MEMO

Dominion Engineering, Inc.

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Subject: Component Test Facility Review

1 Background / Introduction

The objective of the NGNP (next generation nuclear plant) project is to demonstrate the viability of High Temperature Gas-Cooled Reactors (HTGR) for electricity production, hydrogen production, and process heat generation for industrial applications. Under the Energy Policy Act of 2005 the NGNP program is scheduled to design and build a prototype high temperature gas reactor (HTGR) by the year 2021.

To support the development of the NGNP, in particular components requiring development or the application of new technologies, the construction of a dedicated component test facility (CTF) near INL was proposed. The CTF would enable full scale component tests to be conducted at conditions representative of those expected in the NGNP (i.e., pressure, flow rate, and temperature) and support the entire lifecycle planned for the NGNP project. Working with INL, DEI reviewed the functional requirements and potential alternatives to the planned component test facility (CTF) intended to support the lifecycle (development, construction, commissioning, and commercial deployment) of the NGNP. This memorandum summarizes the results of the review.

2 Objectives

The objectives of this review are as follows:

- Review the CTF functional and operational requirements (F&ORs) with respect to the expected technology needs of the NGNP (Section 4).
- Review and identify possible alternative facilities that may be used to satisfy the F&ORs of to the proposed CTF.

- Identify and review capabilities of existing and planned high-temperature gas reactor technology test loops that may be able to satisfy the F&ORs of the proposed CTF (Section 5).
- Identify separate test facilities that may be used for component-level or process-level development and testing (Section 6).

Note that facilities already well known to INL personnel or previously identified by INL as potential alternative facilities are not discussed in this review.

3 Conclusions

Based on DEI's review, the following conclusions were drawn regarding the suitability of the proposed CTF for support of the NGNP program:

- The technological capabilities of the proposed CTF satisfy the key F&ORs of the NGNP program [1].
- Alternative high temperature test loops have been identified with similar capabilities to the proposed CTF but will not be suitable for lifecycle support of the NGNP.
  - Existing loops give scheduling priority to their country/organization of origin.
  - Most loops are too small for full-scale NGNP component testing.
- Additional independent facilities were identified for component-level and process-level testing. Due to limitations listed below, these facilities do not supplant the need for the proposed CTF.
  - Component-level test facilities do not have access to high temperature and high pressure helium.
  - Component-level test facilities are not sufficiently large to perform full-scale testing.
  - Test facilities with NGNP related process experience (i.e., SI or Hybrid SI Loops) do not have the size or power infrastructure for full-scale testing.

4 Review of Functional and Operational Requirements of NGNP CTF

To support the NGNP project, the CTF must meet the following criteria:

- Support the complete NGNP lifecycle including development, construction, commissioning, and commercial deployment. Key to satisfying this criterion is the provision of representative NGNP operating conditions summarized as follows:
  - Maximum heating power: 30-50MWth
  - Helium flow rate: 25kg/s
  - Helium pressure: 9MPa
  - Maximum temperature: 950°C
- Development of critical systems, structures and components (SSCs) with both laboratory and engineering-scale testing require the following:

  - Testing and qualification under representative NGNP operating conditions.
  - Instrumentation must support verification and validation (V&V) of computer codes.
  - Conduct both steady-state and transient tests for expected NGNP conditions.
  - Test operational and control philosophies.
- Support secondary loop conditions for qualification of process heat applications and hydrogen production.
- Support investigations of alternative heat transfer fluids.
- Support procedure development and training for the NGNP maintenance and support program along with development of in-service inspection (ISI) requirements.
- Conduct parallel testing to support the scheduled NGNP milestones and key dates.

The plan for the CTF, set forth by the vendors in Reference [1], was reviewed by DEI. The review indicated that all key criteria will be met. Specifically, the proposed CTF meets the criteria as follows:

- Location at or near INL would ensure the availability of the facility for the entirety of the NGNP program, and provide preferential testing to NGNP-related projects.
- Infrastructure and facilities will permit testing of the necessary components, a variety of heat transfer fluids, and provide:
  - Large scale component test capability including the intermediate heat exchanger, hot gas ducting, and hydrogen production components.
  - Large scale processes test capability, such as Sulfur Iodine (SI) loops or high temperature electrolysis (HTE) systems, for hydrogen production.
  - Flexibility to test the effectiveness of alternative heat transfer fluids (i.e., Nitrogen).
- Efficient materials and process development and qualification via simultaneous testing and off-line troubleshooting capability.

In summary, based on DEI's review of the proposed CTF, all key F&ORs for support of the NGNP program are satisfied.

5 Review of Potential Alternative Test Loops

High temperature gas test loops (existing and planned) evaluated as to their potential viability for the development of NGNP technology are discussed in this section. Prototype and test reactors are not considered due to expected licensing difficulties associated with experimental components or processes. The potential alternative test facilities newly identified as part of this review are listed in Table 1 and described in the following sections. The last row of Table 1 contains the recommended operating conditions of the proposed CTF.

Table 1: Existing and planned high temperature gas test loops

Facility	Country	Heating Power [MW]	Helium Flow Rate [kg/s]	Pressure [Mpa]	T_{max} [°C]	Status
HE-FUS3	Italy	0.21	0.35	10	530	Functional since 1995
HETL	China	NA	NA	3	950	Functional
PBMM	South Africa	0.42	2.05 (Nitrogen)	0.35	650	Functional since 2002
CLAIRE	France	NA	0.2 (Air)	0.6	500	Functional since 2006
HTR-E	Germany	NA	NA	7	NA	Planning stages
CTF	USA	30-50	25	9	950	Planning stages

5.1 Existing Loops

5.1.1 HE-FUS3 - Italy

The Euratom Association (ENEA) operates a small helium loop at Brasimone Italy. Recently this loop has been used to test thermo-mechanical properties of prototype module assemblies for the International Thermonuclear Engineering Reactor (ITER) [2]. Though potentially available for component or process-level testing, the loop does not meet operational requirements, as shown in Table 1. Both maximum operating temperature and helium flow rate are below estimated requirements for NGNP development testing.

Also at the Brasimone site are the Chemistry and Operations Loops, CHEOPE I, II and III, used to investigate thermal-hydraulics, liquid metal heat transfer and physical properties [3]. These loops are potentially available for testing of alternative working fluids, though scheduling preferences for Italian and EU research groups will likely delay the NGNP development timeline.

5.1.2 Helium Test Loop - China

The Helium Test Loop (HETL) was used in the development of the hot gas ducts for the HTR-10 test reactor. The loop operating pressure and temperature are listed in Table 1[4, 5]. As shown in the table, the operating pressure of the HETL is below the required ~9MPa, reducing its suitability for NGNP testing. Furthermore, scheduling preference would be granted to Chinese research organizations.

5.1.3 Pebble Bed Micro Model - South Africa

The Pebble Bed Micro Model (PBMM) is a closed cycle, three-shaft, intercooled recuperative Brayton cycle using nitrogen. It is primarily used for verification of thermal-fluid analysis codes, such as "Flownex" [6,7]. The facility has also been used in the study of reactor startup and shutdown behavior, due to its small size and operating range (see Table 1). Since the working fluid planned for U.S. HTGRs is helium and much of the necessary development is specific to the use of helium, the PBMM is likely to be of limited utility for NGNP development testing. However, the facility could be considered for evaluating nitrogen as a potential working fluid.

5.1.4 CLAIRE - France

CEA, AREVA NP and EDF partnered to construct the CLAIRE loop in 2006 to test the capability of high temperature intermediate heat exchangers [8]. As listed in Table 1, the CLAIRE loop operates with air at the appropriate temperature but has a lower flow rate and pressure than that required for the CTF. Consequently, the CLAIRE loop will not meet F&ORs of the NGNP development process. The loop may be considered to evaluate air as a working fluid but this choice is not likely due to the expected high rates of oxidation associated with the use of high-temperature air.

CEA also operates a facility at Colima where it conducts research on thermo-chemical cycles for hydrogen production, as well as testing of thermal insulation and bearings for helium circuits [9]. The Colima test center could be considered for component-level testing, though scheduling restrictions may adversely affect the NGNP development schedule.

5.2 Loops Under Construction - HTR-E

The European Union (EU) is building a component test facility for development of NGNP technology. The system will be designed to test components of both pebble bed modular reactors (PBMRs) and gas turbine modular helium reactors (GT-MHRs). Specific components planned to be tested include:

- High pressure and temperature helium turbines
- Helium/helium heat exchanger (recuperator)
- Large capacity magnetic bearings
- Helium rotating seals (leak-tightness)
- Sliding components (tribology)

- Helium purification system

The HTR-E test facility is still in the planning stage and the exact capabilities were not investigated in this review. The EU has placed highest priority on testing of the high-temperature helium turbine due to its necessity for a direct Brayton cycle process. To properly simulate operational conditions, the loop would require helium gas at 850°C, with a heating power of 100-300MWth [10]. The HTR-E would therefore likely meet many of the NGNP F&ORs for a CTF. However, given the uncertain completion schedule of the HTR-E in addition to the fact that, upon its completion, scheduling priority is expected to be given to EU research organizations, the likelihood of the HTR-E being a suitable surrogate for the proposed CTF is considered low.

6 Review of Component-Level and Process-Level Test Facilities

Individual test facilities that may be used for smaller-scale, component- or process-level testing are discussed in this section. The test facilities were separated into four categories as follows:

- Category 1: Test facilities with high temperature test capabilities that perform research associated with NGNP components or processes.
- Category 2: Test facilities with high temperature test capabilities that perform research in areas not directly related to NGNP components or processes.
- Category 3: Low temperature test facilities with component or process testing related to NGNP development.
- Category 4: Low temperature test facilities with no component or process testing related to NGNP development.

6.1 Category 1 Test Facilities

6.1.1 Commercial and Government Test Facilities

6.1.1.1 KUFA/NACOK - Germany

KUFA is a high temperature furnace developed at Jülich in the 1970's to test the performance of post irradiated high temperature reactor (HTR) fuel elements at temperatures up to 1800°C [11]. It was relocated at the Institute of Transuranium Elements (ITV) in January 2003 and testing of hot components was re-initiated in March 2003.

Jülich also houses the NACOK experimental unit designed to study air ingress phenomena in HTGRs. Specific test conditions were not investigated in this review but testing has focused on quantifying the temperature distributions/heat transfer, flow rates, and friction in pebble bed cores.

The facilities at Jülich are operated by the EU Joint Research Centre (JRC) and therefore provide preferential scheduling to EU research organizations which may preclude extensive use of this facility in support of the NGNP program [12,13]. However, given the extremely high temperatures available at KUFA, it may still be practical to perform limited very high temperature testing of small (fuel element sized) components at KUFA.

6.1.1.2 Korea Atomic Energy Research Institute - Korea

The Korea Atomic Energy Research Institute (KAERI) is currently conducting benchtop scale research on a closed loop SI cycle. This cycle operates at a hydrogen flow rate of $0.02Nm^3/hr$ (at standard temperature and pressure) at 5bar. The flow rate of hydrogen and the pressure are scheduled to be increased to $1.0Nm^3/hr$ and 20bar, respectively, in the near future [14]. In the next two years KAERI also plans to construct a pressurized helium high-temperature loop to operate at 950°C, though with a heating power of only 10kW. Long term plans also call for a 300MWth HTGR to be built by 2019 for the production of 30,000 tons of hydrogen annually.

Timely NGNP development testing will be difficult as scheduling priority will be given to Korean research organizations. Additionally, the facilities expected to be available in the near term are benchtop loops that do not meet the requirements for full-scale testing necessary for NGNP development [15].

6.1.1.3 Toshiba - Japan

Toshiba currently operates a benchtop scale SI cycle at ~1000°C producing H_2 at a rate of 1 NL/hr. Additionally, there are plans to construct a HTE process as well operating at ~900°C. In the process of developing this test loop, Toshiba has also performed some high temperature materials testing. The Toshiba facility is expanding, but is currently too small to support NGNP testing [16].

6.1.2 University Test Facilities

6.1.2.1 Massachusetts Institute of Technology

The Massachusetts Institute of Technology (MIT) is conducting air ingress and flow bypass experiments on pebble bed geometries for the NGNP program. MIT is also involved in materials testing with INL for Alloy 617 and Alloy 230 in the range of 450°C to 950°C [17]. Although it is expected that the results of the MIT testing will be useful in guiding more comprehensive testing at the CTF, the scope and scale of the testing are likely to be smaller than required for NGNP development.

6.1.2.2 University of California - Berkeley

The University of California at Berkeley (UCB) is conducting research in conjunction with Sandia National Laboratories (SNL) and Oak Ridge National Laboratory (ORNL) on the use of molten salts in high temperature reactors [18]. The research considers high-temperature closed helium cycles for use with molten salt or liquid metal cooled reactors, as well as high performance ceramic composite heat exchangers for high temperature applications (800 – 1000°C). Although smaller in scale, technologies developed at UCB could potentially be considered for the NGNP.

6.1.2.3 University of Nevada - Las Vegas

The University of Nevada at Las Vegas (UNLV) is currently working with General Atomics, SNL, UCB, MIT and ORNL to develop high temperature heat exchangers for use in advanced nuclear reactors [19]. As stated previously, although likely to be smaller in scale than that required for full scale NGNP testing, these technologies and the knowledge base acquired in their development could prove useful for the NGNP program.

6.2 Category 2 Test Facilities

6.2.1 NASA Arc Jet Center

The NASA Arc Jet Center is involved in testing materials at temperatures up to 1850°C in order to simulate atmospheric re-entry [20]. Though this center does not specifically test components intended for the nuclear industry it is possible that some NGNP components could be tested at very high temperatures here. Large scale or extended testing would likely be impractical due to expected scheduling difficulties. In addition, the Arc Jet Center does not have access to high temperature and high pressure helium, exposure to which is a critical part of NGNP development testing.

6.2.2 General Electric Gas Turbine Test Laboratory

General Electric Co. (GE) operates a gas turbine test lab (GTTL) in Greenville, South Carolina where it conducts flame holding, emissions, dynamics, operability, performance and reliability testing [21]. Though the facility has experience testing full-size components, it will likely not support NGNP development testing as they do not have a supply of high temperature and high pressure helium.

6.2.3 BAGIRA - Hungary

The Budapest Advanced Gas-Cooled Irradiation Rig Assembly (BAGIRA) was rebuilt in 1993 and has operated since 1998 conducting radiation embrittlement experiments [22]. Limited testing has also been conducted on alternative materials for reactor pressure vessel construction. The test rig has a heating power of 20MW, and a design temperature of 500°C. Due to the low operational temperature, this facility does not meet F&ORs for the NGNP development testing.

6.2.4 AREVA Research Center - France/Germany

AREVA has several facilities that conduct testing of high temperature materials and investigation of electrochemical and physical/chemical properties in Paris and Cadarache, France [3]. Specific testing capabilities were not investigated in this review. These are small scale test facilities and are unlikely to be suitable for testing full-scale NGNP components.

AREVA also operates four component test facilities in Germany, which carry out materials, corrosion, thermal hydraulics, welding, and systems level processes testing [23]. Component-level testing may be possible at these facilities, though the specific test capabilities of the AREVA facilities were not investigated in this review.

AREVA also operates the BWR and PWR test loops, KATHY and PKL [24]. However, the operating temperatures at these test loops will not allow for component or process level NGNP testing.

6.3 Category 3 Test Facilities

6.3.1 Paul Scherrer Institute - Switzerland

The Paul Scherrer Institute (PSI) conducts hot cell testing including material science, neutron scattering, and LWR fuel research. In the past, PSI has also conducted HTR research.

The PROTEUS nuclear reactor is a zero power research reactor that has been in operation since February 1968 [25]. Though the reactor is currently conducting tests to increase burn up in light water reactor (LWR) fuel, PROTEUS was also used to conduct tests on water ingress and pebble loading arrangements similar to HTR loadings between 1992 and 1996. Pebble loading experiments permitted the study of the flow through the matrix and leakage or "streaming" effects to be investigated. However, the maximum power of the system is 1kW, permitting the reactor to reach only 40°C. Consequently high temperature testing is not feasible, though flow and some heat transfer testing could still be conducted.

6.3.2 Waste Management Technologies LTD. - UK

Waste Management Technologies (WMT) LTD is an independent service provider for removal and treatment of radioactive wastes, including tritium [26]. WMT also provides laboratory, hot component testing expertise, high temperature chemistry and radioactive materials transport testing, as well as tritium handling and processing capabilities. Though WMT is not capable of full scale component testing, their expertise may be considered on a subcontractor level for NGNP development.

6.4 Category Four Test Facilities

6.4.1 Commercial and Government Test Facilities

6.4.1.1 Heat Transfer Research Inc.

Heat Transfer Research Inc. (HTR) develops numerical heat transfer models and conducts laboratory heat transfer testing at their facility in College Station, Texas [27]. This company could be considered for the development of methods and software for the design of heat exchangers or reactor flow once the CTF is functional and producing data. HTRI's test facility has several experimental units. However, the maximum achievable temperature and heat input in these facilities is 400°C and 3.6kW, respectively. These performance parameters are insufficient for NGNP testing. Construction of a new test facility with heating power of 4.98MW and compressed air available at ~200cfm was initiated in 2005 but this is still below the needs for NGNP development.

6.4.1.2 BNFL Technology Centre - UK

British Nuclear Fuels LTD. (BNFL) operates a research center to support its own activities in the areas of advanced reactor design, fuel manufacturing, waste encapsulation, and decontamination [3]. Specific test capabilities were not evaluated in this review. The company is also closely affiliated with the UK National Nuclear Laboratory which performs hot and cold research on combined heat and power generation, materials testing, corrosion and nuclear chemistry testing, and plant process support [28].

6.4.1.3 Electricite de France Laboratories - France

Electricite de France (EDF) operates several test facilities which conduct research on material properties, high temperature electrochemistry, creep testing, thermal aging, and shock-cycle testing of valves, fittings, and other components, at pressures up to 160bar and temperatures up to 260°C [3]. These test facilities could be considered for small component-level testing.

6.4.1.4 Institutt for Energiteknikk - Norway

The Institutt for Energiteknikk in Norway conducts hot and cold materials testing (specifically on Hastelloy alloys), fuel research, corrosion testing and radiochemical experiments [29]. Some tests are also conducted at the University of Oslo. Hastelloy testing uses low temperature test loops running at ~180°C, which is too low for the NGNP development testing.

6.4.1.5 BOR-60 - Russia

Russia's BOR-60 is a sodium cooled reactor with thermal capacity of 60MW [30]. The loop is a hot facility which operates up to 550°C. The low temperature of operation makes this loop unsuitable for NGNP development related testing.

6.4.1.6 RRC KI - Russia

Since 1994 the Russian Research Center "Kurchatov Institute" (RRC KI) has conducted testing on severe accident conditions in nuclear reactors and concurrently studied low temperature (600°C) activity coefficients for uranium fuel [31]. This is a low temperature apparatus which makes this facility unsuitable for NGNP development related testing.

6.4.2 University Test Facilities

6.4.2.1 Oregon State University

Oregon State University (OSU) is currently funded by the DOE to conduct thermal-hydraulic testing on advanced reactor designs [32]. Technologies developed at OSU could potentially be considered during the NGNP project but would likely require additional full-scale testing in the CTF.

6.4.2.2 University of Maryland

The University of Maryland currently operates a prototype reactor that employs spent fuel as an energy source. The reactor has been used to test a thermal-hydraulic "heat cavity" system which successfully increased the thermal efficiency from 30-36% to 56% [33]. The reactor is small and does not operate at HTGR temperature and is therefore of limited utility for the NGNP component level testing.

6.4.2.3 University of Missouri - Rolla

The University of Missouri operates a 200kW nuclear reactor for material irradiation testing [34]. This facility could be considered as a hot facility for small component testing, but the reactor is too small for other NGNP development tests.

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