Appendix 3.0
Gas-Cooled Fast Reactor

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Acronyms

AFCI	Advanced Fuel Cycle Initiative
CERCER	Ceramic fuel particles dispersed in a ceramic material matrix
CR	Control Rod
ETDR	Experimental Technology Demonstration Reactor
Euratom	European Commission
FY	fiscal year
GFR	Gas-Cooled Fast Reactor
GIF	Generation IV International Forum
GT-MHR	Gas-Turbine Modular Helium Reactor
I-NERI	International Nuclear Energy Research Initiative
LFR	Lead-Cooled Fast Reactor
MSR	Molten Salt Reactor
NERI	Nuclear Energy Research Initiative
PBMR	Pebble Bed Modular Reactor
PRA	Probabilistic Risk Assessment
R&D	research and development
S-CO_2	supercritical carbon dioxide
SCWR	Supercritical-Water-Cooled Reactor
SFR	Sodium-Cooled Fast Reactor
SSC	System Steering Committee
VHTR	Very-High-Temperature Reactor

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A3.1 INTRODUCTION AND BACKGROUND

The Gas-Cooled Fast Reactor (GFR) is primarily envisioned for missions in electricity production and actinide management, although it may be able to support hydrogen production as well. The GFR, (see Figure A3.1) was chosen as one of the Generation IV nuclear reactor systems to be developed. This selection was based on its excellent potential (1) for sustainability through reduction of the volume and radiotoxicity of both its own fuel and other spent nuclear fuel, and (2) for extending/utilizing uranium resources orders of magnitude beyond what the current open fuel cycle can realize. In addition, energy conversion at high thermal efficiency and cogeneration is possible with the current designs being considered, increasing the economic benefit of the GFR. However, research and development (R&D) challenges include the ability to use passive decay heat removal systems during accident conditions, survivability of fuels and in-core materials under extreme temperatures and radiation, and economic and efficient fuel cycle processes. The GFR was therefore chosen as one of six Generation IV systems to be pursued based on its ability to meet the Generation IV goals of sustainability, economics, safety and reliability, proliferation resistance, and physical protection.

Under the Generation IV International Forum (GIF), six international partners have identified their interest in participating in research related to the development of the GFR. These are European Commission (Euratom), France, Japan, Switzerland, the United Kingdom, and the United States.

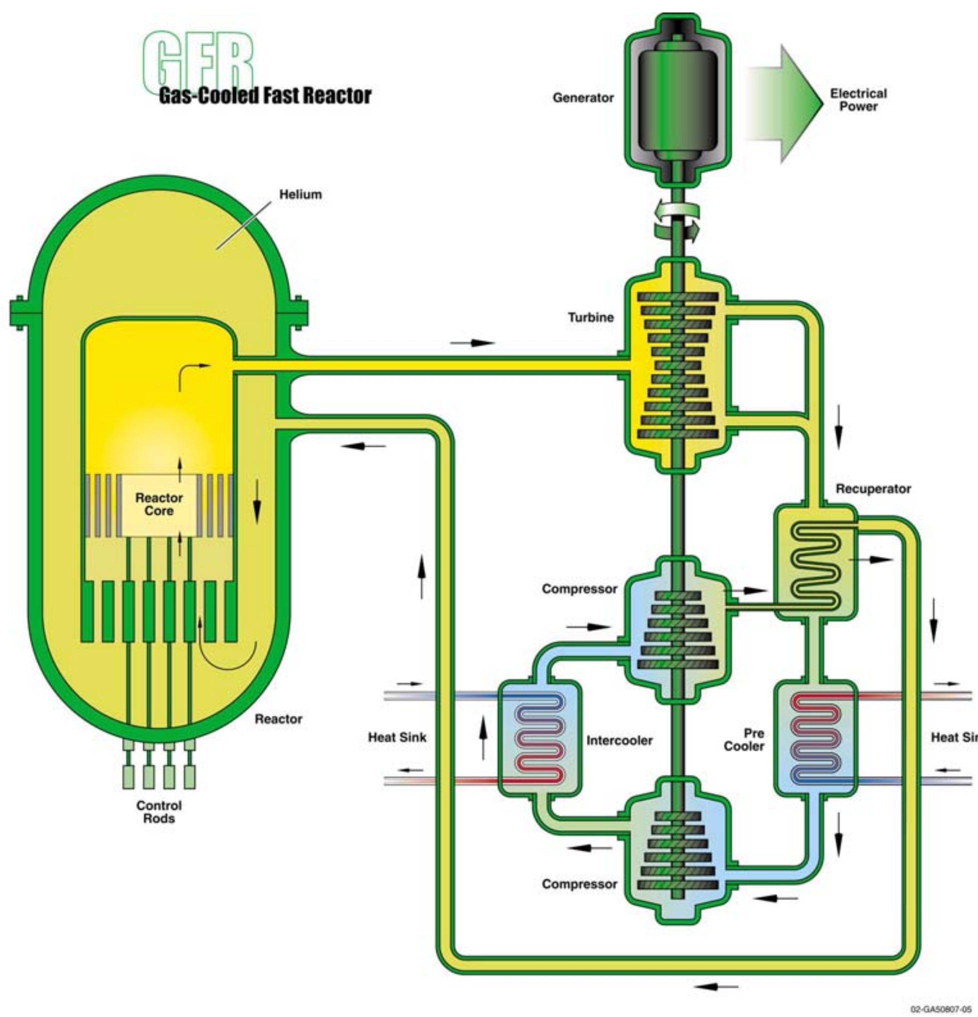

Figure A3.1. Conceptual GFR system.

A3.1.1 System Description

The reference GFR system features a fast-spectrum, helium-cooled reactor and closed fuel cycle (see Figure A3.2). This was chosen as the reference design due to its close relationship with the Very-High-Temperature Reactor (VHTR), and, thus, its ability to utilize as much VHTR material and balance-of-plant technology as possible. Like thermal-spectrum, helium-cooled reactors such as the Gas-Turbine Modular Helium Reactor (GT-MHR) and the Pebble Bed Modular Reactor (PBMR), the high outlet temperature of the helium coolant makes it possible to deliver electricity, hydrogen, or process heat with high conversion efficiency. The GFR reference design will utilize a direct-cycle, helium turbine for electricity (42% efficiency at 850°C) and process heat for thermo-chemical production of hydrogen.

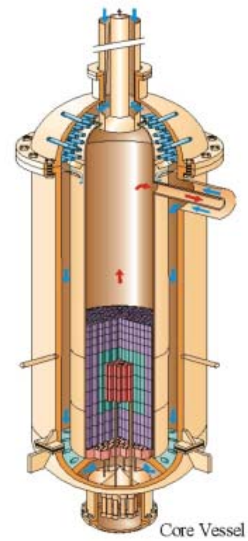

Figure A3.2. Possible GFR vessel and core configuration for block/plate core.

In order to withstand the high temperatures within the reactor, special consideration must be given to the fuel and in-core materials. The reference fuel matrix for the Generation IV GFR is a ceramic dispersion fuel in a refractory ceramic matrix (CERCER), based on a balance between conductivity and high temperature capability.

It is important to note that of the six Generation IV concepts, only two do not benefit from previous construction or operational experience: the GFR and the Supercritical-Water-Cooled Reactor (SCWR). The other Generation IV systems benefit as follows:

- The VHTR can draw on German and Chinese pebble-bed experience, Japanese High-Temperature Engineering Test Reactor experience, and Fort St. Vrain and Peach Bottom experience
- The Sodium-Cooled Fast Reactor (SFR) can employ Experimental Breeder Reactor (EBR)-I, EBR-II, JOYO, MONJU, Phenix, etc., experience
- The Lead-Cooled Fast Reactor (LFR) can utilize the experience from seven Russian submarines (Alpha Class) and two on-shore lead-alloy-cooled prototypes
- The Molten Salt Reactor (MSR) can make use of experience from the Oak Ridge National Laboratory MSR campaign.

However, even the SCWR will rely on current light water reactor fuel technology (i.e., metal clad, UO_2 solid solution/pellet fuel), and balance-of-plant experience from coal-fired supercritical plants. On the other hand, there have been no GFR test or prototype reactors built; only paper studies and designs have been performed that utilize a modified SFR core (with metal cladding and structures) operating at relatively low temperatures and high power densities. As such, the current Generation IV GFR project cannot accelerate the time frame for development due to the new and innovative designs, fuels, and materials as compared to the previous GFR work. Therefore, 2025 would be a reasonable estimate as to when a prototype could be realized.

The Experimental Technology Demonstration Reactor (ETDR) is to be constructed to support the development of the GFR, and current plans have it sited and constructed in France. It would be a small power (< 50 MW) test reactor—the first GFR ever built. Under the GIF research and development (R&D)

plan, the ETDR design and development is fully integrated in the System Design and Safety project. It will have to follow the same constraints but contribute to the GFR demonstration phase; this early GFR will have to offer the required flexibility to test those open options for the GFR. The starting core of ETDR will implement a different fuel technology than the prototype GFR, which has to be taken into account in the fuels project. This fuel would likely be in the form of cladded pins, similar to current technology. Future work would "bootstrap" actual GFR fuels into subsequent core reloads, and the ETDR would be the test bed for an eventual GFR prototype fuel. Specific goals for the ETDR include:

- For the core:
  - High power density
  - High fissile content in the fuel.
- For the starting core:
  - Already proven or nearly proven technology.
- Conceptual design and safety analysis:
  - Consistent design and performance choices with GFR.
- Specific safety analysis:
  - Experimental safety demonstrations
  - Specific devices and monitoring.

A3.1.2 Overall System Timeline

The international community has issued a detailed R&D plan to establish the viability of the GFR by 2012, to complete a conceptual design by 2019, and to build a prototype by 2025. The first phase of research will deal with the viability and feasibility of the system. This research is mainly focused on those items that are critical to the initial advancement of the GFR, which are given in more detail in Section A3.2.3 of this appendix. The second phase of the research will begin once the main viability phase is complete, and the reactor concept is deemed feasible for further study. This second phase will be the start of performance phase research where phenomena, processes, and capabilities are verified and optimized under prototypical conditions.

It is important to note that not all GIF participants are expected to contribute equally in the research and development of the GFR, which somewhat complicates the division of work and tasks between the international partners. This will affect the associated cost of the R&D per GIF member and will, in turn, affect the schedule. Furthermore, one would expect that a minimum commitment would be required from each participant if that participant expects to benefit from/acquire all research performed on the GFR.

A3.2 RESEARCH AND DEVELOPMENT STRATEGY

The main characteristics of the GFR are: a self-generating core (i.e., conversion ratio = 1) with a fast neutron spectrum, robust refractory fuel, high operating temperature, direct energy conversion with a gas turbine, and full actinide recycling (possibly with an integrated, on-site fuel reprocessing facility). The approach to development of the reference GFR is to rely, as much as possible, on technologies being utilized for the VHTR.

Within the United States, the research is divided into functional areas: system design and evaluation, materials, energy conversion, and fuels and fuel cycle. These will be discussed in more detail in subsequent sections of this appendix.

A3.2.1 Objectives

The main objective of the GFR is to meet or exceed the goals and expectations outlined in *A Technology Roadmap for Generation IV Nuclear Energy Systems* (DOE 2002), namely superior economics, safety and reliability, sustainability, and proliferation resistance and physical protection.

The specific GFR research objectives aimed at accomplishing those Generation IV goals include:

1. System design and safety research, which involves conceptual studies of a reference GFR system, assessing options, analyzing the safety approach and specific safety features, and developing computational tools for these studies
2. Materials research to identify and/or develop materials that can withstand the high temperatures and high fluence that will be encountered within the core region, and to develop out-of-core materials that will withstand the high temperatures
3. Energy conversion research that offers the best in power conversion systems for both direct and indirect cycles
4. Fuel and fuel cycle research, which will identify and fabricate those fuels that will perform well under extreme temperature and radiation conditions, handle the addition of minor actinides, and be recyclable in an economic manner.

Overall, research on the GFR will update the definition and performance assessment of all components of the GFR, and will verify that the Generation IV criteria are being met.

A3.2.2 Scope

The broad Generation IV goals translate into specific goals and work scope for GFR R&D. This includes:

- Define a GFR reference conceptual design and operating parameters meeting the following requirements:
  - Has self-breeding cores without the need for fertile blankets
  - Is capable of multi-recycling of plutonium and minor actinides
  - Has an adequate power density to meet requirements in terms of economics, ease of deployment of the reactor fleet, and management of safety issues
  - Has a coupling between the reactor and process heat applications.
- Identify and assess alternative design features regarding the Generation IV goals and criteria (e.g., lower temperatures, indirect cycle)
- Perform a safety analysis for the reference GFR system and its alternatives:
  - Define the safety approach for GFR
  - Define and evaluate specific safety systems and requirements for fuel and materials behavior to cope with accident situations

- Perform transient analyses (loss of coolant accident /depressurization, reactivity initiated accident, etc.,) and verification that the off-site impact is consistent with the Generation IV objectives
- Implement a core melt exclusion strategy
- Perform a simplified probabilistic risk assessment (PRA) for the system.

- Assess economics including:
  - The impact on investment and operating costs of the simplified and integrated fuel cycle
  - The modularity of the reactor (series production, in-factory prefabrication, and sharing of on-site resources).
- Develop and validate computational tools needed to design and analyze operating transients (design basis accidents and beyond):
  - Benchmark and validate against experimental data
  - Identify required test facilities to obtain missing experimental data to qualify calculation tools.
- For the core, ensure:
  - High heavy metal content in the dedicated fuel volume
  - Use of refractory materials with low neutron absorption and moderation effects
  - Geometries allowing efficient cooling (pressure drop in the core, etc.)
  - High level of fission product confinement
  - Resistance to impurities in the Helium coolant
  - Plutonium content in the range of 15 to 20%, with the ability to incorporate minor actinides
  - Potential for high burnups (target of 15% fissions of initial metal atoms)
  - Ability to reprocess (grouped actinide management)
  - Ability to sustain high temperatures and doses.
- Assess the following:
  - Fabrication and welding capability of candidate materials
  - Initial characteristics of physical, neutronic, thermal, tensile, creep, fatigue, and toughness properties under low to moderate neutron flux and dose
  - Microstructure and phase stability under irradiation
  - Irradiation creep, in-pile creep, and swelling properties
  - Initial and in-pile compatibility with helium (and impurities).
- Several small technological facilities devoted to:
  - Purification and control of the coolant quality and inventory
  - Generic technology: tribology, leak tightness, thermal insulation
  - Instrumentation qualification.
- Multi-purpose helium loops (~ 1 MW) for:
  - Small component and system qualification
  - Pressure drop studies

- Sub-assembly hydro-dynamic characterization.

- Demonstration Helium loop (~ 20 MW) for:
  - Large component qualification
  - Reactor system (direct cycle) studies in normal and abnormal situations
  - Operation and safety code qualification
  - Studying the GFR safety case
  - Operation training.

A3.2.3 Viability Issues

The main near-term viability issues were identified by the GFR System Steering Committee (under the auspices of the GIF) and include safety system design, fuels, in-core materials, and fuel cycle processes. With regard to the safety system design, decay heat removal is very challenging due to the high power density and low thermal inertia. Regarding the fuels, in-core materials, and fuel cycle processes, the high temperature and extreme radiation conditions (specifically the high neutron fluences) are difficult challenges for fuels/materials design and fabrication.

The R&D planned is intended to address the needs of the viability and performance phases that are defined for GFR in the Roadmap (DOE 2002). The objectives and endpoints of the viability and performance phases, as defined in that document, can be seen in Table A3.1.

Table A3.1. Objectives and endpoints of viability and performance phases.

Viability Phase	Performance Phase
Objectives	
Basic concepts, technologies, and processes are proven under relevant conditions, with all potential technical show-stoppers identified and resolved.	Engineering-scale processes, phenomena, and material capabilities are verified and optimized under prototypical conditions.
Endpoints	
Preconceptual design of the entire system, with nominal interface requirements between subsystems and established pathways for disposal of all waste streams.	Conceptual design of the entire system, sufficient for procurement specifications for construction of a prototype or demonstration plant, and with validated acceptability of disposal of all waste streams
Basic fuel cycle and, if applicable, energy conversion process flow sheets established through testing at appropriate scale.	Processes validated at scale sufficient for demonstration plant
Cost analysis based on preconceptual design.	Detailed cost evaluation for the system.
Simplified probabilistic risk assessment for the system.	Probabilistic risk assessment for the system.
Definition of analytical tools.	Validation of analytical tools.
Preconceptual design and analysis of safety features.	Demonstration of safety features through testing, analysis or relevant experience.
Simplified preliminary environmental impact statement for the system.	Environmental impact statement for the system.
Preliminary safeguards and physical protection strategy.	Safeguards and physical protection strategy for system, including cost estimate for extrinsic features.
Consultation(s) with regulatory agency on safety approach and framework issues.	Pre-application meeting(s) with regulatory agency.

Viability phase work will continue, to some extent, through the conceptual design. However, the major viability issues described above will need to be resolved between 2010 and 2012.

A3.2.4 Research Interfaces

Within the GFR research effort, several programs contribute to the advancement of the system. The Generation IV effort is based on international participation through the GIF, and before the official Generation IV effort, the United States has participated in the Nuclear Energy Research Initiative (NERI, domestic) and International-NERI (I-NERI, international bilateral) programs. These programs will continue to provide important research interfaces with the overall Generation IV effort both domestically and internationally.

A3.2.4.1 Relationship to Generation IV International Forum Research and Development Projects

The GIF is currently comprised of eleven participating nations that will agree upon a framework for international cooperation on R&D of future nuclear energy systems. The selection of the systems was accomplished in several steps: (1) definition and evaluation of candidate systems, (2) review of evaluations and discussion of desired missions (national priorities) for the systems, (3) final review of evaluations and performance to missions, and (4) final decision on selections to Generation IV and identification of near-term deployable designs. This process culminated in the selection of six concepts: the VHTR, SCWR, GFR, LFR, SFR, and MSR.

The GFR was top-ranked in sustainability, and was rated good in safety, economics, and proliferation resistance and physical protection. Based on the estimates given in the Generation IV Roadmap, deployment of the GFR is estimated to occur in approximately 2025. The GIF was organized and envisioned, and a roadmap issued, based on international participation, in part so that no single country should have to bear the full burden of the development of a reactor system; the point of organizing the GIF was to involve the international community as a whole. The vision was to have each GIF member that expressed interest in a particular system contribute to the development of that system through research activities (or cost share of activities).

To better coordinate the research, System Steering Committees (SSCs) were formed, and they have the responsibility to organize and integrate the research among all participating GIF members for a particular system. This includes the nomination of technical experts to participate on Project Management Boards, which oversee the day-to-day research activities. These experts will report their progress to the SSCs and receive input/direction as to the next developmental steps. The SSC in turn reports to the GIF Policy Group as outlined in the approved Terms of Reference. As stated previously, six GIF members have expressed interest in the development of the GFR: the European Union, France, Japan, Switzerland, the United Kingdom, and the United States. Important to note is that agreements will be made between the participants to protect intellectual property rights, and to allow those participants (GIF or other) that contribute the most to developmental costs to access the majority of data (or results) generated. In other words, it is anticipated that GFR participants will only be allowed access to that data or those results they are entitled to based on the level of participation (as research contributions or actual financial contributions). The details of these agreements are currently in the process of being defined.

Under the GIF, R&D needs for the GFR are structured into two specific projects: (1) System design and safety and (2) Fast neutron fuel, other core materials, and specific fuel cycle process. The two common R&D projects for the GFR and the VHTR are (1) Materials and components and (2) High performance power conversion. Note that the fuel cycle processes research will be a common project between the GFR and SFR.

For the two common projects with the VHTR, the international R&D plan only proposes specific objectives and tasks for the GFR that complement their description in the VHTR R&D program. All R&D projects address crucial feasibility and performance issues, such as:

- Definition of a reference design, identification of core layout with a suitable neutronic spectrum, breeding gain and reactivity characteristics, resolution of safety issues—especially those specific to the high power density required for the GFR, and assessment of economic performance.
- Development of advanced fast neutron fuel with adequate high heavy atom content and the ability to sustain high temperature, high burnups, and high fast neutron fluence compatible with a full recycling of all actinides and robust fuel reprocessing and fabrication routes.
- Development of in-core and near-core structural materials able to sustain high temperatures and fast neutron fluence.
- Feasibility of the fuel treatment and refabrication is a key issue and will have to be demonstrated before the corresponding full-scale facility construction decision is made (it is to be part of the prototype GFR system). This calls for the production, at a relevant scale, of several kg of irradiated fuel in representative GFR conditions, and then its refabrication with the selected processes (recycle experiment).
- Development of the specific components and safety systems required for the GFR. An adequate answer is required in terms of experimental means in helium loops.

A detailed schedule for the GFR can be seen in Figure A3.3.

A3.2.4.2 University Collaborations

Several universities have contributed to GFR research over the past three years. These include:

- Massachusetts Institute of Technology – performed initial PRA to evaluate current safety systems and designed an in-pile CO_2 radiolysis experiment
- Auburn University – performing studies of oxide dispersion-strengthened alloy joining/welding
- University of Nevada-Las Vegas – performed dissolution studies of GFR fuels in specific gases
- University of Wisconsin-Madison – performed materials research in grain boundary engineering and radiation resistance of specific materials.

In addition to the support given to the above universities, student interns at the laboratories have spent their summers performing work in thermal-hydraulics and safety analysis, core physics, and materials research.

Currently, the NERI program will be used to fund the majority of university work under the Generation IV Program. The calls for proposals were specific to the major viability issues associated with the GFR, and awards were made in fiscal year (FY) 2005.

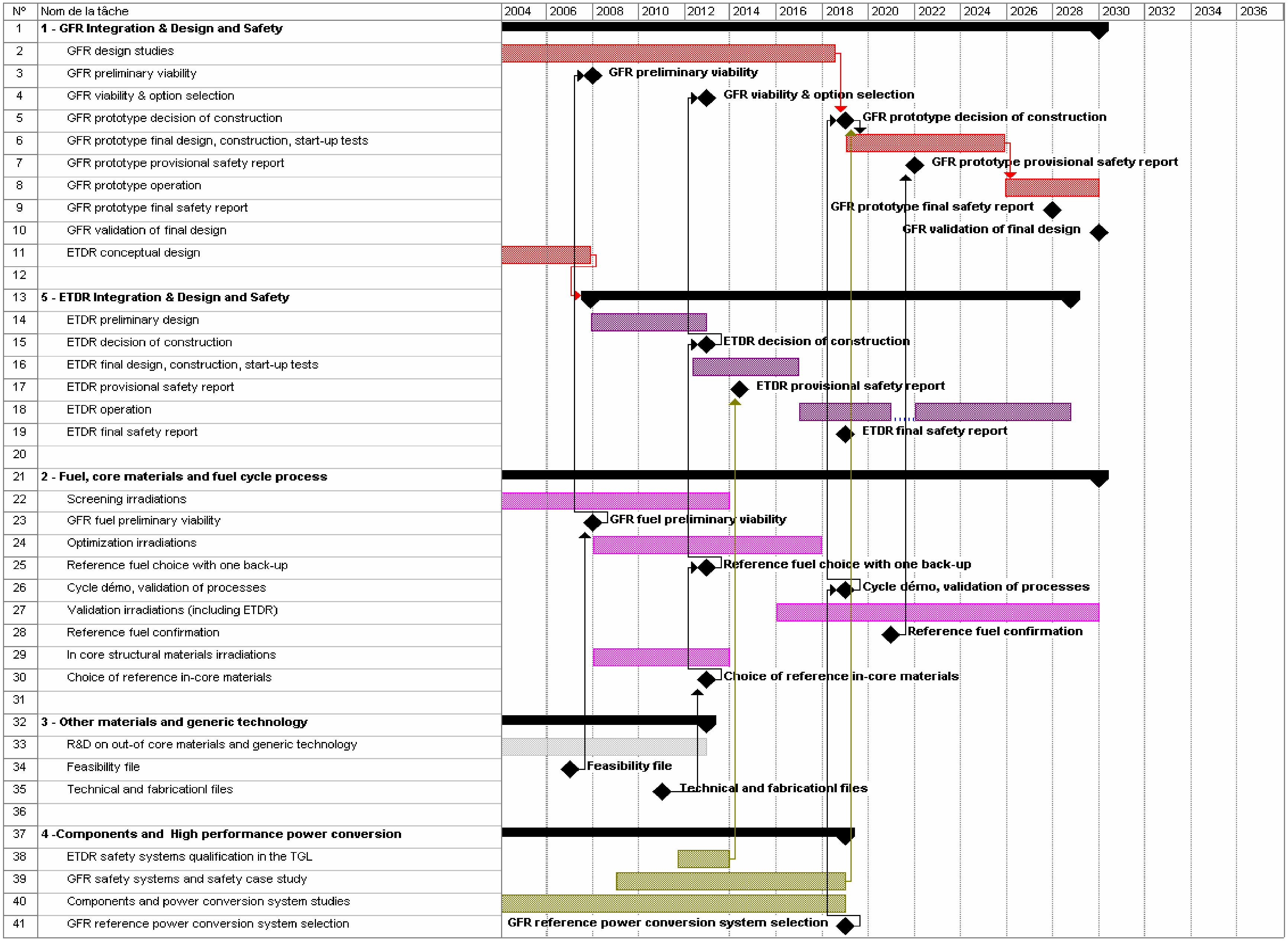

Figure A3.3. GIF R&D schedule.

A3.2.4.3 Industry Interactions

There are currently two industrial firms working on the GFR:

- Framatome – performed plant design work under the Argonne National Laboratory (ANL)/French Commissariat á l'Energie Atomique (CEA) I-NERI project
- General Atomics – currently performing guard containment system designs under the ANL/CEA I-NERI project.

Both firms will continue to work on the GFR given that funding levels are sufficient to support their tasks.

A3.2.4.4 International Nuclear Energy Research Initiative/Nuclear Energy Research Initiative

The following GIF countries/members have, or are planning to have, bilateral I-NERI agreements with the United States: Brazil, Canada, Euratom, France, Japan, and Korea. Of these, the following GFR participants plan to participate in specific GFR research:

- France – research includes all aspects of the GFR
- Euratom – research includes all aspects of the GFR, with emphasis on the fuel
- Japan (no agreement signed yet, but anticipated) – research includes system design and safety, and fuels.

The remaining GFR-related GIF members (Switzerland and the United Kingdom) either have relationships through current I-NERI agreements (through Euratom) and are planning to participate in specific research at a later date or have related programs that will contribute to the development of specific subsystems or components.

As was mentioned previously, the NERI program is dedicated to university work, and began work during FY 2005.

A3.3 HIGHLIGHTS OF RESEARCH AND DEVELOPMENT

Note that up to this point, all research needed for the development of the GFR has been described/listed. In the subsequent sections, those portions that the United States intends to participate in are outlined.

A3.3.1 System Design and Evaluation Methods

The major activities within the System Design and Evaluation research include safety system design and evaluation of passive and active safety systems for decay heat removal, system control and transient analysis, design and construction of experiments for thermal-hydraulic/safety tests and coolant chemistry control, and code development/adaptation for neutronic and thermal-hydraulic analysis.

A3.3.2 Fuels and Fuel Cycle

Per direction from DOE, the Advanced Fuel Cycle Initiative (AFCI) will no longer perform research in this area. However, the direction and results of the international fuels and fuel cycle research will need to be tightly integrated with the GFR system design and safety task and correlated with the materials work that is being performed.

The major activities within the fuels and fuel-cycle research include fuels feasibility, fabrication, and testing; recycle process feasibility studies; and studies on the viability of refabrication.

A3.3.3 Energy Conversion

The major activities within Energy Conversion R&D include feasibility studies of a direct Brayton cycle (including component testing) and development of the turbomachinery for helium and CO_2 systems.

A3.3.4 Materials

The major activities within the Materials R&D include screening and testing of high temperature materials (including welding and fabrication) and possible corrosion studies using supercritical carbon dioxide (S-CO_2).

A3.4 PROJECT COST AND SCHEDULE

A3.4.1 Fiscal Year 2006 Project Budget

Given the overall budget of ~$940M required for development of the GFR and the participation of six GIF members (the European Union, France, Japan, Switzerland, the United Kingdom, and the U. S.), an initial assumption was made that the U.S. contribution will be approximately 16.5% (1/6th) of the total, or ~$157M. This gives a rough yearly budget of $9M per participant or a total budget of ~$55M per year for the project. The FY 2006 U.S. budget is shown in Table A3.2.

Table A3.2. FY 2006 budget profile for GFR activities ($K).

Task	FY-06[a]
System Design and Evaluation	829
Materials	607
Energy Conversion[b]	10
Fuels and Fuel Cycle[b]	35
Total	1,481

a. FY 2006 budget includes FY 2005 carryover funds.
b. Monitoring of other programs for design integration. AFCI is no longer providing funds for fuels research.

A3.4.2 Ten-Year Project Schedule

The overall project budget and schedule are shown in Figure A3.4.

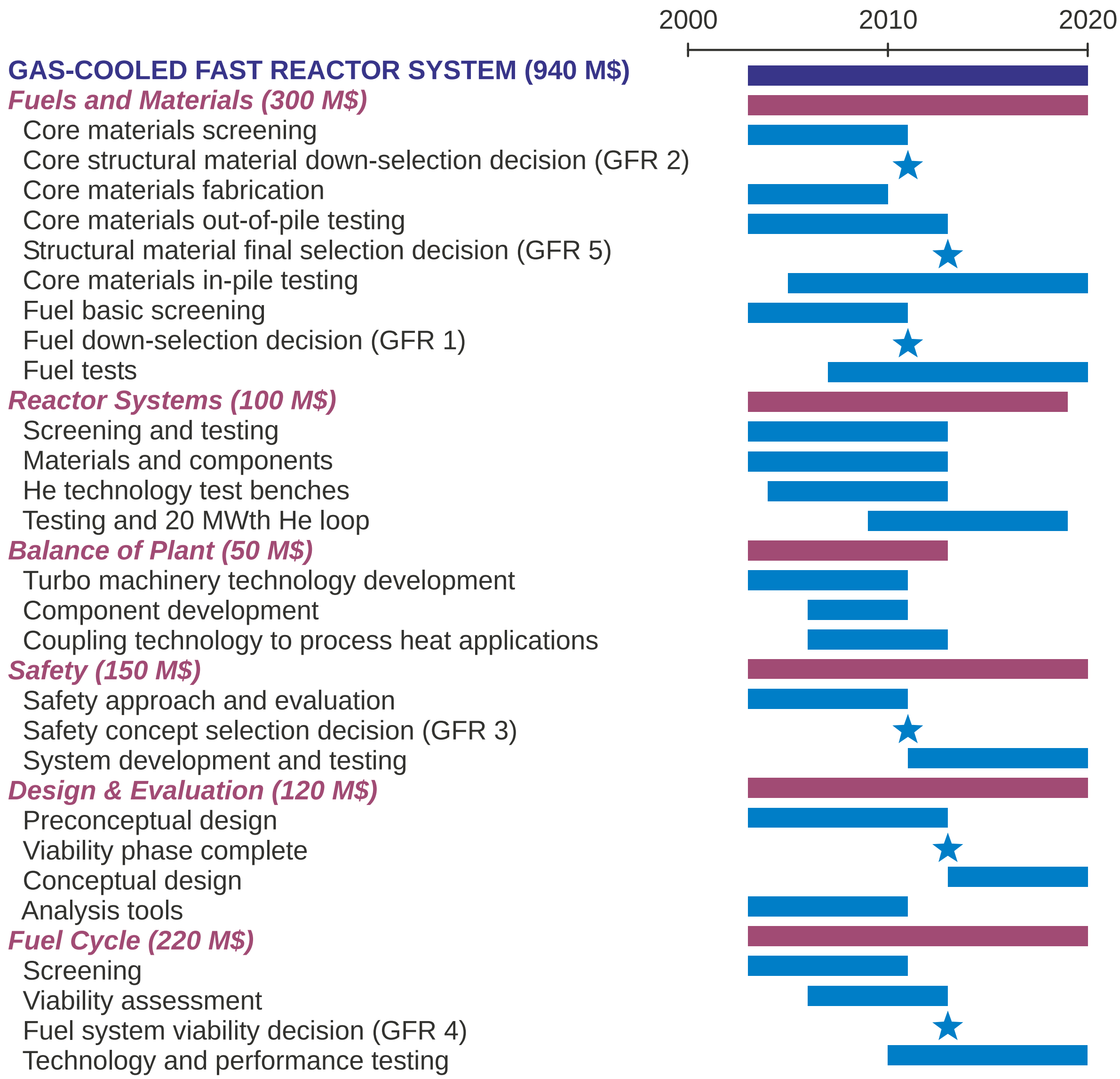

Figure A3.4. GFR general budget and R&D schedule.

A3.4.3 Ten-Year Project Milestones

The major milestones associated with the budget and schedule are as follows:

FY 2011

- Fuel down-select
- Core structural material down-select
- Safety concept down-select.

FY 2012

- Fuel cycle viability
- Core structural material final selection
- GFR viability decision.

A3.5 REFERENCES

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

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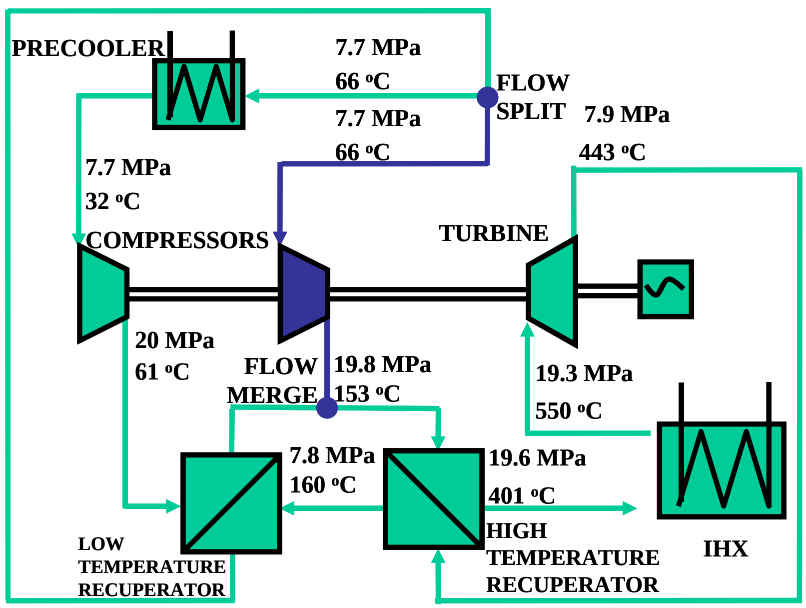
ADDENDUM A3-1: GAS-COOLED FAST REACTOR

The current reference GFR system features a fast-spectrum, helium-cooled reactor and closed fuel cycle. This was chosen as the reference design due to its close relationship with the VHTR and, thus, its ability to utilize as much VHTR material and balance-of-plant technology as possible. Like thermal spectrum, the high outlet temperature of the helium coolant in helium-cooled reactors such as the GT-MHR and the PBMR makes it possible to deliver electricity, hydrogen, or process heat with high conversion efficiency. The GFR reference design uses a direct-cycle, helium turbine for electricity (42% efficiency at 850°C) and process heat for thermo-chemical production of hydrogen.

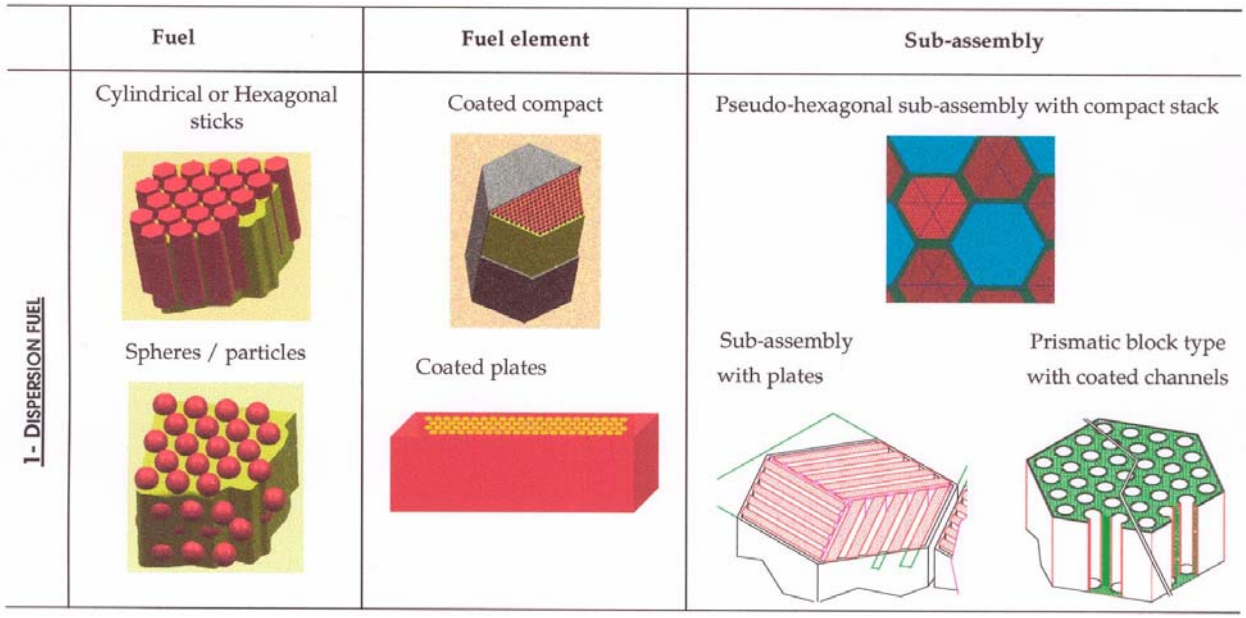
The alternate design is also a helium-cooled system, but it utilizes an indirect Brayton cycle for power conversion. The secondary system of the alternate design utilizes S-CO_2 at 550°C and 20 megapascals (MPa) (see Addm A3: Figure 1). Compared to the direct cycle, this allows for more modest outlet temperatures in the primary circuit (~ 600-650°C), stricter fuel, fuel matrix reduction, and material requirements, while maintaining high thermal efficiency (~ 42%).

The optional design is an S-CO_2 cooled (550°C outlet and 20 MPa), direct Brayton cycle system. The main advantage of the optional design is the modest outlet temperature in the primary circuit, while maintaining high thermal efficiency (~ 45%). Again, the modest outlet temperature (comparable to sodium-cooled reactors) reduces the requirements on fuel, fuel matrix/cladding, and materials, as well as allowing for the use of more standard metal alloys within the core. This has the potential of significantly reducing the fuel matrix/cladding development costs, compared to the reference design, and the potential for reducing the overall capital costs due to the small size of the turbomachinery and other system components. The power conversion cycle is equivalent to that shown in Addm A3: Figure 1, where the intermediate heat exchanger would be replaced by the reactor and reactor pressure vessel.



Addm A3: Figure 1. Schematic of the S-CO_2 recompression cycle.

The safety system design will be affected by the choice of primary coolant, whether a direct or indirect power conversion cycle is used, and the core geometry (i.e., block, plate, pin). The trade-off between high conductivity and high temperature capabilities has led to the choice of ceramics, including refractory ceramics. The reference fuel matrix for the Generation IV GFR is a CERCER dispersion fuel, based on a balance between conductivity and high temperature capability. Addm A3: Figure 2 is a graphical representation of the dispersion fuel types being considered.



Addm A3: Figure 2. Dispersion fuel concepts.

Current fuel designs are based on dispersion fuels (either as fibers or as particles) in an inert plate/block type matrix or solid solution fuel clad in a refractory ceramic (e.g., SiC/SiC composites). The reference fuels chosen for the GFR are uranium nitride and uranium carbide for their high heavy metal density, high conductivity, and minimal impact on neutron spectrum (although limited irradiation data exists). The matrix materials are dependent on the coolant and operating temperatures, and can be classified into three categories: ceramic (for high temperatures), refractory metal (for modest to high temperatures), and metal (for modest temperatures). As the fuels are of ceramic composition, the resulting fuel forms can be classified into two categories: CERCER and CERMET. The fuel would be extruded into the matrix, where the matrix would have a “honeycomb” appearance. The particles may be coated but, unlike the thermal spectrum gas reactor fuel, they will most likely have one coating to maximize the heavy metal content within the matrix.