the control rod are comprised of two structural parts that enclose the boron carbide (B_4C) compacts, and ball-joints connect these sections to form the flexible control rod assembly. The B_4C containment parts in each section of the control include the outer sleeve that provides lateral containment for the B_4C

3 The design impurity levels were obtained from (GA 2008b) and are applicable to both the MHTGR and GT-MHR. The expected impurity levels are applicable to the GT-MHR. The design impurity levels are considerably higher than the levels that would be expected during equilibrium operating conditions.

compacts, and the threaded end caps that screw into the top and bottom ends of the sleeves. A graphite shock absorber is located at the bottom of each control rod channel to absorb the energy of the impact in the event of an uncontrolled drop of the control rod resulting from failure of the control rod cable, an end cap, or a ball-joint.

Following definition of the design requirements for the control rods (Section 3.1.1), the conceptual control rod design will be developed. Based on the results of the CFD analyses, finite element analyses (FEA) and seismic analyses will be performed to calculate the expected mechanical and seismic loads for the control rods. This activity will also include initial development of the composite material models needed for control rod design. These models will be used to predict the changes that occur in control rod dimensions, strength, etc. as a function of time due to the temperature and neutron flux environment in which the control rods operate. Initial model development is needed to define the material properties to be included in the models. This is necessary to ensure that the correct tests are performed to obtain the materials property data needed for the models.

3.2.2 Test Requirements

This activity does not require any testing. The design work and analyses will be performed by the reactor vendor (assumed to be GA) or GA's designated subcontractor(s) using FEA and seismic analysis codes that have been verified and validated in accordance with the applicable requirements of ASME NQA-1.

3.2.3 Schedule and Cost

The activities described in Section 3.2.1 will start immediately following completion of the activities described in Section 3.1.1. These activities are estimated to require about 3 months to complete. The estimated cost is about $200K.

3.3 Develop Composite Architectures and Obtain Samples for Testing

3.3.1 Activity Description

The reactor designer or its designated subcontractor(s) will perform a review of the ceramic composite materials knowledge base and the composites supply network to identify potential composite materials and composite part manufacturers based on the applicable design requirements. In GA Report 911125, a three-dimensional C/C composite, FMI-222, was identified as the material of choice for the control rods based primarily on the availability of an irradiation data base for this material. This material choice will need to be confirmed, particularly in view of the information presented in Paper HTR2008-58050.

After preliminary selection of the composite material(s) and part manufacturer(s), the reactor designer (or its designee) and part manufacturer(s) will work together to develop the necessary composite architecture and manufacturing processes for the various control rod parts. Shapes having the same composite architecture anticipated for the various parts will then be fabricated and specimens will be cut from these parts for material properties testing, corrosion testing, and irradiation testing as described in Sections 3.4 and 3.5 below.

As previously noted, an ASTM task group is currently developing standard procedures for baseline mechanical properties testing of tubular geometry components made of fiber-reinforced ceramic matrix composites. Ideally, these ASTM standards (and other ASTM standards) will be available in time to be used in preparing test samples from the composite material shapes fabricated in this activity. However, it is highly uncertain that these standards will be available, so the sampling and testing may have to be performed on an experimental basis, and could actually contribute to development of the ASTM standards.

Based on Rolls-Royce's extensive aerospace experience with composite materials; their in-house system for developing and controlling specifications and standards for materials, manufacturing processes, quality, and design of safety critical components; and their current participation in the NGNP Project as a member of the GA NGNP team, GA considers it probable that Rolls-Royce would take the lead in this activity.

3.3.2 Test Requirements

This activity does not require any testing. The reactor vendor or its designated subcontractor(s) will perform the review of the ceramic composite materials knowledge base and the composites supply network to make a preliminary selection of the composite material(s) and the part manufacturer(s). Shapes having the same composite architecture anticipated for the actual parts will be manufactured at the part manufacturer's facility. Appendix G in GA Report 911125 discusses a number of major suppliers of composite materials and parts[4].

3.3.3 Schedule and Cost

This activity will start in parallel with the design activity described in Section 3.2. The review of the ceramic composite materials knowledge base and the composites supply network to identify potential composite materials and composite part manufacturers is expected to require about 6 months. The estimated cost of this activity is about $350K. The duration of the activity to develop the composite architecture(s) and manufacturing process(es) for the control rod sleeves, end caps, and ball-joints; to fabricate shapes representative of the parts and to obtain

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[4] The potential supplier review in Appendix G of GA Report 911125 was provided by Rolls-Royce based on an Internet search, a review of the Literature, and Rolls-Royce's interaction with composite material and parts suppliers in the aerospace industry.

test specimens from these shapes will be about one year. The estimated cost of this activity is $3M.

3.4 Ceramic Composites Baseline Properties Screening Tests

3.4.1 Activity Description

Testing of the test specimens from activity 3.3.1 will be performed to obtain the following material properties data:

- Thermal properties, including expansivity, conductivity, and specific heat
- Elastic modulus and stress-strain relationship
- Tensile, compressive, flexural, and low-cycle fatigue strength
- Friction and wear characteristics

Measuring the material properties on the samples from activity 3.3.1 ensures that the data will be valid for the actual product forms to be used for the control rod components. This is essential because the properties of C/C composites depend on the fiber type and fiber architecture, type of matrix material, and the processing conditions.

3.4.2 Test Conditions

Baseline physical and mechanical properties tests will be performed at standard temperature and pressure (STP), and over a range of temperatures including the nominal steady-state operating temperature for the control rods (about 900°C) and the maximum temperature during a CCD event (1500°C).

3.4.3 Test Configuration

An ASTM task group is currently developing standard procedures for baseline mechanical properties testing of tubular geometry components made of fiber-reinforced ceramic matrix composites. The tests will be conducted in accordance with these ASTM standard procedures if they are available and applicable to the particular composite materials being tested. If ASTM standard test procedures are not available, the reactor designer and testing organization will agree on the test configurations and procedures for the various tests.

3.4.4 Required Measurements

The properties identified in Section 3.4.1 will be measured under the test conditions identified in Section 3.4.2. Each property will be measured on a minimum of two test specimens.

3.4.5 Test Location

If applicable ASTM standard test methods are available, the physical and mechanical properties measurements can be performed at any number of commercial testing laboratories that are qualified to perform testing of ceramic composite materials to the standard test methods. Two potential testing laboratories identified by a quick Internet search include the following.

<u>Touchstone Research Laboratory</u>
The Millennium Centre
Triadelphia, WV 26059
304-547-5800

Touchstone's website indicates that its engineers have extensive experience in specialized tabbing and alignment of samples, critical to mechanical properties testing of composite materials per ASTM C1275. The resulting data from ASTM C1275 ("Standard Test Method for Monotonic Tensile Behavior of Continuous Fiber-Reinforced Advanced Ceramics with Solid Rectangular Cross-Section Test Specimens at Ambient Temperature") includes tensile strength, fracture strength, Poisson's ratio, modulus of elasticity, modulus of resilience, and modulus of toughness (at ambient temperature)

Pacific Testing Laboratories (PL)
24950 Avenue Tibbitts
Valencia, CA 91355\661-257-1437

PL's website indicates that PL offers a very comprehensive range of testing services to the Printed Circuit Board (PCB), Aerospace, Automotive, Plastics, Composites, Rubber, Metals, Wood Flooring, Electronic Device, and Medical Device industries, and that their expertise extends to many fields, including: Electrical, Optical, Mechanical, Environmental, Metallurgical, Chemical, Thermal, Physical, Analytical, Forensic, and Failure Analysis.

If ASTM standard testing procedures are not available, the testing will have to be conducted on an experimental basis. If this is the case, it is recommended that the testing be performed at the INL and/or ORNL. The testing performed at either National Laboratory could potentially contribute to development of the new ASTM standard test procedures for the ceramic composite materials selected for the NGNP control rods.

3.4.6 Data Requirements

All testing shall be conducted in accordance with a Quality Assurance program that ensures the required data accuracy and precision, and data traceability. If the measurements are performed in accordance with ASTM standard methods, the precision and accuracy requirements will be as specified in the ASTM standard. If the measurements are performed on an experimental basis, the precision and accuracy requirements will be determined by the reactor designer and the testing laboratory. In all cases, appropriate laboratory procedures will be used to ensure data traceability.

3.4.7 Test Evaluation Criteria

The conditions for successful completion of the ceramic composites baseline physical and mechanical properties screening tests are: (1) the required measurements as identified in Section 3.4.4 have been completed and (2) the data satisfies the data quality requirements as defined in Section 3.4.6.

3.4.8 Schedule and Cost

This activity will begin as soon as the test specimens from activity 3.3.1 are available. The duration and cost of testing will be greatly influenced by whether the testing is performed per ASTM standard test methods at commercial testing laboratories or are performed on an experimental basis at the INL and/or ORNL. The cost and schedule will also be heavily dependent on how many composite architectures are subjected to testing. Assuming that the number of composite architectures is limited to about six and the testing is done mostly at commercial laboratories, the duration of this task is estimated to be about one year and the cost is estimated to be about $1M.

3.5 Environmental Effects Screening Tests

3.5.1 Activity Description

Testing will be performed on samples from activity 3.3.1 to ascertain environmental effects on candidate ceramic composite product forms for the control rod components:

- The effect of irradiation on the material properties measured on unirradiated test specimens in section 3.4
- Irradiation induced dimensional change and creep
- Effects of corrosion due to helium impurities at the reactor operating temperatures and pressure on the material properties measured on unirradiated test specimens in section 3.4

3.5.2 Test Conditions

Key service conditions for the control rods as given in GA Report 911125 are as follows. All of these values are preliminary and must be confirmed during conceptual design.

Primary coolant helium impurity concentrations: See Table 2 above
Maximum temperatures

- Normal operation: 895°C
- Pressurized CCD event: 1273°C
- De-pressurized CCD event: 1474°C

Max. fast neutron fluence: 8.4 x 10^{25} n/m^2 (E> 0.18 MeV)
Reactor operating pressure: 7.07 MPa

The test program to determine the effects of helium impurities on the ceramic composite materials will include tests with the impurity concentrations at the design levels shown in Table 2 (or at the design levels for NGNP, if these are determined to be different than those in Table 2). It is anticipated that the tests will be run for at least 3,000 hours, but the tests could be of shorter duration if there is adequate confidence in the material models to extrapolate the results of shorter duration tests.

The conditions for the irradiation tests will be based on the expected reactor conditions identified above (but to be verified for the NGNP during conceptual design).

3.5.3 Test Configuration

The ceramic composite material screening irradiations will be performed in the Advanced Test Reactor (ATR) at the INL and/or the High Flux Isotope Reactor (HFIR) at ORNL. The irradiation test rigs will be designed by INL or ORNL based on the specifications for the individual tests as defined in the ceramic composite materials program plan. Post irradiation testing to determine irradiation-induced dimensional changes and creep, and the effects of irradiation on the baseline materials properties (as determined per Section 3.4) will be performed in Hot Cells at INL and/or ORNL.

The tests to determine the effects of helium impurities on the ceramic composite materials at reactor operating temperatures should be performed at INL and/or ORNL using the laboratory-scale helium flow test facilities that were specifically constructed to support the NGNP Program.

3.5.4 Required Measurements

Post-irradiation testing (PIE) of the irradiated samples will be performed to determine irradiation-induced dimensional changes and creep, and the effects of irradiation on the baseline physical and mechanical properties of the materials (as determined per Section 3.4).

Post-heating testing of the corrosion-test samples will also be performed to determine the effects of aging in the reactor helium environment on the baseline physical and mechanical properties of the ceramic composite materials.

3.5.5 Test Facilities

The irradiations and PIE will be performed at INL and/or ORNL as discussed in Section 3.5.3.

The tests to determine the effects of helium impurities on the ceramic composite materials at reactor operating temperatures should be performed at INL and/or ORNL using the laboratory-scale helium flow test facilities that were specifically constructed to support the NGNP Program. If the baseline physical and mechanical properties measurements were performed at commercial testing laboratories (see Section 3.4.5), the post-heating physical and mechanical properties measurements on the corrosion test samples could be performed by the same laboratories.

3.5.6 Data Requirements

All testing shall be conducted in accordance with a Quality Assurance program that ensures the required data accuracy and precision, and data traceability. If the measurements are performed in accordance with ASTM standard methods, the precision and accuracy requirements will be as specified in the ASTM standard. If the measurements are performed on an experimental basis, the precision and accuracy requirements will be determined by the reactor designer and the testing laboratory. In all cases, appropriate laboratory procedures will be used to ensure data traceability.

3.5.7 Test Evaluation Criteria

The conditions for successful completion of the screening tests to determine environmental effects on the candidate ceramic composites baseline physical and mechanical properties are: (1) the required environmental conditioning and post-conditioning measurements as identified in Section 3.4.4 have been completed and (2) the data satisfies the data quality requirements as defined in Section 3.5.6. Further, it is necessary that the test data confirm that there is at least one viable composite architecture for each of the control rod structural components in order for the TRL of the control rods to advance from TRL 2 to TRL 3.

3.5.8 Schedule and Cost

3.5.8.1 Irradiation Testing

The duration of the candidate material screening irradiations and PIE will depend on several variables including the location of the test reactor, the availability of irradiation and PIE facilities, the number of samples to be irradiated, etc. These variables will be defined in the ceramic composites technical program plan (see Section 1.2). However, for the control rod composite materials development and qualification program to support NGNP startup by 2021, these tests must be completed in about a three-year time frame (inclusive of PIE and data reporting) starting in the middle of 2011, which is the earliest date by which the test specimens are expected to be available per the schedule in Section 9.

It is difficult to estimate the cost of this activity without knowing the details of the overall ceramic materials development and qualification program. However, the estimated cost of the baseline graphite development and qualification program is of the order of about $120M and it is reasonable to expect that the cost of the overall composites development and qualification program would be in the same ballpark (although the composites development program might benefit from some of the work completed on the graphite program). The cost of the screening irradiation tests for just the candidate composite architectures for the control rods would perhaps be of the order of $15M to $20M.

3.5.8.2 Corrosion Testing

These tests (on just the candidate materials for the control rods) will start as soon as the test specimens are available (about the middle of 2011 per the schedule in Section 9) and will take about two years to complete. The estimated cost of the testing is $1M.

3.6 Selection of Composite Materials and Architectures

3.6.1 Activity Description

Upon completion of the ceramic composite material (and architecture) screening tests described in Sections 3.4 and 3.5, selection of the composite materials and architectures to be used for the control rod sleeve, end caps, and ball-joints will be made based on review and analysis of the test results.

3.6.2 Test Requirements

This activity does not require any testing. The data evaluation and material/architecture selections will be performed by the reactor vendor (assumed to be GA) or GA’s designated subcontractor(s).

3.6.3 Schedule and Cost

This activity will start as soon as the test reports from the screening tests are available and will take about three months to complete. The cost is estimated to be about $200K.

4 TEST PLAN TO ADVANCE CONTROL RODS FROM TRL 3 TO TRL 4

A TRL of 4 is achieved when technical feasibility ands functionality has been verified at bench-scale. The control rod design activities and ceramic composite material screening test program outlined in Section 3 established proof-of concept (TRL of 3) and culminated in a preliminary selection of the ceramic composite material(s) and architectures to be used for fabrication of the structural elements of the control rods. The following activities are required to advance the TRL from 3 to 4:

1. Finalize the composite architecture for each of the control rod structural elements based on the ceramic composite material(s) and architecture(s) selected based on the results of the screening tests performed to advance the TRL from 2 to 3. Fabricate pieces that are representative of the final composite architecture(s) and cut specimens from these parts for testing.

2. Conduct sufficient physical and mechanical properties tests, irradiation tests, and corrosion tests to develop the statistically significant engineering data base needed for the composite material(s).

3. Complete development and validation of the composite materials behavior and failure models.

These activities are discussed in the following sections. An overall schedule and cost estimate summary is provided in Section 9.

4.1 Finalize Composite Architectures and Obtain Samples for Testing

4.1.1 Activity Description

After selection of the composite material(s) and the part manufacturer(s), the reactor designer (or its designee) and part manufacturer(s) will work together to finalize the composite architecture and manufacturing processes for the various control rod parts. Shapes having the composite architecture to be used for the various parts will then be fabricated and specimens will be cut from these parts for material properties testing, corrosion testing, and irradiation testing as described in Sections 4.2 and 4.3 below. It is assumed likely that Rolls-Royce will again take the lead in this activity for the GA NGNP team.

It is also assumed that ASTM standards will be available in time to be used in preparing the test samples from the composite material shapes fabricated in this activity.

4.1.2 Test Requirements

This activity does not require any testing. Shapes having the same composite architecture anticipated for the actual parts will be manufactured at the part manufacturer's facility. Appendix G in GA Report 911125 discusses a number of major suppliers of composite materials and parts.

4.1.3 Schedule and Cost

This activity will begin immediately after the composite material(s) to be used for the control rod have been selected. The duration of the activity to develop the final composite architecture(s) and manufacturing process(es) for the control rod sleeves, end caps, and ball-joints; to fabricate shapes representative of the parts; and to obtain test specimens from these shapes will be about six months. The estimated cost of this activity is $2M.

4.2 Develop Baseline Material Properties for Engineering Data Base

4.2.1 Activity Description

Testing of the test specimens from activity 4.1.3 will be performed to obtain the following material properties data:

- Thermal properties, including expansivity, conductivity, and specific heat
- Elastic modulus and stress-strain relationship
- Tensile, compressive, flexural, low-cycle fatigue strength, and fracture toughness
- Friction and wear characteristics

Measuring the material properties on the samples from activity 4.1.3 ensures that the data will be valid for the actual product forms to be used for the control rod components. This is essential because the properties of C/C composites depend on the fiber type and fiber architecture, type of matrix material, and the processing conditions.

4.2.2 Test Conditions

Baseline physical and mechanical properties tests will be performed at standard temperature and pressure (STP), and over a range of temperatures including the nominal steady-state operating temperature for the control rods (about 900°C) and the maximum temperature during a conduction cooldown event (1500°C).

4.2.3 Test Configuration

It is assumed that ASTM standard test methods will be available for ceramic composites testing and that the tests will be conducted in accordance with these ASTM standard procedures. If

ASTM standard test procedures are still not available, the reactor designer and testing organization will agree on the test configurations and procedures for the various tests.

4.2.4 Required Measurements

The properties identified in Section 4.2.1 will be measured under the test conditions identified in Section 4.2.2. The types and numbers of samples to be tested will be defined in the Ceramic Composites Technical Program Plan (see Section 1.2).

4.2.5 Test Location

If applicable ASTM standard test methods are available, the physical and mechanical properties measurements can be performed at any number of commercial testing laboratories that are qualified to perform testing of ceramic composite material to these standard test methods. Two potential testing laboratories include Touchstone Research Laboratory and Pacific Testing Laboratories. Contact and capabilities information for these laboratories are provided in Section 3.4.5.

If ASTM standard testing procedures are not available, the testing will have to be conducted on an experimental basis. If this is the case, it is recommended that the testing be performed at the INL and/or ORNL. The testing performed at either of these National Laboratories could potentially contribute to development of the new ASTM standard test procedures for the ceramic composite materials selected for the NGNP control rods.

4.2.6 Data Requirements

All testing shall be conducted in accordance with a Quality Assurance program that ensures the required data accuracy and precision, and data traceability. If the measurements are performed in accordance with ASTM standard methods, the precision and accuracy requirements will be as specified in the ASTM standard. If the measurements are performed on an experimental basis, the precision and accuracy requirements will be determined by the reactor designer and the testing laboratory. In all cases, appropriate laboratory procedures will be used to ensure data traceability.

4.2.7 Test Evaluation Criteria

The conditions for successful completion of the ceramic composites baseline physical and mechanical properties testing are: (1) the measurements as identified in Section 4.2.4 to develop a statistically significant engineering data base for the selected control rod composite architectures have been completed and (2) the data satisfies the data quality requirements as defined in Section 4.2.6.

4.2.8 Schedule and Cost

This activity will begin as soon as the test specimens from activity 4.1.1 are available. The duration and cost of testing will be greatly influenced by whether the testing is performed per ASTM standard test methods at commercial testing laboratories or are performed on an experimental basis at INL and/or ORNL. Assuming that the testing is done mostly at commercial laboratories, the duration of this task is estimated to be about one year and the cost is estimated to be about $1000K.

4.3 Environmental Effects Testing for Engineering Data Base

4.3.1 Activity Description

Testing will be performed on samples from activity 4.1.1 to ascertain environmental effects on candidate ceramic composite product forms for the control rod components:

- The effect of irradiation on the material properties measured on unirradiated test specimens in section 4.2
- Irradiation induced dimensional change and creep
- Effects of corrosion due to helium impurities at the reactor operating temperatures and pressure on the material properties measured on unirradiated test specimens in section 4.2

4.3.2 Test Conditions

Key service conditions for the control rods as given in GA Report 911125 are as follows. All of these values are preliminary and must be confirmed during conceptual design.

Primary coolant helium impurity concentrations: See Table 2 in Section 3.3.1
Maximum temperatures
- Normal operation: 895°C
- Pressurized CCD event: 1273°C
- De-pressurized CCD event: 1474°C

Max. fast neutron fluence: 8.4 x 10^{25} n/m^2 (E> 0.18 MeV)
Reactor operating pressure: 7.07 MPa

The test program to determine the effects of helium impurities on the ceramic composite materials will include tests with the impurity concentrations at the design levels shown in Table 2 (or at the design levels for NGNP, if these are determined to be different than those in Table 2). It is assumed here that the tests will be run for at least 3,000 hours, but the tests could be of shorter duration if there is adequate confidence in the material models to extrapolate the results of shorter duration tests.

The conditions for the irradiation tests will be based on the expected reactor conditions identified above (but to be verified for the NGNP during conceptual design).

4.3.3 Test Configuration

The ceramic composite material screening irradiations will be performed in the Advanced Test Reactor (ATR) at the INL and/or the High Flux Isotope Reactor (HFIR) at ORNL. The irradiation test rigs will be designed by INL or ORNL based on the specifications for the individual tests as defined in the ceramic composite materials program plan. Post irradiation testing to determine irradiation-induced dimensional changes and creep, and the effects of irradiation on the baseline materials properties (as determined per Section 4.2) will be performed in Hot Cells at INL and/or ORNL.

The tests to determine the effects of helium impurities on the ceramic composite materials at reactor operating temperatures should be performed at INL and/or ORNL using the laboratory-scale helium flow test facilities that were specifically constructed to support the NGNP Program.

4.3.4 Measurements

Post-irradiation testing (PIE) of the irradiated samples will be performed to determine irradiation-induced dimensional changes and creep, and the effects of irradiation on the baseline physical and mechanical properties of the materials (as determined per Section 4.2).

Post-heating testing of the corrosion-test samples will also be performed to determine the effects of aging in the reactor helium environment on the baseline physical and mechanical properties of the ceramic composite materials.

4.3.5 Test Facilities

The irradiations and PIE will be performed at INL and/or ORNL as discussed in Section 4.3.3.

The tests to determine the effects of helium impurities on the ceramic composite materials at reactor operating temperatures should be performed at INL and/or ORNL using the laboratory-scale helium flow test facilities that were specifically constructed to support the NGNP Program. If the baseline physical and mechanical properties measurements were performed at commercial testing laboratories (see Section 4.2.5), the post-heating physical and mechanical properties measurements on the corrosion test samples could be performed by the same laboratories.

4.3.6 Data Requirements

All testing shall be conducted in accordance with a Quality Assurance program that ensures the required data accuracy and precision, and data traceability. If the measurements are performed in accordance with ASTM standard methods, the precision and accuracy requirements will be as specified in the ASTM standard. If the measurements are performed on an experimental basis, the precision and accuracy requirements will be determined by the reactor designer and the testing laboratory. In all cases, appropriate laboratory procedures will be used to ensure data traceability.

4.3.7 Test Evaluation Criteria

The conditions for successful completion of the tests to determine environmental effects on the baseline physical and mechanical properties of the ceramic composite architecture(s) chosen for the control rod structural components are: (1) the required environmental conditioning and the post-conditioning measurements as identified in Section 4.3.4 to develop a statistically significant material properties engineering data base have been completed, and (2) the data satisfies the data quality requirements as defined in Section 4.3.6.

4.3.8 Schedule and Cost

4.3.8.1 Irradiation Testing

As with the screening irradiations (Section 3.5), the duration of the engineering data base development irradiations and PIE will depend on several variables including the location of the test reactor, the availability of irradiation and PIE facilities, the number of samples to be irradiated, etc. These variables will be defined in the Ceramic Composites Technical Program Plan (see Section 1.2). For the control rod composite materials development and qualification to support NGNP startup by 2021, these tests must be completed in a two-year time frame starting around the middle of 2015 (the earliest date by which the test specimens are expected to be available per the schedule in Section 9)[5,6]

As previously discussed in Section 3.5.7.1, it is difficult to estimate the cost of the irradiation and PIE activities without knowing the details of the overall ceramic materials development and qualification program. However, the estimated cost of the baseline graphite development and

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5 Test specimens can be fabricated on a special schedule for prototype configurations for running tests. Final configuration will be close enough for the data to be valid for final design.

6 If testing of the composite architectures for the control rods are given priority over testing of candidate composite architectures for other reactor internals and highly-accelerated irradiations are run in HFIR, it might be possible to complete the control rod related tests within two years; however, this schedule is considered to be somewhat unrealistic.

qualification program is of the order of about $120M and it is reasonable to expect that the cost of the overall composites development and qualification program would be in the same ballpark (although the composites development program might benefit from some of the work completed on the graphite program). The cost of the engineering data base development irradiation tests for just the control rod composite architectures would perhaps be of the order of $20M.

4.3.8.2 Corrosion Testing

These tests (on just the materials for the control rods) will start as soon as the test specimens are available (about the middle of 2015 per the schedule in Section 9) and will take about two years to complete. The estimated cost of the testing is $2M.

4.4 Complete Control Rod Composite Materials Behavior and Failure Models

4.4.1 Activity Description

Upon completion of the engineering data base development testing described in Sections 4.2 and 4.3, the test reports will be reviewed and analyzed, and an engineering data base for the control rod materials will be compiled from the test data. The composite materials behavior and failure models for the control rods will be finalized and validated using the engineering data base.

4.4.2 Test Requirements

This activity does not require any testing. The data evaluation and material/architecture selections will be performed by the reactor vendor (assumed to be GA) or GA's designated subcontractor(s).

4.4.3 Schedule and Cost

This activity will start as soon as the test reports from the engineering data base development testing are available and will take about six months to complete. The cost is estimated to be about $400K.

5 TEST PLAN TO ADVANCE FROM TRL 4 TO TRL 5

A TRL of 5 is achieved when the control rod components have been demonstrated at experimental scale in a relevant environment. For the control rods, this demonstration will be achieved by engineering analysis.

5.1 Activity Description

Engineering analyses will be performed to show that the control rod components meet design and safety requirements, including thermal-hydraulic, corrosion and stress, dynamic and seismic, life, reliability, and maintainability requirements. The engineering analyses will be performed using computer codes that have been verified and validated in accordance with the applicable requirements of ASME NQA-1, and the ceramic composite material irradiation-behavior models developed as described in Section 4.

5.2 Test Location

This activity does not require any testing. The analyses will be performed by the reactor vendor (assumed to be GA) or GA's designated subcontractor(s).

5.3 Schedule and Cost

This activity will start about half way through final design and will take about 12 months to complete. The cost is estimated to be about $1M based on the estimated level-of-effort for each subtask shown in Table 3.

Table 3. Estimated Duration and Man-Months for Engineering Analyses (TRL 4 – TRL 5)

Subtask	Duration (months)	# People	Man-Months
Thermal-hydraulic analyses	6	2	12
Corrosion & stress analyses	6	1	6
Dynamic & seismic analyses	9	1	9
Lifetime analysis	3	1	3
Reliability analysis	3	2	6
Total	12	N/A	36

6 TEST PLAN TO ADVANCE FROM TRL 5 TO TRL 6

A TRL of 6 is achieved when components have been integrated into a subsystem and demonstrated at a pilot scale in a relevant environment. For the control rods, this demonstration will be achieved by engineering analysis.

6.1 Activity Description

Engineering analyses will be performed to show that the control rods can be inserted into the guide tubes and core graphite elements without interference for all normal and off-normal events and that the design helium coolant flow through the guide tubes, core graphite elements, and around the control rods will adequate for cooling. The engineering analyses will be performed using computer codes that have been verified and validated in accordance with the applicable requirements of ASME NQA-1, and the ceramic composite material irradiation-behavior models developed as described in Section 4.

6.2 Test Location

This activity does not require any testing. The analyses will be performed by the reactor vendor (assumed to be GA) or GA's designated subcontractor(s).

6.3 Schedule and Cost

This activity will require about 6 months and should be completed about two years before completion of final design. The cost is estimated to be about $200K.

7 TEST PLAN TO ADVANCE FROM TRL 6 TO TRL 7

To achieve a TRL rating of 7, the control rod assembly must complete integrated engineering-scale demonstration in a relevant environment. The following activities are required to advance the TRL from 6 to 7:

1. Conduct vibration testing of a full-scale control rod inside a guide tube and inside a column of graphite control-rod fuel elements. (DDN C.11.03.02)

2. Conduct a control rod shock absorber test (DDN C11.03.05)

3. Conduct a test to assess the structural behavior and integrity of the control rod assemblies to confirm design margins. Full size control rod assemblies will be subjected to operational and accident loads and temperatures to quantify margins against functional failure. The tests will also determine ultimate load capacity and elongation at failure for these conditions. (C11.03.06)

These activities are discussed in the following sections. An overall schedule and cost estimate summary is provided in Section 9.

7.1 Vibration Testing

7.1.1 Test Objective

The NGNP control rods will be longer than the FSV control rods, will be subjected to different flow conditions, and will be made from ceramic composite materials. Control rod vibration tests were performed in 1975 on the FSV metallic control rod design. These tests showed that the control rods were susceptible to flow-induced vibration. These tests were of a limited nature and did not include the effect of crossflow. No data are available for the longer control rods in a 10-block high MHR. Furthermore, the control rods for the GT-MHR and the NGNP will be fabricated from ceramic composite materials.

Potential flow-induced vibration of the control rods could cause impacts with the surrounding graphite channel. Confirmation is required that flow-induced vibrations will not affect the integrity of the ceramic composite control rods and that any potential damage to the control rods or to the graphite channels will not inhibit control rod insertion in service (DDN C.11.03.02).

7.1.2 Test Description

Testing will be performed as described below to obtain the data needed to satisfy DDN C.11.03.02.

7.1.3 Test Conditions

The tests must be performed under expected reactor service conditions. For the NGNP configuration shown in Figure 1, the reactor operating conditions are:

Primary coolant: helium
Maximum temperatures of primary coolant:
- Core inlet: 490°C
- Core outlet: 950°C

Maximum primary coolant pressure: 7.07 MPa
Maximum core pressure drop (nominal + design margin ± tolerance): TBD*
Maximum primary coolant flow:
- Flow through core: TBD*
- Gap flow: TBD*
- Flow per control rod channel: TBD*

*TBD = To be determined. Various design options for reducing the core bypass flow (GA 2007) have been evaluated as a means of reducing maximum fuel temperatures in the core; however, more core design work is needed before these values will be known.

7.1.4 Test Configuration

A full-scale control rod mock-up consisting of a control rod inside a guide tube and a column of graphite control-rod fuel blocks (or simulated control-rod blocks) will be subjected to the aerodynamic loads that would be encountered in a reactor control rod channel. Consideration will also be given to performing the testing at full-scale in air at ambient conditions. If adequate dynamic similarity can be established, such a test would substantially reduce the cost of the testing.

7.1.5 Required Measurements

The effects of control rod insertion position and crossflow shall be evaluated. Mass flow rate will be another test parameter. The primary measurement will be the vibration history of the rod at various locations along the length of the rod.

7.1.6 Proposed Test Location

A large-scale flow and heating test facility is needed. Assuming that it is built, the planned Component Test Facility at the INL would be a potential location for the test. However, there are a number of other possible test locations. One of these is Wyle Laboratories. Another is Hazen Research. Information for Wyle Laboratories and Hazen Research are provided below.

Wyle Laboratories
128 Maryland St.
El Segundo, Ca 90245
(310) 563-6662
john.shimada@wylelabs.com

Wyle Laboratories is headquartered in El Segundo, Calif. and employs approximately 4,200 employees at more than 40 facilities nationwide. Wyle is one of the nation's leading providers of specialized engineering, scientific, and technical services to the Department of Defense, NASA, and a variety of commercial customers. Wyle has been designing and building unique test fixtures, equipment and entire test facilities for industry and government use for more than 50 years. These facilities include centrifugal and linear accelerators, vibration systems with up to six axes of motion, high intensity acoustic chambers, dynamic shock devices like crash barriers, plus rail dynamics test facilities and numerous combined-environment test systems. In the nuclear sector, Wyle has qualified more equipment than anyone else in the industry.

Hazen Research Inc
4601 Indiana Street
Golden, Colorado 80403
Phone: (303) 279 4501
www.hazenusa.com

Hazen services include laboratory-scale research on new processes or adaptation of known technology to new situations, followed by pilot plant demonstration, preliminary engineering, and cost analysis. Projects range from beaker-scale experiments, material testing and analyses to multimillion-dollar continuous pilot or demonstration plants. Activities began at the present location in Golden, Colorado, in 1961 and the staff has since grown to over 120. Sixteen buildings containing an extensive inventory of laboratory and process equipment provide the flexibility for evaluating different unit operations.

If it is determined that the testing can be performed in air at ambient temperature, the Test Tower at General Atomics is also a potential test location.

7.1.7 Data Requirements

Quality Assurance must be in accordance with the requirements for experimental data or validation testing of safety-related components.

7.1.8 Test Evaluation Criteria

The conditions for successful completion of the control rod vibration test are: (1) the required vibration measurements as identified in Section 7.1.5 have been completed, (2) the data satisfies the data quality requirements defined in Section 7.1.7, and (3) the test results confirm that flow-induced vibrations will not affect the integrity of the ceramic composite control rods and that any potential damage to the control rods or to the graphite channels will not inhibit control rod insertion in service.

7.1.9 Test Deliverables

The deliverables include:

- Test specification
- Test plan
- Test procedure
- Test report

The final test report shall include:

- Discussion of test method
- Equipment employed
- Equipment calibration verification
- 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

7.1.10 Schedule, Cost, and Risk

7.1.10.1 Schedule

This test preparation, including fabrication of a prototype control rod, will require about 18 months and must be completed at least three months before the end of final design.

7.1.10.2 Cost

The estimated cost is $1.7M.

7.1.10.3 Risk

The consequence of non-execution could be that it would be necessary to redesign the control rods if excessive vibration were to be encountered at reactor startup. This would result in schedule delays and cost increases.

7.2 Control Rod Shock Absorber Test

7.2.1 Test Objective

The function of the control rod shock absorber is to protect the graphite core support structure in the event that a control rod is accidentally dropped. This is an important function because additional reactor downtime could potentially be caused by a dropped control rod if severe damage occurred to a supporting graphite block. Although shock absorber performance was demonstrated for FSV, the PC-MHR control rods are larger and heavier. Also, unlike the FSV reactor control rod shock absorber, which was metallic and was attached to the bottom of the control rod, the control rod shock absorber in more recent GA MHR designs is located in the graphite core support structure and is non-metallic. Consequently, data are needed to verify the energy absorption characteristics of the control rod shock absorber (DDN 11.03.05).

7.2.2 Test Description

The required data will be obtained by performing drop tests with simulated control rods and prototype shock absorbers to confirm that performance meets requirements. A simulated control rod will be dropped to test various shock absorbers based on three crushable graphite designs. The shock absorber will be stationary and surrounded by a mock-up of the supporting graphite elements, or it will be attached to the control rod itself as in the FSV design. Impact loads will be measured, and damage to the shock absorber and nearby support and channel will be assessed. The shock absorber which best prevents damage to the control rod and surrounding graphite components will be selected for use in the reactor.

7.2.3 Test Conditions

Test data will be obtained using unirradiated material at ambient conditions. (The effects of temperature and irradiation on the performance of the shock absorber will be evaluated based on temperature and irradiation-induced changes to the mechanical properties of the shock absorber material measured in other tests.) The data parameters and service conditions pertinent to the testing are as follows:

Graphite grade: TBD
Service temperature range: 21°C to ~950°C
Maximum fast neutron fluence: [1×10^{25}] n/m^2 (E > 0.1 MeV)
Operating environment: Helium to 7.07 MPa

Characteristics of dropped control rod
- Weight of rod: [93] Kg
- Maximum drop height [9.75] m

Note: TBD = To be determined. Numbers in brackets [ ] are preliminary values provided for scoping purposes only. The actual values will be determined as the NGNP design evolves.

7.2.4 Test Configuration

A simulated control rod will be dropped to test various shock absorbers based on three crushable graphite designs. The shock absorber will be stationary and surrounded by a mock-up of the supporting graphite elements, or it will be attached to the control rod itself as in the FSV design.

7.2.5 Required Measurements

Impact loads will be measured, and damage to the shock absorber and nearby support and channel will be assessed. For each of the three shock absorber variants to be tested, a sufficient data base must be established to provide 90% confidence that the mean value of the data base is at most 20% different form the true mean value.

7.2.6 Proposed Test Location

This test could be performed at any number of commercial testing laboratories, including either of the commercial laboratories identified in Section 7.1.6 as possible candidates for the control-rod vibration testing (e.g., Wyle Laboratories or Hazen Research Inc).

7.2.7 Data Requirements

Quality Assurance must be in accordance with the requirements for experimental data or validation testing for safety-related components.

7.2.8 Test Evaluation Criteria

The conditions for successful completion of the control rod shock absorber test are: (1) the required impact measurements as identified in Section 7.2.5 have been completed, and (2) the data satisfies the data quality requirements defined in Section 7.2.7.

7.2.9 Test Deliverables

The deliverables include:

- Test specification
- Test plan

- Test procedure
- Test report

The final test report shall include:

- Discussion of test method
- Equipment employed
- Equipment calibration verification
- 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

7.2.10 Schedule, Cost, and Risks

7.2.10.1 Schedule

This test will require about one year and should be completed at least a year before the end of final design.

7.2.10.2 Costs

The estimated cost is $600K

7.2.10.3 Risks

Verification of shock absorber performance by testing is considered necessary because of the uncertainties associated with analytical predictions. If the absorption characteristics of the shock absorber were to be inadequate in the event of a dropped control rod, damage to core support components could occur. This would result in a potentially major unscheduled outage to replace the damaged components.

7.3 Control Rod Structural Integrity Test

7.3.1 Test Objective

The control rods are designed to accommodate high temperatures during core conduction cooldown events. The structural behavior and integrity need to be experimentally confirmed because there is significant uncertainty in the analytical predictions of the behavior and failure modes of the control rods during these events. Nonlinear effects associated with creep strain and rupture are difficult to predict accurately. Thus, margins against operational failure and verification of safety need to be confirmed to reduce uncertainty and to provide credible control rod design margins.

7.3.2 Test Description

The testing will be performed to assess the structural behavior and integrity of the control rod assemblies to confirm design margins. Full size control rod assemblies will be subjected to operational and accident loads and temperatures to quantify margins against functional failure. The tests will also determine ultimate load capacity and elongation at failure for these conditions.

7.3.3 Test Conditions

The tests must be performed under expected reactor service conditions. For the NGNP configuration shown in Figure 1, the reactor operating conditions are:

Maximum control rod temperatures

- Normal operation: 895°C
- Pressurized CCD event: 1273°C
- De-pressurized CCD event: 1474°C

Maximum primary coolant pressure: 7.07 MPa

Maximum core pressure drop (nominal + design margin ± tolerance): TBD*

Maximum primary coolant flow:

- Flow through core: TBD*
- Gap flow: TBD*
- Flow per control rod channel: TBD*

*TBD = To be determined. Various design options for reducing the core bypass flow (GA 2007) have been evaluated as a means of reducing maximum fuel temperatures in the core; however, more core design work is needed before these values will be known.

7.3.4 Test Configuration

A full-scale control rod mock-up consisting of a control rod inside a guide tube and a column of graphite control-rod fuel blocks (or simulated control-rod blocks) will be subjected to the aerodynamic loads that would be encountered in a reactor control rod channel.

7.3.5 Required Measurements

The ultimate load capacity and failure modes of the control rod ball-joints will be tested at temperatures up to 950°C. Force and deflection will be measured over the full range of loading. In addition, strain will be measured at selected locations to help interpret the results. The insertion of control rods into a required pre-determined distorted control rod channel shall be established and verified.

7.3.6 Proposed Test Location

A large-scale flow and heating test facility is needed. Assuming that it is built, the planned Component Test Facility at the INL would be a potential location for the test. However, there are a number of other possible test locations. One of these is Wyle Laboratories. Another is Hazen Research. Information for Wyle Laboratories and Hazen Research was previously provided in Section 7.1.6. If it is determined that the testing can be performed in air at ambient temperature, the Test Tower at General Atomics is also a potential test location.

7.3.7 Data Requirements

Quality Assurance must be in accordance with the requirements for experimental data or validation testing for safety-related components.

7.3.8 Test Evaluation Criteria

The conditions for successful completion of the control rod structural integrity test are: (1) the required measurements as identified in Section 7.3.5 have been completed, and (2) the data satisfies the data quality requirements defined in Section 7.3.7, and (3) the test results confirm that the control rod design includes adequate margins against operational failure.

7.3.9 Test Deliverables

The deliverables include:

- Test specification
- Test plan
- Test procedure
- Test report

The final test report shall include:

- Discussion of test method
- Equipment employed
- Equipment calibration verification
- 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

7.3.10 Schedules, Cost, and Risks

7.3.10.1 Schedule

This test will require about 18 months and should be completed at least three months before the end of final design.

7.3.10.2 Cost

The estimated cost is $1.9M

7.3.10.3 Risks

The consequence of non-execution could be in-service failure of a control rod. This would potentially result in an unscheduled outage to replace the control rod.

8 TEST PLAN TO ADVANCE FROM TRL 7 TO TRL 8

A TRL of 8 is achieved by demonstrating an integrated prototype of the system in its operational environment with the appropriate number and duration of tests and at the required levels of test rigor and quality assurance. All NGNP systems, structures, and components must have a TRL of 8 as a prerequisite for hot startup of the NGNP. The control rod will reach a TRL of 8 as a result of successful interface with the neutron control assemblies and control rod guide tubes as demonstrated by an integrated test of the neutron control system.

8.1 Test Objective

Verify the operability of the control rod to be inserted and removed in the control rod channel with the NCA as the motive force.

8.2 Test Description

It is assumed that this test will be part of the integrated test of a neutron control assembly (NCA), control rod guide tube, and control rod described in Section 5 of GA Test Plan 911133 (for reactor control equipment, including the neutron control assemblies). The test will include moving the control rod with the NCA in normal and abnormal control rod channels and measuring the forces required to move the rod. The NGNP is identified as the location for the integrated neutron control system test in Test Plan 911133. An above-reactor test rig (possibly on the NGNP refueling floor) will be required to accomplish the testing.

8.3 Test Conditions

The test will be performed in air at ambient temperature and pressure. (Although this is obviously not the operational environment for the control rods, testing the control rods in the actual operating environment prior to NGNP hot startup is considered impractical and unnecessary.)

8.4 Test Configuration

The control rod will be attached to the NCA with guide tubes between the NCA and a column of reflector elements. The test rig holding the reflector column must be able to hold the reflector column in abnormal configurations for off-normal insertion verification. It is expected that operation of the control rods within the NGNP core will not be allowed prior to hot startup unless some limited operation can be conducted within cold shutdown reactivity margins. Thus, an above-reactor test rig (possibly on the NGNP refueling floor) will be required to accomplish the testing.

8.5 Required Measurements

The ability to insert and to withdraw the control rods from the reflector element column will be verified, and the forces required to move the control rods will be measured.

8.6 Test Location

The NGNP is identified as the location for the integrated neutron control system test in GA Test Plan 911133.

8.7 Data Requirements

Quality Assurance must be in accordance with the requirements for experimental data or validation testing for safety-related components.

8.8 Test Evaluation Criteria

The conditions for successful completion of the integrated control rod system test are: (1) the required measurements as identified in Section 8.5 have been completed, (2) the data satisfies the data quality requirements defined in Section 8.7, and (3) the test results confirm the operability of the control rod to be inserted and removed in the control rod channel with the NCA as the motive force.

8.9 Test Deliverables

The deliverables include:

- Test specification
- Test plan
- Test procedure
- Test report

The final test report shall include:

- Discussion of test method
- Equipment employed
- Equipment calibration verification
- 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

8.10 Schedule, Cost, and Risks

8.10.1 Schedule

This test will be performed as part of the integrated NCA test. It will be completed approximately three months prior to installation of the NCAs and control rods in NGNP.

8.10.2 Cost

The incremental cost of this test is $200K. This is based on about $50K for control rod hardware and $150K for testing manpower. This does not include the cost of test rig fabrication, which is covered under the integrated neutron control system test.

8.10.3 Risks

The consequence of non-execution could be an inability of accomplish the desired movements of control rods in the reactor. This could result in a costly delay in NGNP startup or an unscheduled outage to correct the problem at some later time.

9 COST AND SCHEDULE SUMMARY

Figure 3 provides an integrated schedule for control rod technology development and design and a summary of the estimated costs.

DRL	Activity	Estimated Cost ($K)
	NGNP Schedule	
	Common Conceptual Design	
	Common Preliminary Design	
	NHSS Conceptual and Prelim. Design	
	Final Design	
	Site Work and Construction	
	Startup and Testing	
	Control Rod Design, Fab, & Installation Schedule	
	Conceptual Design	
	Preliminary Design	
	Final Design	
	Prepare and issue control rod procurement documents	
	Fabricate CRs for NGNP	
	Install control rods in NGNP	
	Control Rod Technology Development	
2→3	Finalize NGNP Point Design	NA
	Develop control rod design requirements	350
	Develop CR conceptual design	200
	Review composites knowledge base and supply network; select manufacturers	350
	Dvlp comp. architecture, fab. shapes, obtain test samples	3000
	Baseline properties testing	1000
	Irradiation Testing	20000
	Irradiation capsule design	
	Irradiation testing	
	Post irradiation examination	
	Prepare test reports	
	Corrosion testing	1000
	Select composite materials and architectures	200
3→4	Develop final comp. architecture and fab. shapes	2000
	Baseline properties testing for engineering data base	1000
	Irradiation testing for engineering data base	20000
	Corrosion testing for engineering data base	2000
	Complete CR composites materials models	400
4→5	Engineering analysis	1000
5→6	Engineering analysis	200
6→7	CR vibration testing	1700
	Develop test specification	
	Fab. prototype control rod	
	Set up test facility and prepare test procedures	
	Conduct testing and prepare report	
	CR shock absorber test	600
	CR structural integrity test	1900
	Develop test specification	
	Fab. prototype control rod	
	Set up test facility and prepare test procedures	
	Conduct testing and prepare report	
7→8	Integrated NCA testing at NGNP	200
	Total	57100

Figure 3. Schedule and Cost Estimate Summary for NGNP Control Rod Development

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