

Gas Test Loop Technical and Functional Requirements

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September 2004



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ABSTRACT

This document defines the technical and functional requirements for a gas test loop (GTL) to be designed and constructed to provide a high intensity fast-flux irradiation environment for developers of advanced-concept nuclear reactors. This capability is needed to meet fuels and materials testing requirements of Generation IV (GEN IV) reactors, the Advanced Fuel Cycle Initiative (AFCI) and other programs such as the Space Nuclear Power development program. The overall GTL technical objective is to provide developers with the means for investigating and qualifying fuels and materials needed for advanced reactor concepts. The testing environment includes a fast-flux neutron spectrum of sufficient intensity to perform accelerated irradiation testing. Appropriate irradiation temperature, gaseous environment, test volume, diagnostics, and access and handling features are also needed. This document serves to identify those requirements as well as generic requirements applicable to any system of this kind.

EXECUTIVE SUMMARY

This document has the purpose of identifying functional and operational requirements for a system that can simulate the fast-flux operating environment for advanced fission reactors.

As developers of advanced nuclear reactor concepts prepare to design and build prototypes, it is essential that there be an adequate information base on the behavior in their intended service environments of fuels and materials to be used in those reactors. The Advanced Fuel Cycle Initiative (AFCI) and Generation IV Reactor Program (GEN IV) will be exploring reactor concepts, many of which are fast-flux gas-cooled reactors, and related fuels and materials technologies. Other concepts are for thermal reactors but with advanced fuels and cooling options. A preliminary investigation suggests there is currently no available test facility that can replicate the test environments needed to qualify fuels and materials for those reactors. Other initiatives, such as the NASA program to provide nuclear reactor power for space exploration and planetary surface applications have similar needs for testing in fast-flux environments.

The Gas Test Loop (GTL) Project has been initiated to develop test assemblies that can be used in an existing irradiation facility to provide the test environments needed by these programs. The range of parameters called for by the various programs that may make use of the GTL suggests the greatest economy will be achieved by having two implementations of the GTL concept, each adapted to a different kind of testing. Before any such assemblies can be designed or constructed, it is essential to define the technical and functional requirements they must meet. This document provides those technical and functional requirements.

The various reactor programs will have differing needs for environmental parameters. Indeed, the testing for most programs will involve two distinctly different kinds of testing. One addresses the damage and property changes inflicted on fuels and materials by the neutron (and to a less extent gamma) fields under their intended operating conditions. For such tests, neutron flux and energy spectra are highly important. Other tests will be more concerned with the evolution of fission fragments and activation products from fuels and materials and the transport of those materials through the coolant system. There, heating power will be more important than neutron energy. There, too, meaningful representation of the coolant loop with its flows and thermal conditions will be essential.

Table 2 lists the required features the GTL must have to meet the stated objectives of the developmental reactor programs mentioned. It is important to note that the values shown there are in many cases extremes and that not all requirements will be imposed on each implementation of the GTL system. Testing requirements for the individual programs supported will dictate the specific parameters that must be met in support of that program. The required features listed, where applicable, are considered the minimum acceptable for the GTL. Also listed are desirable features, which will make the GTL more serviceable to users but incorporation of these features will be determined by cost effectiveness and technical feasibility.

Table 1. Summary of features required by the Gas Test Loop. Values in parentheses refer specifically to test implementations where evolution and transport of fission fragments and activation products are the main concerns. Not every requirement will apply to each implementation.

Parameter	Required	Desired	Comments
Test volume length (cm)	15.5	61	
Test volume diameter (cm)	2.54	6.0	
Fast flux intensity (n/cm ² .s, E>0.1 MeV, unperturbed)	1.0E+15 (2.3E+14)	3.0E+15 (1.0E+15)	
Fast/thermal neutron flux ratio	>15 (N/A)	>100 (N/A)	
Flux uniformity in test space (%)	±20	±5	
Peak fuel temperature (°C)	1,800	3,000	
Peak fuel temperature controllability – low temperature (high temperature) (°C)	±20 (±50)	±5 (±30)	greater margin at higher temperatures
Surrounding gas temperature (°C)	280 ±5 – 1,100 ±7	280 ±3 – 1,830 ±5	greater margin for higher temperatures
Loop gas pressure (MPa)	9	25	
Pressure controllability (%)	±3	±1	
Atmospheric compatibility	He, Ne, Ar, Xe, and mixtures thereof	Add H ₂ , CO ₂	
Gas flow to test chamber (mL/min)	(Sufficient for Reynolds number >10,000)		See Section 3.1.9
Instrumentation			
Temperature	15 Channels 10 – 1,400 (°C)	30 Channels 10 – 1,800 (°C)	Higher temperatures may be

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ACRONYMS

ALARA	as low as reasonably achievable
ASME	American Society of Mechanical Engineers
AFCI	Advanced Fuel Cycle Initiative
CFR	Combined Federal Regulations
CRD	Contractor Requirements Document
DOE	U.S. Department of Energy
EBR II	Experimental Breeder Reactor II
GEN IV	Generation IV Reactor Program
GFR	Gas-Cooled Fast Reactor
GTL	Gas Test Loop
HTGR	High Temperature Gas Reactor
LFR	Lead-Cooled Fast Reactor
M&TE	measuring and test equipment
MOX	mixed oxide
MSR	Molten-Salt Reactor
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Standards
NERAC	Nuclear Energy Research Advisory Committee
NFPA	National Fire Protection Association, Inc.
NGNP	Next Generation Nuclear Plant
NHI	Nuclear Hydrogen Initiative
NIST	National Institute of Standards and Technology
NRC	Nuclear Regulatory Commission
NUREG	Nuclear Regulatory Commission report
PCS	primary coolant system
SCWR	Supercritical-Water-Cooled Reactor
SFR	Sodium-Cooled Fast Reactor
SSC	system, subsystem, or component
TBD	to be determined
TRU	transuranic
TSR	technical safety requirement
VHTR	Very-High-Temperature Reactor

1. INTRODUCTION

The U.S. Department of Energy (DOE) has determined that there is a need for a nuclear fuels and materials testing capability, or Gas Test Loop (GTL), in which irradiation testing can be performed for advanced fission reactors.¹ The Advanced Fuel Cycle Initiative (AFCI) has a broad charter to advance nuclear power, particularly by finding a way to close the nuclear fuel cycle or significantly reduce the amount of nuclear waste from reactors. The Generation IV Advanced Reactor Program (GEN IV) is the program that will be developing a number of reactor concepts needed for sustainable nuclear power.

The May 2001 National Energy Policy recommended that the U.S. develop advanced reprocessing and fuel technologies and an expansion of nuclear energy that are cleaner, more efficient, less waste intensive, and more proliferation resistant. These technologies are the key components of advanced nuclear fuel cycles that will be needed for next generation nuclear energy systems. To address these challenges, the Office of Advanced Nuclear Research (DOE/NE-20) has adopted an integrated strategy consisting of the GEN IV, the Nuclear Hydrogen Initiative (NHI), and the AFCI. The GEN IV-AFCI integrated program will develop the next generation of nuclear energy systems, capable of providing energy for generations of Americans. AFCI is closely coupled with the GEN IV Nuclear Energy Systems Initiative, which seeks to deploy a new generation of power plants by 2030. Together, these two programs enable an expanded role for nuclear power as a greenhouse-emission-free, sustainable energy resource that will address long-term U.S. energy security, environmental, and economic concerns.

The mission of the AFCI is to develop proliferation-resistant spent nuclear fuel treatment and transmutation technologies in order to enable a transition from the current once through nuclear fuel cycle to a sustainable, closed nuclear fuel cycle. The primary goals of the AFCI program are to:

- Develop technologies that will reduce the cost of geological disposal of high-level waste from spent nuclear fuel, enhancing the repository performance.

The U. S. currently stores more than 46,000 metric tons (tonnes) of spent nuclear fuel at commercial nuclear power plants, and ~103 operating reactors generate an aggregate of approximately 2,000 tonnes of additional spent fuel each year. At this generation rate, the statutory limit of 63,000 tonnes allocated for civilian spent nuclear fuel within the planned geologic repository will be reached by 2015.

- Enable proliferation resistant recovery of energy contained in spent fuel.

By 2003, 460 tonnes of plutonium inventory would have already accumulated in commercial spent fuel in the U.S. alone and in 2015, the plutonium inventory would reach 750 tonnes. The U.S. has become increasingly concerned about the global accumulation of plutonium, which presents an important proliferation risk worldwide.

- Develop reactor fuel and fuel cycle technologies to support GEN IV nuclear energy systems.

Improved use of energy resources, such as the plutonium and uranium in spent fuel, is an important element of a sustainable energy strategy. If the Secretary of Energy's Nuclear Power 2010 Initiative is successful, the U.S. will start building new nuclear power facilities within the next ten years

that will operate until at least 2070 depending on fuel cycle.

The AFCI research and development program is an integrated research effort aimed at addressing both intermediate-term and long-term issues.

The Generation IV International Forum, along with U. S. DOE's Nuclear Energy Research Advisory Committee (NERAC), has published "A Technology Roadmap for Generation IV Nuclear Energy Systems"^a. It has identified six advanced reactor designs that offer the promise of commercial deployment before 2030. Several of these designs use fuel cycles significantly different from those used by existing U.S. reactors. Although various fuel types have been proposed for these reactors, the final fuels that will be demonstrated have not yet been designed, fabricated, tested or qualified.

A fuel development and qualification program is underway to fabricate, irradiate and perform post-irradiation simulated operating and accident conditions testing. The test fuels will be used to verify that fuels manufactured under reference process conditions perform satisfactorily under the full range of normal operating and accident conditions. This work will require significant resources over an extended period with a goal to qualify and fabricate the first GEN IV reactor fuel by 2011.

^a The GEN IV International Forum includes ten countries-Argentina, Brazil, Canada, France, Japan, the Republic of Korea, the Republic of South Africa, Switzerland, the United Kingdom, and the United States.

1.1 Programs With Irradiation Needs

1.1.1 GEN IV Concepts

The GEN IV program identified the following six reactor concepts.

- Lead-Cooled Fast Reactor (LFR)
- Molten-Salt Reactor (MSR)
- Sodium-Cooled Fast Reactor (SFR)
- Supercritical-Water-Cooled Reactor (SCWR)
- Very-High-Temperature Reactor (VHTR)
- Gas-Cooled Fast Reactor (GFR)

Brief descriptions of the Gen IV reactor concepts are provided in Appendix A. Table 2 lists the principal characteristics and operating environments associated with these various designs.

1.1.2 Space Nuclear Concepts

Another important initiative is the determination by the National Aeronautics and Space Administration (NASA) to make use of nuclear reactor power for space applications.² These may be vehicle power systems to provide propulsion in deep space where conventional fuels and solar power will be ineffective, or they may include modular surface power systems for supplying energy needs for exploration. Propulsion may be nuclear electric, in which the reactor is used to generate electricity to be used with an ion propulsion system; nuclear thermal, where the reactor heats hydrogen and expels it to provide thrust; or a combination of nuclear thermal propulsion and secondary electric power generation in a bi-modal reactor concept. This program is a potential customer for the GTL.

Table 2. Principal characteristics and operating environments for the Gen IV reactors.³

Concept	Flux	Coolant	Coolant Outlet Temperature (°C)	Coolant Pressure (MPa)	Fuel Form
LFR	fast	Pb/Pb-Bi	500 – 800	0.1	clad pellets
MSR	epithermal/ thermal	NaF, ZrF ₄	750 – 800	0.01	molten UF ₆ /ThF ₄
SFR	fast	Na	550	0.1	clad pellets
SCWR	thermal	Supercritical H ₂ O	510	25	clad pellets
VHTR	fast	He	1,000	5 – 8 (process dependent)	blocks, pins, or pebbles
GFR	fast	He	850	7 – 9	pebbles or clad pellets

1.2 Irradiation Needs

All these programs will have needs for irradiation testing of advanced fuels and materials in an environment representative of the environment of their intended service. For some tests, the main concern will be the effects of neutrons on reactor fuels and structural materials. In other tests, the focus will be on the emission and transport of fission and activation products from the fuel assemblies.

The need for a GTL capability has been established within DOE-NE.¹ A single GTL may not meet all the needs of all the programs because, as evident in Table 2, the needs of the various programs differ.

Examination of Table 2 suggests two kinds of testing will be needed.

In one, the main focus will be on neutron irradiation effects on fuels and materials. There, the key capabilities will include intense neutron flux of appropriate energies and the ability to achieve the desired temperatures and temperature gradients in the test articles.

In the other main category of testing, attention will focus on appropriate coolant/material interactions and the transport of any evolved fission or activation products through the cooling system. Combined, these two testing capabilities will

Parameter	Required	Desired	Comments
			witnessed by melt wires
Pressure	3 channels internal 10 channels external 0 – 9 (MPa), $\pm 3\%$	5 channels internal 10 channels external 0 – 25 (MPa), $\pm 3\%$	
Gas composition	3 channels internal 10 channels external down to 1 (mg/kg), $\pm 3\%$	5 channels internal 10 channels external down to 0.11 (mg/kg), $\pm 3\%$	Fully independent
Radioassay	Determined by experiment	On-line spectrometry	
Data access	Remote real-time visibility		
Safety and environment	Avoid hazardous-mixed waste generation Two levels of confinement Automatic safe shutdown Shielded container (< 200 mR/hr)		
Design Lifetime (years)	30	Life of Program	Component replacement acceptable

This list of requirements is not exhaustive. In addition to the specific and quantitative requirements identified here, regulatory and facility interface requirements will be imposed. These may include requirements for physical fit, compliance with facility Technical Safety Requirements, and compliance with criteria and assumptions in the facility Safety Analysis Report.

provide a versatile resource within which to advance technology and science.

1.3 Facility Modification Identification

The requirements for the GTL system do not necessarily require the modification of any facility. Rather, the GTL system consists of assemblies that can be installed in an existing irradiation facility. Such a facility may be a nuclear reactor or a beam facility capable of meeting the functional requirements defined below.

1.4 Design and Development Process

The process of identifying requirements and producing a design is an interactive one. Basic performance goals come from the known or potential customers for the capability. Program requirements must then be tempered by the physical and operational limitations of the host facility. There will necessarily be continuous communication and negotiation among these entities. These relationships are illustrated in Figure 1.

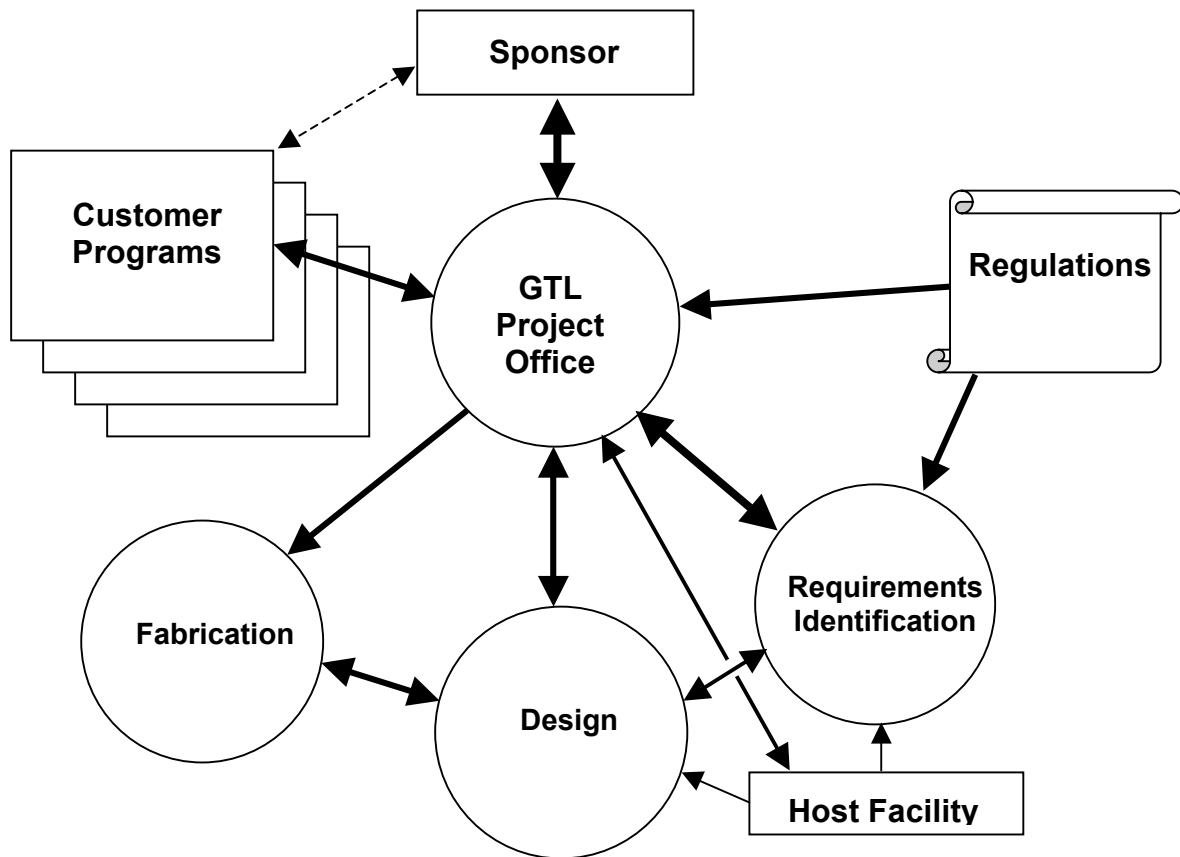


Figure 1. Design of the Gas Test Loop requires coordination at many levels.

1.5 Limitations of the T&FR

The requirements identified in this document are for the performance and operational characteristics of the GTL assemblies. They do not include the many derived requirements associated with installation into any given irradiation facility, nor do they include requirements on the project team with regard to such things as records management, data security, conduct of operations, or integrated safety management.

This document is promulgated by the Fission and Fusion Systems Department of the Nuclear Science and Engineering Directorate at the Idaho National Engineering and Environmental Laboratory.

The purpose of this document is to identify the technical and functional requirements for the GTL. It is intended to be a “living document” (go through several drafts in the process of ultimate completion). When finalized, it will form the basis for the design.

2. Overview

2.1 Facility, Structure, System, Component Functions

The GTL, in its various implementations, will provide a testing environment for fuels and materials of interest to the nuclear community. It is being constructed with particular emphasis on the GEN-IV programs. The testing environments to be provided may include neutron irradiation and gaseous atmospheric control representative of service conditions in the reactors being considered by the programs the GTL will support. Not every aspect of the service environment will need to be included in each GTL implementation. The GTL will also gather information on test articles and the test environment and provide these data to experimenters.

2.2 Facility, Structure, System, Component Safety Category

The GTL is not a Safety-Class system, subsystem, or component (SSC)^b per se, but any part of the GTL that provides a primary coolant or radioactivity containment boundary for the irradiation facility shall be Safety Class. SSCs that do not constitute a primary pressure or confinement boundary shall be Safety-Significant^c because their failure could threaten the safety of the facility in which the SSC is installed.

3. Requirements and Bases

The requirements presented below are to define ranges over which test parameters may vary. It is important to reiterate that not every test implementation will require parameters at the extremes of the values provided below. Note, for example, in Table 2, that the GFR requires 9 MPa of pressure capability but only 850°C coolant exit temperature. The VHTR, on the other hand, requires 1,000°C capability in temperature, but the required pressures will vary dependent on the process the VHTR will be supporting. The GFR and VHTR both require a fast neutron flux, but MSR and SCWR make use only of thermal or epithermal neutron fluxes. Hence, the particular set of capabilities built into a

^b *Safety class structures, systems, and components* means the structures, systems, or components, including portions of process systems, whose preventive or mitigative function is necessary to limit radioactive hazardous material exposure to the public, as determined from safety analyses (10 CFR 830.3)

^c *Safety significant structures, systems, and components* means the structures, systems, and components which are not designated as safety class structures, systems, and components, but whose preventive or mitigative function is a major contributor to defense in depth and/or worker safety as determined from safety analyses (10 CFR 830.3)

particular GTL implementation will depend on the program it is supporting.

3.1 Functional and Performance Requirements

Based on the anticipated and stated programmatic needs of potential users, the following are limits of parameters that may constitute requirements for GTL's technical performance. *Requirements* listed in the following sections are minimum acceptable features and correspond to *shall*s in conventional parlance. *Desired* features would provide benefit but are not necessarily required. They represent extensions in capability, the incorporation of which is optional.

3.1.1 Test Volume

The test volume required depends on the nature of the tests being performed. Tests of fuel or material damage from irradiation can be made on small fuel rod segments or mechanical test specimens. Tests that involve evolution and transport of fission and activation products will require prototypic structures that will generally be larger.

3.1.1.1 Damage Tests

Requirement: The test chamber volume shall accommodate specimens 15.5 cm long and 2.54 cm diameter.

Basis

The GTL justification document¹ indicates that for GEN IV/AFCI, the volume must be able to accommodate 15.5-cm (6-inch) long fuel pins of ~1 cm² cross-sectional area, 2.5-cm (1-inch) diameter test wafers, or possibly fuel pebbles (6-cm spheres). That is a clear volume, independent of any other volume required for instrumentation, cooling systems, gas flow paths, radioactivity containment boundary, etc. It is a test

volume appropriate for irradiation damage testing of clad pellet type fuel and mechanical test specimens of other reactor materials.

Desired: Accommodate test specimens 40 cm long.

Basis

Fuel rods in most reactor designs will be longer than 15.5 cm. Greater test volume length will accommodate longer test specimens or multiple specimens. The desired length of 40 cm is based on the position of the 90% flux intensity points above and below core mid-plane in a typical research reactor.

Desired: Accommodate test specimens 61 cm long and 5 cm in diameter.

Basis

Space nuclear fuel elements may be as long as 61 cm and as large as 5 cm in diameter.

3.1.1.2 Transport Tests

Requirement: The test chamber volume shall accommodate specimens 15.5 cm long and 6 cm diameter.

Basis

GFR and possibly VHTR pebbles are planned to be 6 cm in diameter. The 15.5-cm length would accommodate the same test articles as those addressed in paragraph 3.1.1.1 Damage Tests.

Desired: Accommodate test specimens 61 cm long.

Basis

Space nuclear fuel elements may be as long as 61 cm and as large as 5 cm in diameter.

3.1.2 Neutron Flux

The characteristics of the neutron flux required will depend on the specific program and reactor concept for which the GTL implementation is designed. Here, flux requirements are grouped into damage testing and transport testing.

3.1.2.1 Damage Tests

Requirement: Provide a fast neutron flux ($E > 0.1$ MeV) of $1.0E+15$ n/cm²-s with a fast/thermal ratio >15

Basis:

The justification document¹ requires that fast neutron flux ($E > 0.1$ MeV) shall be greater than 10^{15} n/cm²-s. This is interpreted to mean that the mean value of the neutron flux intensity averaged over the test volume in an unperturbed flux (GTL assembly in place without test article present) shall be at least 1.0×10^{15} n/cm²-s and that the fast to thermal flux intensity ratio shall be at least 15 at all locations in the test volume.

Desired: Provide a fast ($E > 0.1$ MeV) neutron flux of $3.0E+15$ n/cm²-s with a fast/thermal ratio >100 .

Basis

Higher flux rates mean shortened irradiation time to meet specific irradiation objectives. It is desired that the thermal neutron flux should be essentially absent, as in the typical fast reactor spectrum shown in Figure 2.⁴ A desired goal is shown as the lower dashed line in Figure 2. That goal has the thermal neutron flux no more than 1% of its intensity in the thermal fission spectrum. Values for flux intensity are for an unperturbed flux and averaged over the test volume. Fast to thermal ratio applies over the entire test volume.

3.1.3 Flux Intensity Uniformity

Requirement: Flux intensity shall be uniform within 20% over the specimen volume.

Basis

Anticipated requirements of experimenters are that at no point in the test volume shall the intensity of the neutron flux in an unperturbed test space depart by more than 20% from the mean value over the test space.

Desired: Provide flux intensity uniformity of $\pm 5\%$ averaged over the test space.

Basis

Except when flux gradient effects are of specific interest, experimenters will want the neutron flux over the volume of a test specimen to be as uniform as possible to allow correlation of results with theories.

3.1.2.2 Transport Tests

Requirement: Provide a total neutron flux of at least $2.3E+14$ n/cm²-s.

Basis:

Studies of evolution and transport of fission and activation products from fuels and other structures depend on fuel heating and power developed far more than on neutron energy spectra. Therefore, the only requirement with regard to neutron flux is for total available neutronic power. The required power level is typical of that anticipated in advanced reactor operating scenarios. This value is approximately that for a prismatic VHTR.

Requirement: Provide a total neutron flux of at least $1.0E+15$ n/cm²-s.

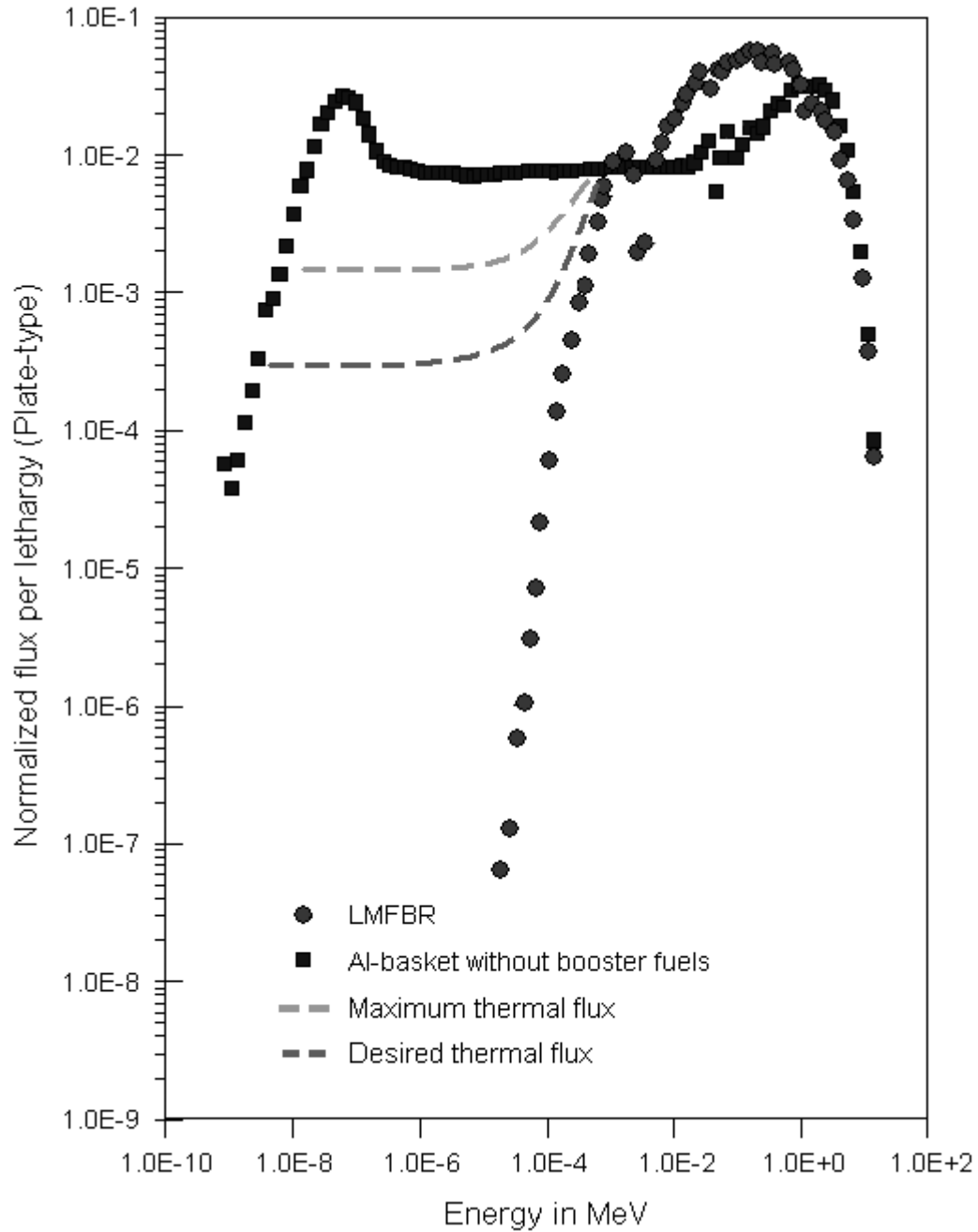


Figure 2. Comparison of fast-fission spectrum (LMFBR) with typical thermal fission spectrum from ATR showing required and desired thermal flux suppression for fast-fission spectrum simulation.

Basis:

Higher flux than expected operating conditions will allow accelerated testing to be conducted. The actual goal is imprecise.

3.1.4 Peak Fuel Temperature

The peak fuel temperature requirement will depend on the reactor concept being tested. Listed here are the extreme values that could be needed. The extreme temperatures will not be needed in all GTL implementations.

Requirement: Provide test conditions that will support a centerline temperature in experimental fuel of 1800 °C, controllable to ± 20 °C. Desired controllability is ± 5 °C.

Basis

1,800°C is the temperature required for a survivable accident in the VHTR.⁵ Controllability requirement is based on anticipated needs of experimenters.

Desired: Provide test conditions that will support an experimental fuel centerline temperature of 3,000 °C, controllable to ± 50 °C. Desired controllability is ± 30 °C

Basis

3,000°C for peak fuel temperature is that anticipated for nuclear-thermal rocket fuel.⁶ Temperatures that high will be unlikely to achieve the same controllability as lower temperatures. Values given are estimates of attainable controllability and anticipated experimenter desires.

3.1.5 Gas Temperature

The requirements for temperature of the gases surrounding test articles will depend on the reactor concept being tested. Listed here are the extreme upper and lower values that could be needed. The extreme

temperatures will not be needed in all GTL implementations (see Table 2).

Requirement: Provide the means of achieving temperature in the gases surrounding the test article of 280 ± 5 °C to $1,100 \pm 7$ °C.

Basis

The temperature of the gas surrounding the test article in the GTL system shall be controllable between temperatures of 280°C and 1,100°C, depending on the particular implementation. The upper end of that range derives from the VHTR, where the design core outlet temperature is 1,000°C. There must be capability to exceed the maximum test temperature by a sufficient amount that modest excursions (10%) from nominal heat loads will not cause the system to fail. The lower end of the controllable gas temperature range is the coolant inlet temperature of the SCWR.⁷ Controllability is based on the anticipated needs of experimenters and estimates of capability.

Desired: Provide the means of achieving temperature in the gas surrounding the test article to $1,830 \pm 10$ °C.

Basis

The desired goal for the maximum controllable surrounding gas temperature of 1,830°C comes from space nuclear power needs. A near-term space reactor turbine inlet temperature of 1,650°C has been discussed with 1,830°C as a goal in the intermediate future.⁸ Controllability requirement is based on the anticipated needs of experimenters and estimates of capability.

3.1.6 Pressure

Pressures required will depend on the specific reactor concept addressed by the

GTL implementation. Extremes are listed here.

Requirement: Provide the means for achieving pressure in the gas surrounding the test article up to 9 MPa.

Basis

Pressures identified for several of the reactors whose fuel would be tested in the GTL are listed in Table 2. The basis of the required value is the operating pressure of the GFR.

Desired: Provide the means for achieving pressure in the gas surrounding the test article up to 25 MPa.

Basis

The desired goal is that used in the SCWR, as listed in Table 2. It should be noted that testing SCWR concepts may involve surrogates for the supercritical water coolant

3.1.7 Pressure Controllability

Requirement: Provide the means to control gas pressure to ± 3 %.

Basis

This requirement is based on anticipated needs of experimenters and present capability.

Desired: Provide the means for controlling gas pressure to ± 1 %.

Basis

This requirement is based on anticipated needs of experimenters and desired capability.

3.1.8 Atmosphere

Requirement: The GTL shall be compatible with He, Ne, Ar, Xe, and mixtures thereof.

Basis

Most of the advanced gas reactors use helium as the coolant. This is mainly due to its chemical stability at high temperatures and very low potential for materials degradation. Mixtures of He with heavy inert gases are used to control thermal conductance across gas gaps.

Desired: The GTL shall also be compatible with H_2 , and CO_2 .

Basis

The nuclear-thermal propulsion reactors use hydrogen because of its ability to maximize specific impulse. The hydrogen tank also is an excellent neutron shield.

The goal for CO_2 compatibility comes from anticipated research that could lead to improved plant efficiencies using a supercritical CO_2 Brayton cycle turbine.⁹ Because of its dissociation at temperatures above $700^\circ C$, compatibility with CO_2 would not be over the full range of operating temperatures.

Desired: The GTL shall also be compatible with supercritical water.

Supercritical water appears in Table 2, but compatibility is closely tied to the pressure capabilities of the GTL implementation. Only if pressures that will support supercritical water are attainable and manageable, would compatibility with this fluid be considered. Dissociation to oxygen and hydrogen becomes an issue at high temperatures in this fluid.

3.1.9 Gas Flow

Requirements for gas flow are determined by the nature of the testing to be performed. For damage tests, flow will generally not be required except as a tool to control test article temperature by varying gas mixtures. That is not considered a requirement of the GTL but a means of meeting the temperature controllability requirement. Therefore, the following applies only to transport test implementations.

Requirement: Gas flow to and from the irradiation volume shall be provided with a minimum flow rate sufficient to produce Reynolds numbers of 10,000 or greater in the vicinity of the test article.

Basis

The capability shall be provided for the GTL to have gas flowing to the test chamber in those tests where evolution and transport of fission and activation products are primary test objectives. This is necessary to allow gas sampling for determining fission product release and gathering evidence of other activity. The requirement is set by anticipated experimenter needs for fully turbulent flow to maximize heat and mass transfer from the test articles and adjacent ducts.

3.1.10 Instrumentation

Instrumentation shall be provided in the following areas, to the precisions indicated.

3.1.10.1 Temperature

Requirement: Provide temperature measurement capability in the irradiation volume with at least 15 channels, capable of measuring temperatures from 10 – 1,400 °C, with resolution of ± 5 °C to 500 °C and $\pm 1.0\%$ above 500 °C

Basis

Temperatures of gases, selected surfaces, and at selected internal points shall be measured to a precision of $\pm 5^\circ\text{C}$ at temperatures to 500°C. Above 500°C, temperature measurement precision shall be within 1.0%. As a minimum, 15 channels of temperature data shall be provided. The basis of these requirements is anticipated needs of experimenters and current state-of-the-art in temperature collection.

Desired: Provide temperature measurement capability in the irradiation volume with at least 30 channels, capable of measuring temperatures from 10 – 1,800 °C, having a resolution of ± 2.5 °C to 1,000 °C and $\pm 0.5\%$ above 1,000 °C.

Basis

A desired goal is for 30 channels of temperature data to be available. The desired goal is for temperature precision of $\pm 2.5^\circ\text{C}$ to 1,000°C and $\pm 0.5\%$ above that temperature. It is recognized that different experiments may use different means of temperature measurement, depending on the temperature ranges of interest in those experiments. For temperatures not measurable in real time using available technologies, temperature witness samples(melt wires) may be considered.

3.1.10.2 Pressure

Requirement: Provide pressure measurement capability with 3 channels internal to the test volume and 10 channels external to the test volume with a range of 0- 9 MPa and a resolution of $\pm 3\%$.

Basis

Means shall be provided to monitor at least 3 channels of pressure measurements

inside the test space of the GTL to a precision of $\pm 3\%$ over the range of pressures measured. Minimum required upper pressure limit is 9 MPa. This is in addition to at least 10 other channels of pressure data that may be gathered outside the test space. For designs where all gases are flowing or are otherwise connected to the outside of the GTL, measurements made outside the test loop can be made to suffice. However, for restricted flow passages or where gas volumes are not connected with the outside of the test space, there will be a need to collect pressure information in the test space itself. Channel numbers and precision are based on anticipated experimenter needs and available pressure measurement technology.

Desired: Provide pressure measurement capability with 5 channels internal to the test volume and 10 channels external to the test volume, having a range of 0 - 25 MPa and a precision of $\pm 1\%$.

Basis

A desired goal is that 5 channels of in-situ pressure measurements be available. Desired upper pressure limit (see Table 2) is 25 MPa. Another desired feature is that precision of pressure measurement be within $\pm 1\%$. Channel numbers and precision are based on anticipated experimenter needs and available pressure measurement technology.

3.1.10.3 Gas Composition

Required: Provide means for determining gas composition on 3 channels of flow to and from locations internal to the test volume and 10 channels for locations external to the test volume, with a sensitivity of 1 mg/kg and a precision of $\pm 3\%$.

Basis

Values are derived from anticipated experimenter needs and available technology. Means shall be provided for determining the elemental composition of gas in flowing streams to a quantitative precision of $\pm 3\%$ on each chemical species present and with the ability to detect components down to 1 atomic part per million (appm). Channels shall be fully independent to prevent mixing of gas streams.

Desired: Provide means for determining gas composition on 5 channels of flow to and from locations internal to the test volume and 10 channels for locations external to the test volume, with a sensitivity of 0.1 mg/kg and a precision of $\pm 1\%$.

Basis

A further goal is to detect not only component species, but individual isotopes to a resolution better than 0.1 mg/kg. Values are derived from anticipated experimenter needs and available technology.

3.1.10.4 Radiological

Requirement: Radioactivity measurements shall be provided to detect gamma emitters in flowing gas to a precision of $\pm \text{TBDCi/m}^3$, beta emitters to a precision of $\pm \text{TBDCi/m}^3$, and alpha emitters to a precision of $\pm \text{TBDCi/m}^3$.

Basis

Values are based on anticipated experimenter needs and technical capabilities.

Desired: Provide on-line spectral analysis of the radioactivity measurements on the gases.

Basis

In addition to total beta and gamma measurements, it is important to know the detailed isotopic composition of beta and gamma signals.

The GTL design shall accommodate the withdrawal of witness plates or coupons placed in the experiment to measure plate-out of gas components in regions of varying temperature. This shall be done without removal of the test article or major GTL components from the irradiation facility.

Means shall be provided to indicate neutron flux and fast-to-thermal neutron flux ratio in the test volume. This shall include cumulative measurements in at least three locations (near, above, and below core mid-plane) and an on-line measurement (quasi-real-time) in at least one location.

3.1.10.5 Data Access

Requirement: Provide remote, real-time visibility of experiment data.

Basis

Means shall be provided for an experimenter using the GTL to have remote, off-site visibility of test data. This does not include command functions, but only passive observation. Care shall be taken to ensure that access to data not directly associated with the GTL is not accessible. Need based on anticipated experimenter requirement and available capability

3.1.11 Safety and Environment

Requirement: Comply with federal, state, site-specific and other applicable requirements for safety and environment issues.

Basis

See the list of potentially applicable regulations in Table 3. Site-specific requirements will be derived from Technical Safety Requirements and Safety Analysis Reports of the host facility.

3.1.12 Design Lifetime

Requirement: The required design lifetime of the GTL system shall be 30 years.

Basis

The requirement is based on anticipated experimenter needs and typical useful lifetimes of host irradiation facilities. It does not preclude replacement of system components, including the in-core components (if in a reactor), in times shorter than that; but any replacement must be achievable within the limits of a normal facility outage or be accomplished while the facility is operating.

3.1.13 Codes, Standards, and Regulations

A listing of applicable codes, standards, and regulations that should be considered in designing the GTL is in Table 2

3.2 Special Requirements

Any irradiation facility in which the GTL can be accommodated will have a number of technical constraints that must be met. Several of these are sufficiently general that they become design requirements for the system.

3.2.1 Experiment Handling

Means shall be provided for inserting and removing the GTL from its host facility. Removal and installation of loop experiments is accomplished with the irradiation facility shutdown and typically

Table 2. Summary of codes, standards, and regulations applicable^a to the design of the Gas Test Loop

Type	Reference Number	Reference Title	Authors	Additional Information	City/State	Year
ASME	ASME B31.1 (Current version)	Code for Pressure Piping	ASME	American Society of Mechanical Engineers	New York, New York	Current
ASME		Boiler and Pressure Vessel Code	ASME	Section III, "Rules for Construction of Nuclear Power Plant Components," American Society of Mechanical Engineers	New York, New York	Current
ASME		Rules for Inservice Inspection of Nuclear Power Plant Components, Boiler and Pressure Vessel Code, Section XI	ASME	(1989 Edition with 1990 Addenda) American Society of Mechanical Engineers	New York, New York	1989
CFR	10 CFR 20	Standards For Protection Against Radiation	Code of Federal Regulations	Updated as of 8/24/2004	Washington, D.C.	8/24/2004
CFR	10 CFR 52.47	EARLY SITE PERMITS; STANDARD DESIGN CERTIFICATIONS; AND COMBINED LICENSES FOR NUCLEAR POWER PLANTS: Subpart B—Standard Design Certifications: Contents of applications	Code of Federal Regulations	Updated as of 8/24/2004	Washington, D.C.	8/24/2004
CFR	10 CFR 73	Physical Protection Of Plants And Materials	Code of Federal Regulations	Updated as of 8/24/2004	Washington, D.C.	8/24/2004
CFR	10 CFR 835	Occupational Radiation Protection	Code of Federal Regulations	Updated as of 8/24/2004	Washington, D.C.	8/24/2004
CFR	29 CFR 1910	Occupational Safety and Health Administration, Department of Labor	Code of Federal Regulations	Updated as of 8/24/2004	Washington, D.C.	8/24/2004
CFR	40 CFR 100-149	Protection of Environment - ENVIRONMENTAL PROTECTION AGENCY Water Programs	Code of Federal Regulations	Updated as of 8/24/2004	Washington, D.C.	8/24/2004
CFR	40 CFR 50-99	Protection of Environment - ENVIRONMENTAL PROTECTION AGENCY Air Programs	Code of Federal Regulations	Updated as of 8/24/2004	Washington, D.C.	8/24/2004
DOE ORDER	DOE O 413.3	PROGRAM AND PROJECT MANAGEMENT FOR THE	U.S. Department of Energy ORDER	Change 0	Washington, D.C.	10/13/2000

ORDER	DOE O 420.1A	FACILITY SAFETY	ACQUISITION OF CAPITAL ASSETS	Washington, D.C.		
DOE ORDER	DOE O 420.1A	FACILITY SAFETY	U.S. Department of Energy ORDER Washington, D.C.	Change 0	Washington, D.C.	5/20/2002
DOE ORDER	DOE O 435.1	RADIOACTIVE WASTE MANAGEMENT	U.S. Department of Energy ORDER Washington, D.C.	Change 1	Washington, D.C.	8/28/2001
DOE ORDER	DOE O 450.1	Environmental Protection Program	U.S. Department of Energy ORDER Washington, D.C.	Change 0	Washington, D.C.	1/15/2003
DOE ORDER	DOE O 5400.5	Radiation Protection of the Public and the Environment	U.S. Department of Energy ORDER Washington, D.C.	Change 2	Washington, D.C.	1/7/1993
DOE ORDER	DOE P 450.4	SAFETY MANAGEMENT SYSTEM POLICY	U.S. Department of Energy POLICY Washington, D.C.	Change 0	Washington, D.C.	10/15/1996
NFPA	NFPA 704	Standard System for the Identification of Hazards of Materials for Emergency Response	National Fire Protection Association	National Fire Protection Association, inc	Batterymarch Park P.O. Box 9101 Quincy, MA 02269 9101	2001
NRC	RG-2.2	Development of Technical Specifications for Experiments in Research Reactors	Nuclear Regulatory Commission	ML003740125, Nuclear Regulatory Commission, Regulatory Guide 2.2	Washington, D.C.	11/30/1973
NUREG	NUREG/CR-5973	Codes and Standards and Other Guidance Cited in Regulatory Documents	J. R. Nickolaus and K. L. Bohlander	PNL-8462 Rev. 3, Prepared for the U.S. Nuclear Regulatory Commission, Pacific Northwest National Laboratory	Battelle Boulevard, Richland, Washington	Aug-1996

^aThe most recent version or replacement should be used.

requires that a heavy cask be positioned over the reactor vessel or primary facility enclosure. Each facility has specific heights such loads are allowed to be lifted to preclude catastrophic damage in the event of an inadvertent drop. There may be additional requirements for irradiation facility shut-down during such maneuvers. Design and planning of the GTL shall comply with such requirements at the host facility.

Availability of an adequate cask in which to accomplish the transport required for post-irradiation examination or disposal must be considered in the design. Such a cask may require DOT and/or NRC certification before use.

The design functions of the experiment handling equipment shall ensure that (a) the GTL or any of its components are installed and removed from the irradiation facility without damage to the facility internals, closure plates, or biological shielding, (b) those components are installed, removed and stored in the hot holding facility (e.g., reactor facility canal) without damage to that facility, and (c) to provide radiation shielding for personnel performing handling operations.

3.2.3 General Design Criteria

General Design Criteria for most irradiation facilities require that the experiment facilities and their associated out-of-facility SSCs important to safety shall meet applicable requirements of DOE Order 420.1A. Applicable requirements for GTL include

- Nuclear Safety Design Criteria
- Nuclear Criticality Safety
- Natural Phenomena Hazards Mitigation

3.2.4 Materials Compatibility

All materials that are exposed to the primary coolant shall be resistant to the corrosive action of the coolant. These are generally limited to aluminum, austenitic stainless steel, and nickel based alloys. The GTL design shall comply with material compatibility requirements for the host irradiation facility.

If the host facility is a nuclear reactor, materials that are incompatible with the reactor fuel element cladding, the reactor primary coolant, canal water, or with the reactor primary coolant system (PCS) structural materials shall be contained to ensure they are not released to the PCS or canal as a result of a Condition 2 (anticipated) or 3 (unlikely) fault.

Incompatible materials, normally used as activation monitors, shall be secured to minimize the likelihood of being lost in the reactor PCS. The following are examples of materials that are chemically incompatible with the PCS: mercury, gold, copper, silver and chlorides. Gold, silver, or other properly reviewed materials may be used as activation monitors, provided they are secured so that the material cannot be lost into the reactor PCS. The preceding materials list is not all-inclusive; there are other materials not listed that are incompatible with the reactor fuel element cladding.

Usage of the following materials shall be shown to be in compliance with the primary experiment safety analyses criterion for the facility.

- Radiologically hazardous activation products
- Radiation sensitive materials
- Highly flammable or toxic materials, per se or as by-products of radiation sensitive materials

- Reactive Materials, which are defined as any solid or liquid having a reactivity index of 2 in National Fire Protection Association Publication 704 or has a disaster or fire hazard indicating detrimental reactions in water or steam.¹⁰

3.2.5 Thermal Hydraulics

The GTL shall be designed such that conduct of the GTL experiments will not adversely affect decay heat transfer from the canal fuel elements or heat transfer from the PCS.

3.3 Special Requirements

3.3.1 Radiation and Other Hazards

The GTL shall meet the requirements of DOE 5480.30 with regard to “defense in depth” and “graded approach” in protection from release of radioactive materials.

3.3.2 ALARA

The design of the GTL shall incorporate ALARA radiation protection principles, meaning that the radiation dose to operators or others will be as low as reasonably achievable (ALARA), consistent with DOE Order 5480.5.

3.4 Engineering Design Requirements

3.4.1 Mechanical Design Criteria—Code Compliance of Experiment Containment

The pressure containment boundary shall be designed in accordance with applicable ASME standards or other appropriate standards.

3.4.2 Chemical and Process

There are no chemical or process requirements imposed on the GTL to meet its functional performance goals except as

may have been previously mentioned in connection with other requirements. Particular implementations may involve chemicals or processes, the safety of which would dictate special requirements.

3.4.3 Electrical Power

There are no inherent electrical power requirements to meet the performance objectives of the GTL except those dictated by accepted codes and standards (see Table 2). Particular implementations may involve electrical power considerations where such requirements would be appropriate.

3.4.4 Measuring and Test Equipment

All calibration control activities shall meet the requirements of the established calibration program for the reactor facility. Calibration intervals are established and maintained to ensure acceptable accuracy and reliability of the measurement devices. Calibration requirements for instruments are to be traceable to the National Institute of Standards and Technology (NIST), formerly the National Bureau of Standards (NBS). If this relationship does not exist, the basis of calibration is documented and approved by responsible managers. The calibration requirements are based on the use, accuracy requirement, stability, and amount of usage of the measuring and test equipment (M&TE).

3.4.5 Computer Hardware and Software

Software developed or customized for the GTL shall comply with the requirements of DOE N 203.1 Attachment 1.

3.4.6 Fire Protection

Basic requirements for fire protection are in DOE Order 420.1 and DOE 440.1 and their corresponding Contractor Requirements

Documents (CRD). Guidance for complying with these orders is in DOE G 440.1-5

3.5 Testing and Maintenance Requirements

3.5.1 Testability

Means shall be provided to allow determination of the GTL's functional readiness, including its ability to provide any required gas mixture, achieve and maintain required temperatures, and measure and record all required data.

3.5.2 Testing and Inspection Requirements

Testing and inspection requirements for GTL are those called for by accepted codes and standards (see Table 2) to which the GTL design will conform. Additional requirements may be imposed on a particular implementation by the program it will support.

3.5.3 TSR-Required Surveillance

Independent nondestructive examinations shall be performed, as necessary, to confirm the integrity of the outer containment of the GTL. These additional tests and inspections may include helium leak tests, radiography, and ultrasonic or liquid penetrant tests on the GTL.

3.5.4 Non-TSR Inspections and Testing

No non-TSR inspection and testing requirements for GTL are inherent to the GTL mission other than those called for by accepted codes and standards (see Table 2) to which the GTL design will conform. Additional requirements may be imposed on a particular implementation by the program it will support.

3.6 Other Requirements

3.6.1 Security and SNM Protection

All activities on the GTL will comply with 10 CFR 73 and its implementing directives.

3.6.2 Special Installation Requirements

Any such requirements will be dictated by the irradiation facility in which the GTL is housed and/or by the users of a particular GTL implementation.

3.6.3 Common-Mode Failures

The failure of systems that are common to both the experiment facilities and experiments and to the plant will not cause interactions (from this common use) that result in total consequences exceeding those specified by the facility protection criteria.

3.6.4 Availability and Reliability

Experiments placed in the GTL shall be capable of being installed or changed within the limits of a normal irradiation facility outage.

3.6.4 Quality Assurance

A Quality Assurance plan shall be developed and observed that conforms to the requirements of DOE Order 414.1B.

3.6.5 Miscellaneous

Any such requirements will be dictated by the irradiation facility in which the GTL is housed and/or by the users of a particular GTL implementation.

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APPENDIX A GENERATION IV REACTOR CONCEPTS

Information on the Generation IV reactor concepts comes from *A Technology Roadmap for Generation IV Nuclear Energy Systems*, December 2002, GIF-002-00, U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum.

A.1 Gas-Cooled Fast Reactor

The GFR system features a fast-spectrum helium-cooled reactor and closed fuel cycle. The GFR uses a direct-cycle helium turbine for electricity and can use process heat for thermo-chemical production of hydrogen. Through the combination of a fast neutron spectrum and full recycle of actinides, GFR minimize the production of long-lived radioactive waste isotopes. The GFR's fast spectrum also makes it possible to utilize available fissile and fertile materials (including depleted uranium from enrichment plants) two orders of magnitude more efficiently than thermal spectrum gas reactors with once through fuel cycles. The GFR reference assumes an integrated, on-site spent fuel treatment and fabrication plant.

A summary of design parameters for the GFR system is given in Table A-1.

Table A-1. Design parameters for the Gas-Cooled Fast Reactor system.

Reactor Parameters	Reference Value
Reactor Power	600 MWth
Net plant Efficiency (direct helium cycle)	48%
Coolant inlet/outlet temperature	490 °C/850 °C
Pressure	90 bar (9 MPa)
Average power density	100 MWTH/m ³
Reference fuel compound	UPu/SiC (70/30%) with about 20%Pu content
Volume fraction, Fuel/Gas/SiC	50/40/10%
Conversion ratio	Self-sufficient
Burnup, Damage	5% FIMA or 250 GWD/MTHM; 60 dpa (up to 100-150 dpa)
Fuel center line temperature (operating)	1400 °C

Fuel:

A composite ceramic-ceramic fuel (cercer) with closely packed, coated (U, Pu) C kernels or fibers is the best option for fuel development. Alternative fuel options include fuel particles with large (U, Pu) C kernels and thin coatings or ceramic-clad solid-solution metal (cermet) fuels. The need for high densities of heavy nuclei in the fuel leads to actinide-carbide as the reference fuel and actinide-nitrides with 99.9% enriched nitrogen as the backup.

Other:

The structural materials, in-core and out-of-core, pose a great challenge in designing of the reactor as it will have to withstand high fast-neutron fluence and temperature, up to 1600 °C in accident situations.

R&D activities need to identify the materials that offer the best compromise regarding:

- Ability to fabricate and weld
- Chemical and neutronic compatibility with the core environment.

A.2 Lead-Cooled Fast Reactor System

Lead cooled fast reactor (LFR) systems are Pb or Pb-Bi alloy cooled reactors. They feature a fast neutron spectrum and closed fuel cycle. The LFR system is strong in sustainability because a closed fuel cycle is used, and in proliferation resistance and physical protection because it employs a long core-life. The reactor is cooled by natural convection with outlet coolant temperature of 550 °C, possibly ranging up to 800 °C. A summary of design parameters for the LFR system is given in Table A-2.

Table A-2. Design parameters for the Lead-Cooled Fast Reactor system.

Reactor Parameters	Reference Value
Reactor Power	125-3600 MWth
Max Fuel temperature (Normal Operation)	710 °C
Max Cladding temperature (Accident condition)	725 °C
Coolant	Pb or Pb-Bi
Coolant inlet/max outlet temperature	550 – 800 °C
Pressure	1 atm (101.3 kPa)
Average burnup	100 –150 GWD/MTHM
Power Density	140 – 254 kW/l
Reference fuel compound	Metal alloy or mixed nitride
Cladding	Ferritic or ceramic coatings
Conversion ratio	1

Fuel:

The nearer-term options plan to use a nitride or metal alloy fuel. Metal alloy fuel pin performance at 550 °C and U/TRU/Zr metal alloy recycle and remote fabrication technologies are already substantially developed in Na-cooled systems. Nitride fuel development includes fuel/clad interaction, compatibility and performance. Mixed nitride fuel is also possible for the 550 °C options; however, it will be required for the high temperature option.

Other:

Strategies and means for control of ^{210}Po , an activation product of Bi, are needed for the Pb-Bi option. Research and development of composites, coatings, ceramics, and high-temperature alloy for fuel cladding and reactor structure are needed. A long-term goal is to have coolant outlet temperature up to 800 °C.

A.3 Molten-Salt Reactor System

The molten-salt reactor (MSR) produces fission power in a circulating molten salt fuel mixture. MSRs are fueled with uranium or plutonium fluorides dissolved in a mixture of molten fluorides, with Na and Zr fluorides in a closed fuel cycle. The MSR system is strong in sustainability because of its closed fuel cycle and excellent performance in waste burn-down. It is rated good in safety and in proliferation resistance and physical protection. However, the MSR system features an epithermal to thermal neutron spectrum.

A.4 Sodium-Cooled Fast Reactor System

The sodium-cooled fast reactor system (SFR) features a fast-spectrum reactor and a closed fuel recycle system. The SFR size varies from a few hundred MWe to large monolithic reactors of 1500-1700 MWe. The sodium outlet temperature is typically near 550 °C. There are two types of concepts: pool layout, where all primary system components are housed in a single vessel, similar to EBR-II; or in a compact layout similar to one of the Japanese reactor designs. The primary system operates at essentially atmospheric pressure. SFRs have been built and operated in France, Germany, Japan, Russia, United Kingdom and United State of America. There is an extensive technology base in nuclear safety that establishes the passive safety characteristic of the SFR. It has been proven that the reactors can survive fuel damage in the case of anticipated transient without scram events. A summary of design parameters for the SFR system is given in Table A-3.

Table A-3. Design parameters for the Sodium-Cooled Fast Reactor system.

Reactor Parameters	Reference Value
Reactor Power	100's-1700 MWe
Coolant	Sodium
Coolant temperature	530 – 550 °C
Pressure	1 atm (101.3 kPa)
Average burnup	150 –200 GWD/MTHM
Power Density	350 kW/L

Reference fuel compound	Metal alloy or Mixed oxide
Conversion ratio	0.5 – 1.3

Fuels:

Two fuel options exist for the SFR, MOX and mixed uranium-plutonium-zirconium metal alloy. Both are highly developed as a result of many years of experience in several nations. Burnup in both types of fuel has been experimentally demonstrated to be in the range of 150-200 GWd/MT. The database for MOX fuel is considerably more extensive than that for metal fuel.

A.5 Supercritical-Water-Cooled Reactor System

The Supercritical Water Reactor (SCWR) is based on the principle that for pressures above the critical pressure in water there is no phase change of the fluid at any temperature. This offers the potential for higher thermal efficiency (~44%) than light water reactors (LWR) (~35%), lower primary coolant mass, resistance to boiling crisis events, and greater simplicity. The design reflects work in Japan over the last two decades and considerable experience in the fossil power industry. High-pressure coolant (25 MPa) enters the vessel at 280°C. It is heated to about 510°C and delivered to a power conversion cycle, which blends LWR and supercritical fossil plant technology. It can be designed to operate on either a fast or a thermal neutron spectrum. Table A-4 lists some of the key design parameters for a thermal spectrum SCWR design.

Table A-4. Design parameters for a thermal-spectrum Supercritical Water Reactor system.

Reactor Parameters	Reference Value
Reactor power	1,700 MWe
Coolant inlet/outlet temperature	280°C/510°C
Coolant pressure	25 MPa
Average power density	~100 MWth/m ³
Reference fuel	UO ₂ with austenitic or ferritic-martensitic stainless steel, or Ni-alloy cladding
Fuel structural materials	Advanced high-strength metal alloys are needed
Burnup / Damage	~45 GWD/MTHM; 10 – 30 dpa

A.6 Very-High-Temperature Reactor System

The Generation IV roadmap identified the VHTR, based on the current state of technology, potential for successful development of near term and future advanced technologies. The VHTR technology base has primarily evolved from commercial gas-cooled reactors built and operated in Western Europe and the United States and two research reactors currently operating in Japan and China. The VHTR is a next step in evolutionary development of high-temperature gas-cooled reactor which can be a direct or indirect cycle. The reference VHTR is 600 MWth and can produce hydrogen from high temperature steam using thermo-chemical iodine-sulfur (I-S) process. The VHTR can also generate electricity with over 50% efficiency as coolant outlet temperature is expected to be 1000 °C. The VHTR is graphite-moderated, helium-cooled reactor with a thermal neutron spectrum. A summary of design parameters for the VHTR system is given in Table A-5.

Table A-5. Summary of design parameters for the Very-High-Temperature Reactor system.

Reactor Parameters	Reference Value
Reactor Power	600 MWTH
Max Fuel temperature (Normal Operation)	1200 °C
Max Fuel temperature (Accident Condition)	1800 °C
Max Cladding temperature (Accident condition)	TBD °C
Coolant	Helium
Coolant temperature	640-1000 °C
Pressure	Process dependent
Average burnup	150 –200 GWD/MTHM
Power Density	6 –10 kW/l
Reference fuel compound	ZrC-coated particles in blocks, pins or pebbles
Conversion ratio	0.5 – 1.3
Plant Efficiency	>50%

Fuels:

The increase in the coolant outlet temperature of the VHTR will require an increase in the fuel temperature. This will significantly reduce the safety margin, compared to current light water reactors, in core heat-up events. Fuel particles coated with SiC are used in HTGR at fuel temperatures of approximately 1200 °C. New material, such as zirconium-carbide, has been suggested for fuel temperatures above 1200 °C. The Next-Generation Nuclear Plant (NGNP) high level function and requirements document favors TRISO-coated fuel particles, each containing a kernel (0.5mm) of uranium oxycarbide (UCO) or uranium dioxide enclosed in a

coating shell. The fuel particles may be agglomerated into cylindrical compacts or into spherical pebbles (up to 6 cm in diameter).

Other:

Since core outlet temperature is expected to be greater than 1000 °C, a significant amount of materials research work will be needed for the core internals and pressure vessel, which may have a nominal operating temperature of up to 650 °C. In the case of perturbed conditions, potentially higher temperature may exist for tens of hours.

In the original HTGR design, some components of the reactor, such as the side reflector, core blocks, and core support, were made from H-327/H-451 graphite, which is no longer available. A number of replacement graphites may be available; however, irradiation properties and test data are needed.

A.7 Summary Data

A comparative summary of design features of the GEN IV reactors is provided in Tables A-6 and A-6.

Table A-6. Fuel and structural material options for the various GEN IV reactors.

System	Fuel Materials					Structural Materials						
	Oxide	Metal	Nitride	Carbide	Fluoride (Liquid)	Ferritic-Martensitic Stainless Steel Alloys	Austenitic Stainless Steel Alloys	Oxide Dispersion Strengthened	Ni-based Alloys	Graphite	Refractory Alloys	Ceramics
GFR			S	P		P	P	P	P		P	P
MSR					P				P	P	S	S
SFR	P	P				P	P	P				
LFR		S	P			P	P	S			S	S
SCWR-Thermal	P					P	P	S	S			
SCWR-Fast	P	S				P	P	S	S			
VHTR	P					S			P	P	S	P
P: Primary Option S: Secondary Option												

Table A-7. Design features of Generation IV reactor options.

System	Spectrum, T_{outlet}	Fuel	Cladding	In-core	Out-of-core
GFR	Fast, 850°C	MC/SiC	Ceramic	Refractory metals and alloys, Ceramics, ODS Vessel: F-M	Primary Circuit: Ni-based superalloys 32Ni-25Cr-20 Fe- 12.5W-0.05C Ni-23Cr-18W- 0.2 CF-M w/ thermal barriers Turbine: Ni-based alloys or ODS
LFR	Fast, 550°C and Fast, 800°C	MN	High-Si F-M, Ceramics, or refractory alloys		High-Si austenitics, ceramics, or refractory alloys
MSR	Thermal, 700– 800°C	Salt	Not Applicable	Ceramics, refractory metals, High-Mo Ni-base alloys (e.g., INOR-8) Graphite, Hastelloy N	High-Mo Ni-base alloys (e.g., INOR-8)
SFR (Metal)	Fast, 520°C	U-Pu-Zr	F-M (HT9 or ODS)	F-M ducts 316SS grid plate	Ferritics, austenitics
SFR (MOX)	Fast, 550°C	MOX	ODS	F-M ducts 316SS grid plate	Ferritics, austenitics
SCWR- Thermal	Thermal, 550°C	UO ₂	F-M(12Cr, 9Cr, etc.) (Fe-35Ni- 25Cr-0.3Ti) Incoloy 800, ODS Inconel 690, 625, & 718	Same as cladding options	F-M
SCWR -Fast	Fast, 550°C	MOX, Dispersion	F-M (12Cr, 9Cr, etc.) (Fe- 35Ni-25Cr-0.3Ti) Incoloy 800, ODS Inconel 690 & 625	Same as cladding options	F-M
VHTR	Thermal, 1000°C	TRISO UOC in Graphite Compacts; ZrC coating	ZrC coating and surrounding graphite	Graphites PyC, SiC, ZrC Vessel: F-M	Primary Circuit: Ni-based superalloys 32Ni-25Cr-20Fe- 12.5 W-0.05C Ni-23Cr-18 W- 0.2CF-M w/ thermal barriers Turbine: Ni-based alloys or ODS

Abbreviations

F-M:	Ferritic-martensitic stainless steels (typically 9 to 12 wt% Cr)
ODS	Oxide dispersion-strengthened steels (typically ferritic martensitic)
MN:	(U,Pu)
MC:	(U,Pu)C
MOX:	(U,Pu)O ₂