INEEL/CON-03-01150
PREPRINT

The Next Generation Nuclear Plant (NGNP) Project

F. H. Southworth
P. E. MacDonald
D. J. Harrell
E. L. Shaber
C. V. Park
M. R. Holbrook
D. A. Petti

November 16 – 20, 2003

Global 2003

The Next Generation Nuclear Plant (NGNP) Project

F. H. Southworth, P. E. MacDonald, D. J. Harrell, E. L. Shaber, C. V. Park, M. R. Holbrook,
and D. A. Petti
Idaho National Engineering & Environmental Laboratory

Abstract

The Next Generation Nuclear Power (NGNP) Project will demonstrate emissions-free nuclear-assisted electricity and hydrogen production by 2015. The NGNP reactor will be a helium-cooled, graphite moderated, thermal neutron spectrum reactor with a design goal outlet temperature of 1000 °C or higher. The reactor thermal power and core configuration will be designed to assure passive decay heat removal without fuel damage during hypothetical accidents. The fuel cycle will be a once-through very high burnup low-enriched uranium fuel cycle.

This paper provides a description of the project to build the NGNP at the Idaho National Engineering and Environmental Laboratory (INEEL). The NGNP Project includes an overall reactor design activity and four major supporting activities: materials selection and qualification, NRC licensing and regulatory support, fuel development and qualification, and the hydrogen production plant. Each of these activities is discussed in the paper.

All the reactor design and construction activities will be managed under the DOE's project management system as outlined in DOE Order 413.3. The key elements of the overall project management system discussed in this paper include the client and project management organization relationship, critical decisions (CDs), acquisition strategy, and the project logic and timeline. The major activities associated with the materials program include development of a plan for managing the selection and qualification of all component materials required for the NGNP; identification of specific materials alternatives for each system component; evaluation of the needed testing, code work, and analysis required to qualify each identified material; preliminary selection of component materials; irradiation of needed sample materials; physical, mechanical, and chemical testing of un-irradiated and irradiated materials; and documentation of final materials selections.

The NGNP will be licensed by the NRC under 10 CFR 50 or 10 CFR 52, for the purpose of demonstrating the suitability of high-temperature gas-cooled reactors for commercial electric power and hydrogen production. Products that will support the licensing of the NGNP include the environmental impact statement, the preliminary safety analysis report, the NRC construction permit, the final safety analysis report, and the NRC operating license. The fuel development and qualification program consists of five elements: development of improved fuel manufacturing technologies, fuel and materials irradiations, safety testing and post-irradiation examinations, fuel performance modeling, and fission product transport and source term modeling.

Two basic approaches will be explored for using the heat from the high-temperature helium coolant to produce hydrogen. The first technology of interest is the thermochemical splitting of water into hydrogen and oxygen. The most promising processes for thermochemical splitting of water are sulfur-based and include the sulfur-iodine, hybrid sulfur-electrolysis, and sulfur-bromine processes. The second technology of interest is thermally assisted electrolysis of water. The efficiency of this process can be substantially improved by heating the water to high-temperature steam before applying electrolysis.

1. Introduction

In the coming decades, the United States, the other industrialized countries, and the entire world will need energy supplies and an upgraded energy infrastructure to meet growing demands for electric power and transportation fuels. The Generation IV project identified reactor system concepts for producing electricity that excelled at meeting the goals of superior economics, safety, sustainability, proliferation resistance, and physical security. [1] One of these reactor system concepts, the Very High Temperature Gas Cooled Reactor System (VHTR), is also uniquely suited for producing hydrogen without the consumption of fossil fuels or the emission of greenhouse gases. DOE has selected this system for the Next Generation Nuclear Power (NGNP) Project, a project to demonstrate emissions-free nuclear-assisted electricity and hydrogen production by 2015.

"Hydrogen holds the potential to provide a clean, reliable, and affordable energy supply that can enhance America's economy, environment, and security." [2] The U.S. hydrogen industry currently produces nine million tons of hydrogen per year [a] for use in chemicals production, petroleum refining, metals treating, and electrical applications, and the current use is experiencing rapid growth as more and more hydrogen is used to convert the lower-cost Western hemisphere heavy crude oils to gasoline. With a larger supply of hydrogen, the production of liquid fuels per barrel of oil could be increased by up to 15%, which would significantly reduce our imported crude oil.

Although hydrogen is the most abundant element in the universe, it does not naturally exist in large quantities or high concentrations on Earth. Steam reforming of methane accounts for more than 95% of the current hydrogen production in the U.S. Unfortunately, steam methane reforming diverts valuable natural gas from home heating uses [b] and releases large quantities of carbon dioxide into the atmosphere. A much more environmentally friendly method of producing hydrogen would be to crack water at high temperatures using nuclear heat, and the current growth in hydrogen demand is already sufficient to justify the development of such methods. As efficient fuel cells are developed and the transportation sector is revolutionized, [c] the worldwide demand for hydrogen will eventually rival that for electricity. Given these additional needs, it is appropriate to start the development of nuclear energy systems designed for large-scale production of hydrogen.

The objectives for the NGNP project are

- Demonstrate a full-scale prototype NGNP by the year 2015
- Demonstrate high-temperature Brayton Cycle electric power production at full scale
- Demonstrate nuclear-assisted production of hydrogen (with maybe 10 to 20% of the heat)
- Demonstrate by test the exceptional safety capabilities of the advanced gas cooled reactors
- Obtain an NRC License to construct and operate the NGNP, to provide a basis for future performance-based, risk-informed licensing
- Support the development, testing, and prototyping of hydrogen infrastructures such as refueling stations, the "Freedom Car" initiative, petrochemical extension, heavy crude oil or tar sands "sweetening," and other industrial hydrogen applications

---

[a] Nine million tons of hydrogen per year is enough to fuel 20 to 30 million fuel cell cars, or enough to power 5 to 8 million homes.

[b] Hydrogen production currently uses 5% of the natural gas consumed in the United States.

[c] The first production fuel cell vehicles may be sold within a decade, and a hydrogen economy will be a significant enterprise within several decades.

The NGNP reference concept will be a helium-cooled, graphite moderated, thermal neutron spectrum reactor with a design goal outlet temperature of 1000 °C or higher. [3] The reactor core could be either a prismatic graphite block type core or a pebble bed core; the final selection of a reference core concept will be made following completion of the preconceptual designs for each. The NGNP will produce both electricity and hydrogen. The process heat for hydrogen production will be transferred to the hydrogen plant through an intermediate heat exchanger (IHX). The reactor thermal power (about 600 MWt) and core configuration will be designed to assure passive decay heat removal without fuel damage during hypothetical accidents. The fuel cycle will be a once-through very high burnup low-enriched uranium fuel cycle.

The basic technology for the NGNP has been established in former high-temperature gas-cooled reactor plants (DRAGON, Peach Bottom, AVR, THTR, Fort St. Vrain). In addition, the technologies for the NGNP are being advanced in the Gas Turbine-Modular Helium Reactor (GT-MHR) Project [4], and the South African state utility ESKOM sponsored project to develop the Pebble Bed Modular Reactor (PBMR). Furthermore, the Japanese HTTR and Chinese HTR-10 projects are demonstrating the feasibility of some of the planned NGNP components and materials. (The HTTR is expected to reach a maximum coolant outlet temperature of 950 °C in 2003.) Therefore, the NGNP project is focused on building a demonstration reactor, rather than simply confirming the basic feasibility of the concept. Table 1 lists the operating conditions and other important features of the *demonstration NGNP* and provides direct comparisons with the GT-MHR and the Fort St. Vrain reactor designs. [3,4] Note that the higher outlet temperature is achieved through thermal-hydraulic optimization of the core, not by means of increases in the fuel operational and accident temperature limits.

Table 1. Comparison of example VHTR operating conditions and features with GT-MHR and Fort St. Vrain (from Reference 3).

Condition or Feature	Fort St. Vrain HTGR	GT-MHR	NGNP
Power Output [MW(t)]	841	600	600/700/800 (depends on core height)
Average power density (w/cm^3)	6.3	6.5	6.5
Coolant @ Pressure (MPa / psia)	Helium @ 4.83 / 700	Helium @ 7.12 / 1032	Helium @ 7.12 / 1032
Moderator	Graphite	Graphite	Graphite
Core Geometry	Cylindrical	Annular	Annular
Safety Design Philosophy	Active Safety Sys	Passive	Passive
Plant Design Life (Years)	30	60	60
Core outlet temperature (°C)	785	850	1000
Core inlet temperature (°C)	406	488	490
Fuel – Coated Particle	HEU-PyC/SiC Th/ ^{235}U (93% enriched)	LEU-PyC/SiC	a) LEU-PyC/SiC b) LEU-PyC/ZrC
Fuel Max Temp – Normal Operation (°C)	1260	1250	a) ~1250 (SiC coated) b) ~ 1400 (ZrC coated)
Fuel Max Temp – Emergency Conditions (°C)	Active safety system cools fuel.	1600	a) 1600 b) TBD

One or more technologies will use heat from the high-temperature helium coolant to produce hydrogen. The first technology of interest is the thermochemical splitting of water into hydrogen and oxygen. There are a large number of thermochemical processes that could produce hydrogen, the most promising of which are sulfur-based and include the sulfur-iodine, hybrid sulfur-electrolysis, and sulfur-bromine processes (which operate in the 750 to 1000 °C range). The second technology of interest is thermally assisted electrolysis of water. The high efficiency Brayton cycle enabled by the NGNP may be used to generate the hydrogen from water by electrolysis. The efficiency of this process can be substantially improved by heating the water to high-temperature steam before applying electrolysis.

The NGNP is the nearest term of the six reference Generation IV Roadmap reactor concepts.[1] It is envisioned that a deliberate and focused program of research and development in support of a disciplined design and construction project could make a demonstration NGNP, with a small-scale hydrogen production system, operational by 2015. The significant advantages of high fuel burnup, passive safety, low operating and maintenance cost, and potential modular construction were evident in the Generation IV submitted concepts. The final design of the demonstration NGNP will be constrained to maintain these advantages.

This paper provides a description of the project at the Idaho National Engineering and Environmental Laboratory (INEEL) to build the NGNP. The NGNP Project includes an overall facility design and construction project and four major supporting activities:

- The NGNP materials selection and qualification program
- The NRC licensing and regulatory support activities
- The fuel development and qualification program
- The nuclear hydrogen initiative.

Each of these major activities is discussed separately below.

2. The Overall NGNP Project Management

The NGNP project is sponsored by the DOE Office of Nuclear Energy, Science and Technology (DOE-NE) and managed under the DOE's project management system as outlined in DOE Order 413.3, *Program and Project Management for the Acquisition of Capital Assets.* [5] DOE Order 413.3 uses a systematic approach to turn a complex and undefined need into a finished product or facility. Projects begin with a broad need and a rough order magnitude cost and schedule range and then progress through logical steps of higher maturity. With each consecutive phase, the scope is defined better and cost estimates and schedules become progressively more accurate. Quality gates, or critical decisions in the case of Order 413.3, ensure readiness to progress to the next phase. Thus complete definition, mature planning, and final decisions are not expected at the beginning, but evolve through an iterative and systematic process. Application of a project management system ensures that a quality plan and implementation strategy is in place and risk is managed through the end of the project.

The key elements required in Order 413.3 are also found in commercial project management systems and are consistent with the Project Management Institute's system of project management. Several of the elements are discussed below:

Client / project management organization relationship. An organization structure with vertical accountability, authority, and communication protocol is clearly defined in DOE Order 413.3 for major capital expenditures. The Deputy Secretary of Energy, as the Secretarial Acquisition Executive (SAE), has line accountability, responsibility and authority in the acquisition of Major Systems Projects. In this regard, the SAE, along with the appropriate Program Secretarial Officer, support and field offices, and other partners and advisors, are the client for the project. This "Acquisition Board" directs the project by identifying the high-level policies, approving the mission need, setting budgets, etc. An Integrated Project Team (IPT) within DOE carries out the planning, integration of contractors, and execution of the project. The IPT will consist of a Federal Project Manager, or Director as is now specified in DOE Manual 413.3-1 [6], and representatives from various other DOE functional areas, such as budget and financial, legal, safety, and contracting. In addition, the formation of a Senior Advisory Group of independent senior nuclear and industrial experts is envisaged.

The INEEL's Management and Operations (M&O) Contractor project team will provide technical and project management support to the DOE NGNP Project Director during the various project phases. The INEEL will complete and integrate specifically assigned technology development and system confirmatory and verification tasks, conduct design reviews, and test and operate the NGNP. The NGNP will be sited at the INEEL. Research and development support in the areas of system design and evaluation, materials development and testing, and energy conversion will also be provided from other DOE laboratories. A "notional" pre-conceptual functional breakdown structure is shown in Figure 1 below.

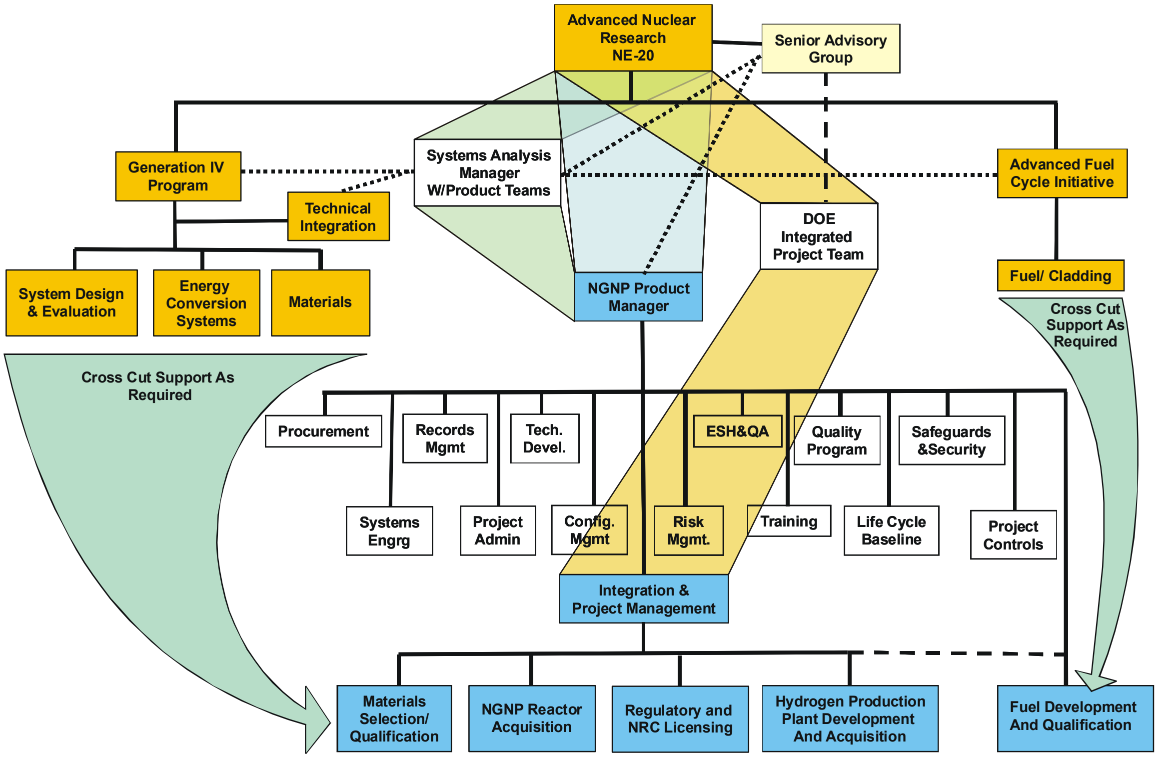


Figure 1. NGNP functional work breakdown structure.

The relationship and communication between the client and project management organization is extremely important for a project to be successful. Timely critical decisions require that the client is involved and aware of the project status and path forward even before an actual major decision gate briefing.

Critical Decisions (CDs). Critical decisions (also called quality gates, phase exits, stage gates, or kill points in commercial projects) provide opportunity for the client to review key deliverables and project performance and to determine if the project should continue into its next phase. Figure 2 illustrates project phases that provide the iterative process with critical decisions between phases.

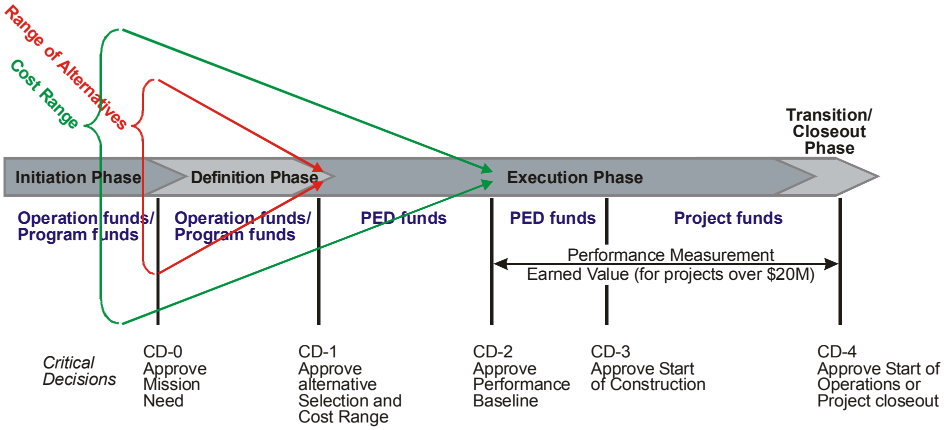


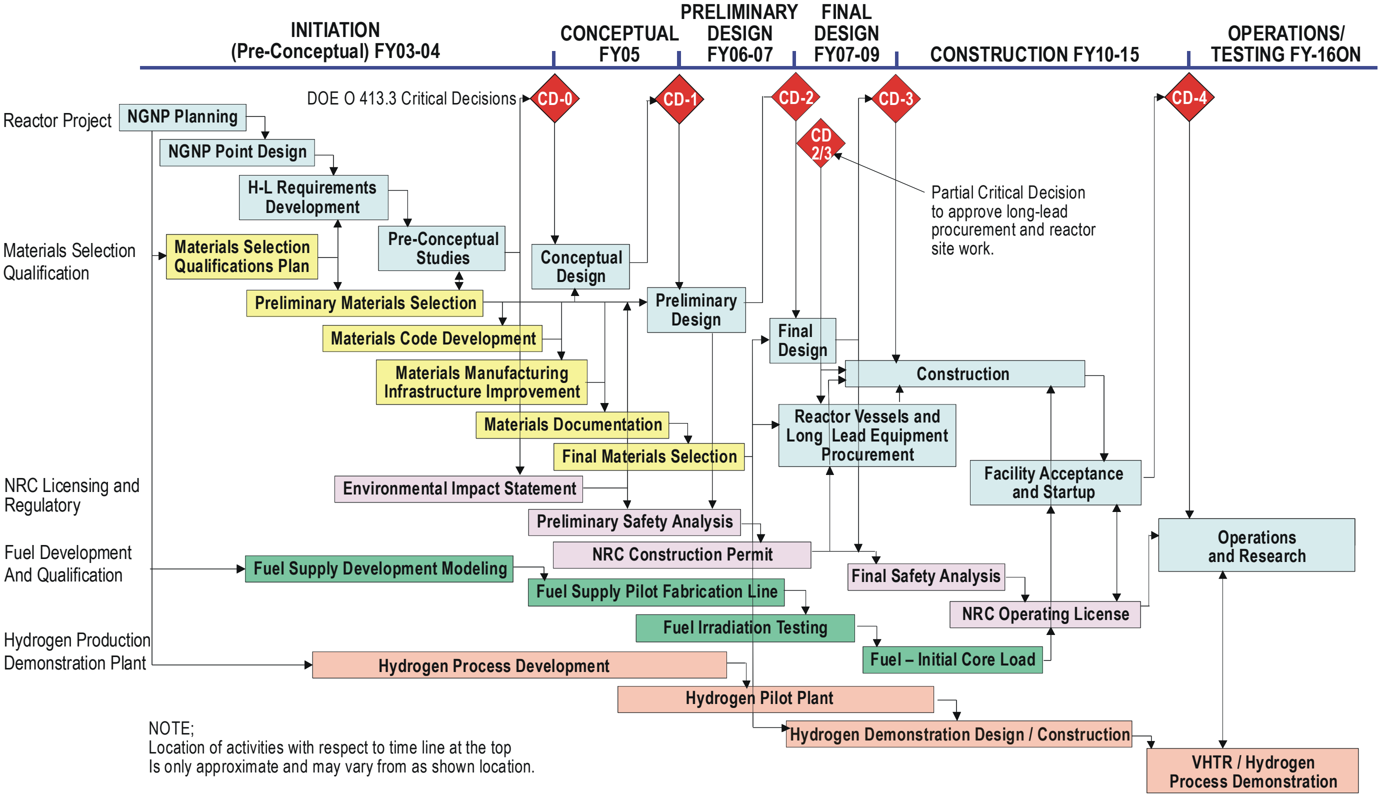
Figure 2. DOE Project Management System (Taken from DOE M 413.3-1) [4]

Acquisition Strategy. In the case of Order 413.3, the formal overall strategy for procurement and delivery of the physical products of the project is not required until CD-1. The acquisition strategy has not yet been developed for the NGNP, but it will be determined near the end of FY-05. It is envisioned that acquisition will be through some configuration of design and build competitive sub-contracts and may include teams made up of international public and /or private partners.

Project Logic and Timeline. As mentioned above, the NGNP project includes five major activities:

- The overall reactor design project
- The materials selection and qualification
- The NRC licensing and regulatory support activities
- The fuel development and qualification
- The hydrogen production and demonstration plant.

A high-level project logic diagram is shown in Figure 3 below to illustrate the interdependencies and interfaces between these major activities. These interfaces demand that the research and development for materials selection, fuel development, and the hydrogen plant along with the NRC licensing activities be project driven and closely managed to meet the aggressive schedule for the project. The current goal is to complete the NGNP by 2015. This puts the research and development and NRC licensing work on a very critical path. Although final decisions have not been made as to whether some of the major components of the project will be broken out as separate projects, the interdependencies dictate that all the work should be managed as one project in order to control and coordinate a timely completion.



NOTE;
Location of activities with respect to time line at the top
Is only approximate and may vary from as shown location.

Figure 3. Preliminary schedule for the major NGNP project activities.

As design inputs are obtained from the technology development activities, these are factored into the conceptual design and related trade-off studies. Similarly, early system level trade-off studies in the pre-conceptual and conceptual design activities will refine and narrow the scope of development activities.

The Reactor and Balance of Plant activities are broken down by the project phases and major products necessary to complete the project. The Pre-conceptual Project Initiation phase provides time for mission definition, planning, and budget development. Alternatives are investigated, a conceptual design is developed, and the technical and functional requirements are developed during the Conceptual Design Phase. Materials selection and qualification, other research and development, NRC construction permit reviews, and NEPA activities are also initiated and developed during the Conceptual Design. This is followed by preliminary design, final design, construction, and then operation.

3. The NGNP Materials Selection and Qualification Program

The objective of the NGNP Materials Selection and Qualification Program is to provide the essential materials selection and qualification activities needed to support the design of the reactor and balance of plant. Potential materials for the NGNP reactor, power conversion, intermediate heat exchanger systems, and associated balance of plant components will be assessed. The materials for the hydrogen production plant will be addressed in the Hydrogen Production and Demonstration Plant Program discussed below.

The materials program is being initiated prior to the formal design effort to ensure that materials test irradiations, long term testing (e.g. creep), and materials codification activities are initiated early enough to support the design process. An additional early objective of the materials program is to provide the preliminary materials information required to support initial reactor design trade studies that will be used to set reactor system requirements. As an integral part of the reactor project, the NGNP materials program must interface directly with the reactor design and component specification efforts in an iterative process of component requirements refinement and materials applicability considerations leading to final selection of needed materials.

The major activities associated with the materials program are listed below:

- Development of a plan for managing the selection and qualification of all component materials required for the NGNP
- Identification of specific materials alternatives for each system component
- Evaluation of the needed testing, code work, and analysis required to qualify each identified material
- Preliminary selection of component materials
- Performing irradiation of needed sample materials
- Physical, mechanical, and chemical testing of irradiated and un-irradiated materials
- Documentation of final materials selections in support of the design function.

The selection process is shown graphically in Figure 4. Narrowing the scope of the materials program to those materials that need to be carried through a testing and qualification program is essential. Therefore, the preliminary selection activity involves a documented process of comparing known materials properties of candidate materials to component requirements to determine if there is sufficient justification for expenditure of project funds on qualification testing. In some cases, the requirements may be such that appropriate materials cannot be identified. In those situations the tradeoff between the expected design requirements and boundary conditions for the component and the potential for a successful material selection must be analyzed. The preliminary selection criteria include

- Technical acceptability – will the material meet technical requirements for usage?
- Regulatory acceptability – is the material licensable for its intended purpose?
- Manufacturability – can the material be fabricated into the desired component?
- Cost – is the cost of the material prohibitive?
- Longevity – will the material meet the design life requirements?
- Qualification timing – can the material achieve qualification on a schedule that will support the reactor program?

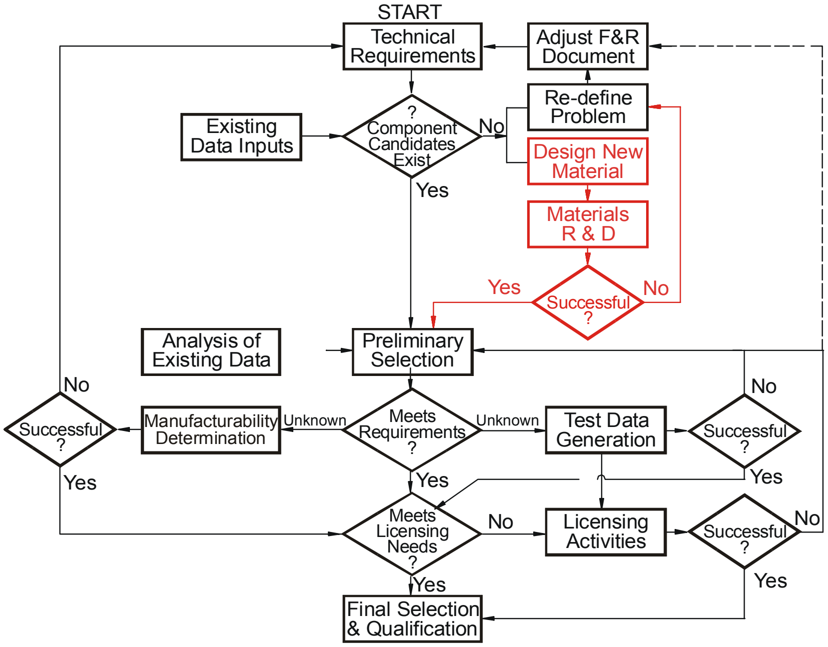


Figure 4. Material selection and qualification logic.

4. NRC Licensing and Regulatory Support Activities

The Nuclear Regulatory Commission (NRC) regulates the various commercial and institutional uses of nuclear energy. Under its responsibility to protect public health and safety, the NRC has three principal regulatory functions:

- Establish standards and regulations
- Issue licenses for nuclear facilities and users of nuclear materials
- Inspect facilities and users of nuclear materials to ensure compliance with the requirements.

In accordance with the Energy Reorganization Act of 1974, the NGNP will be licensed by the NRC under 10 CFR 50 or 10 CFR 52, for the purpose of demonstrating the suitability of high-temperature gas-cooled reactors for commercial electric power and hydrogen production. The licensing of the NGNP by NRC will demonstrate the efficacy of licensing future advanced gas-cooled reactor concepts for commercial applications. In particular, it is anticipated that many of the current issues associated with NRC licensing of a gas-cooled reactor and the use of nuclear power for hydrogen production will be resolved during the licensing of the NGNP at the INEEL. The licensing of the NGNP by NRC should also contribute to the stabilization of future non-LWR licensing activities by identifying any weaknesses or gaps in the licensing data needs and eliminating uncertainties in the cost and schedule associated with obtaining construction and operating licenses for gas cooled reactors.

It is likely that the NGNP will be licensed under the 10 CFR 50 regulations. Part 50 of 10 CFR prescribes a two-step process involving issuance of a construction permit and an operating license. After the NRC reviews and is satisfied with the safety of the preliminary NGNP plant design and the suitability of the prospective site, the agency issues a construction permit that allows the NGNP project to begin building a plant. During construction, the NGNP project submits an application for an operating license, which the NRC issues only if all safety and environmental requirements are met. Based on the 10 CFR Part 50 regulatory processes, the NGNP licensing and regulatory support group will develop necessary products and support the following activities:

- **Environmental Impact Statement –** This document includes impacts on air, water, animal life, vegetation, natural resources, and property of historic, archaeological, or architectural significance. Other items evaluated include economic, social, and cultural impacts. The NRC conducts a review of this document, in accordance with the National Environmental Policy Act (NEPA), to evaluate the potential environmental impacts and benefits of the NGNP. After completion of this review, the NRC issues a final environmental impact statement (FEIS), which addresses all public comments that the agency received.
- **Preliminary Safety Analysis Report –** The Preliminary Safety Analysis report is used to describe the NGNP plant site, reactor design, principal design safety features, design-basis and severe accidents, accident mitigation capabilities, and seismic safety. This document forms the basis for initial reviews of the NGNP design by the NRC.
- **NRC Construction Permit –** The application for a Construction Permit is required to include the Preliminary Safety Analyses report, the environmental review, and financial/anti-trust statements. In addition, the application must include an assessment of the need for the NGNP. The NRC issues the permit after completion of all reviews and public comment. The NRC may authorize an applicant to do some work at a site before a Construction Permit is issued. This "limited work authorization" can only be granted after the Atomic Safety and Licensing Board has made all of the environmental findings required for a construction permit and determined that the proposed site is a suitable location for the NGNP.
- **Final Safety Analysis Report –** The Final Safety Analysis report describes the plant's final design, safety evaluation, operational limits, anticipated response of the plant to postulated accidents, and plans for coping with emergencies.
- **NRC Operating License -** Final NGNP design information and plans for operation will be developed during the construction of the plant. The application for an NGNP Operating License will include the Final Safety Analysis report, and an updated environmental report. The NRC will review the NGNP's emergency plans in consultation with the Federal Emergency Management Agency to determine whether the plans are adequate and whether there is reasonable assurance that they can be implemented. The NRC will issue the NGNP Operating License after completion of all reviews and resolution of public comments.

The integrated safety testing planned for the NGNP will provide the basis for future commercial high-temperature gas-cooled reactor design certifications under 10 CFR 52. The NRC's requirements for reactor safety are grouped under four "Cornerstones of Safety: Initiating Events, Mitigation, Functional Barriers to Radionuclide Release, and Emergency Preparedness". The NGNP integrated test program of loss-of flow, loss-of-coolant, and control rod withdraw (transient overpower) tests will provide the necessary information that will quantify the safety margins intrinsic to the high-temperature gas reactor designs and will identify any areas that may require engineered safety features to provide additional defense in depth. A key NGNP project goal is to verify and to validate the design of passive systems on a commercial-scale prototype basis.

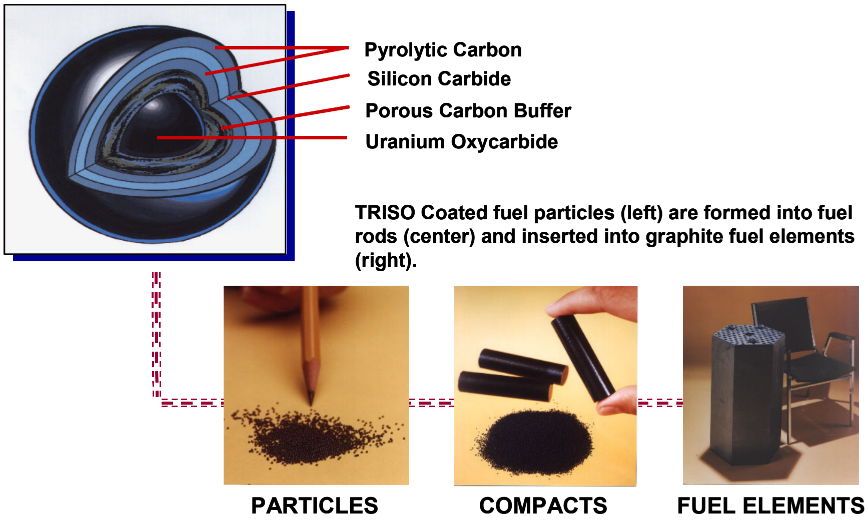
5. The Fuel Development and Qualification Program

The fuel for the NGNP builds upon the potential of the TRISO coated particle fuel design, as demonstrated in Germany and elsewhere. The TRISO coated particle is a spherical layered composite about 1 mm in diameter. It consists of a kernel of uranium oxycarbide (UCO) surrounded by a porous graphite buffer layer that absorbs radiation damage, allows space for fission gases produced during irradiation, and resists kernel migration at high temperatures. Surrounding the buffer layer are a layer of dense pyrolytic carbon, a SiC layer, and a dense outer pyrolytic carbon layer. The pyrolytic carbon layers shrink under irradiation and provide compressive forces that act to protect the SiC layer, which is the primary pressure boundary for the micro-sphere. The inner pyrolytic carbon layer also protects the kernel from corrosive gases that are present during the deposition of the SiC layer. The SiC layer is the primary containment of fission products generated during irradiation and under accident conditions. Each micro-sphere acts as a mini pressure vessel, a feature that is intended to impart robustness to the gas reactor fuel system.

The baseline fuel kernel for the NGNP is low-enriched uranium oxycarbide (UCO). UCO was selected because the mixture of carbide and oxide components results in no free oxygen being released due to fission. As a result, no carbon monoxide is generated during irradiation and little kernel migration (i.e., amoeba effect) is expected. The oxycarbide fuel also ties up the lanthanide fission products as immobile oxides in the kernel, which gives the fuel added resiliency under accident conditions.

For the pebble bed version of a NGNP, the coated particles are overcoated with a graphitic powder and binders. These overcoated particles are then mixed with additional graphitic powder and binders and then molded into a 5 cm sphere. An additional 0.5 cm fuel free zone is added to the sphere prior to isostatic pressing, machining, carbonization and heat-treating.

For the prismatic version of the NGNP, a similar process is envisioned where the overcoated particles are mixed with graphitic powder and binders to form a cylindrical compact approximately 5 cm long and 1.25 cm in diameter. After final heat treatment, these compacts are inserted into specified holes in the graphite blocks. Figure 5 shows a cutaway schematic of a TRISO coated fuel particle and pictures of fuel particles, compacts, and fuel elements used in a high-temperature gas reactor with prismatic fuel (Fort St. Vrain).



TRISO Coated fuel particles (left) are formed into fuel rods (center) and inserted into graphite fuel elements (right).

Figure 5. Cutaway schematic of a TRISO coated fuel particle and pictures of prismatic fueled high-temperature gas reactor fuel particles, compacts, and fuel elements.

The Advanced Gas Reactor Fuel Development and Qualification Program consists of five elements: [7]

- **Fuel manufacture** – This element addresses the work necessary to produce coated-particle fuel that meets fuel performance specifications and includes process development for kernels, coatings, and compacting; quality control (QC) methods development; scale-up analyses; and process documentation needed for technology transfer. This effort will produce fuel and material samples for characterization, irradiation, and accident testing as necessary to meet the overall goals. There will also eventually be work to develop automated fuel fabrication technology suitable for mass production of coated-particle fuel at an acceptable cost; that work will be conducted during the later stages of the program in conjunction with cosponsoring industrial partners.
- **Fuel and materials irradiations** – The fuel and materials irradiation activities will provide data on fuel performance under irradiation as necessary to support fuel process development, to qualify fuel for normal operation conditions, and to support development and validation of fuel performance and fission product transport models and codes. The irradiations will also provide irradiated fuel and materials as necessary for post irradiation examination (PIE) and ex-core high-temperature furnace safety testing. A total of eight irradiation capsules will be used to provide the necessary data and sample materials.
- **Safety testing and PIE** – Data from PIE and safety testing will supplement the in-reactor measurements [primarily fission gas release-to-birth ratio (R/B) measurements] as necessary to demonstrate compliance with fuel performance requirements and support the development and validation of computer codes. This work will also support the fuel manufacture effort by providing feedback on the performance of kernels, coatings, and compacts.
- **Fuel performance modeling** – Computer codes and models will be further developed and validated as necessary to support fuel fabrication process development and plant design and licensing. The fuel performance modeling will address the structural, thermal, and chemical processes that can lead to coated-particle failures. The models will not address the release of fission products from the fuel particle, although they will model the effects of fission product chemical interactions with the coatings, which can lead to degradation of the coated-particle properties.
- **Fission product transport and source term** –The transport of fission products produced within the coated particles will be modeled to provide a technical basis for source terms for advanced gas reactors under normal and accident conditions. The design methods (computer models) will be validated by experimental data, as necessary to support plant design and licensing.

An underlying theme for the fuel development work is the need to develop a fundamental understanding of the relationship between the fuel fabrication process, key fuel properties, the irradiation performance of the fuel, and the release and transport of fission products in the NGNP primary coolant system, although progress has been made recently in this area. [8] Fuel performance modeling and analysis of the fission product behavior in the primary circuit are important aspects of this work. The performance models are considered essential for several reasons, including guidance for the plant designer in establishing the core design and operating limits, and demonstration to the licensing authority that the applicant has a thorough understanding of the in-service behavior of the fuel system. The fission product behavior task will also provide primary source term data needed for licensing. Early program activities are centered on the fuel manufacturing technologies because the production of fuel and materials for irradiation, safety testing, and PIE is the early critical path activity.

6. The Nuclear Hydrogen Initiative

Although there is already significant hydrogen produced in the US, it is primarily produced by steam reforming of natural gas – which is already a high quality fuel. Current production is the equivalent to about 100 GWth of nuclear or fossil power, producing hydrogen at 50% efficiency. As mentioned in the introduction, this process diverts natural gas from home heating and burdens the environment with significant CO_2 release. The hydrogen production methods that do not depend on fossil resources split water molecules using thermal or electrical energy. Although the feedstock is readily available, decomposition of water takes significant energy - about 123 MJ is required to produce one kg of hydrogen. (The energy content of 1 kg of hydrogen is approximately equal to one gallon of gasoline.)

Electrolysis. Electrolysis is the most straightforward approach currently available to produce hydrogen directly from water. Conventional electrolyzers are available today with electrical to hydrogen efficiencies of around 70% at a cost of about $400/kWe installed. This allows distributed sources of hydrogen at somewhat higher costs than steam reforming of methane. High temperature electrolysis (HTE), or steam electrolysis, has the potential for higher electrolysis efficiency. Thermal energy is used to produce high-temperature steam, which results in a reduction of the electrical energy required for electrolysis and therefore a reduction in the total energy required for hydrogen generation.

High temperature electrolysis can be accomplished using the same materials and technology used in solid-oxide fuel cells. Large-scale applications would be composed of many electrolyzer modules, and the cost effectiveness of modular scaling for electrolysis in comparison with the scaling of thermochemical methods is one of the issues to be evaluated. High temperature electrolysis technology is being developed by the DOE Office of Energy Efficiency and Renewable Energy (EE). Therefore, the assessment of the nuclear application will use those EE results and focus on 1) developing a conceptual design for a high-temperature electrolysis system coupled to an advanced high-temperature reactor, 2) evaluating the cell and module options being developed and 3) demonstrate the most promising technology for conditions that optimize the use of the nuclear heat source characteristics.

Thermochemical Processes. Thermochemical cycles produce hydrogen by a series of chemical reactions where the net result is the decomposition of water at much lower temperatures than the direct thermal decomposition of water. Energy is supplied as heat in the temperature range necessary to drive the endothermic reactions, generally in the 750 to 1000 °C range or higher. All process chemicals in the system are fully recycled. There are two types of thermochemical processes: pure and hybrid. The hybrid thermochemical cycles include an electrolysis step of some chemical compound (not water) that usually generates hydrogen. However, the energy requirements for this step are much less than for electrolysis of water.

Thermochemical cycles for hydrogen production were widely investigated in the late 1960's through the mid-1980's. The advantages of thermochemical cycles are generally considered to be high projected efficiencies and attractive scaling characteristics for large-scale applications. The efficiency of hydrogen production is potentially greater with thermochemical processes because production of hydrogen by electrolysis is a three-step process (heat to electricity to hydrogen) whereas thermochemical hydrogen production is a two step process (heat to hydrogen).

Several hundred cycles have been identified and discussed in the literature (References 9 and 10 provide a good review of the various thermochemical cycles). Many of the cycles were found to be unworkable, have low efficiency, or require excessive temperatures. However, 15 processes were demonstrated to be chemically viable, four processes were tested in the laboratory with production of one to hundreds of liters per hour of hydrogen, and a conceptual engineering design and costs were developed for one process. Relatively complete process flow sheets exist for the four processes tested in the various laboratories. At the current time, only one laboratory pilot plant is in operation. That plant, built of glassware, is operating in Japan.

From this information, several "families" of thermochemical cycles emerged as promising options. The various cycles within these families have been evaluated and prioritized based on factors such as theoretical achievable efficiencies, technical risk, and technical maturity. From this evaluation a set of key R&D needs have been developed, along with preliminary recommendations regarding decision points in their cycle development.

The highest priority family of cycles was judged to be the sulfur based cycles. The second priority primary cycles are Ca-Br cycles. The three most promising sulfur cycles, hybrid sulfur, sulfur-iodine, and sulfur-bromine, are described in Figure 6. The expected efficiencies of these cycles are ~50%. The sulfur thermochemical processes have a common oxygen-generating, high-temperature step: dissociation of sulfur trioxide into sulfur dioxide and oxygen. This process step may require temperatures of 850ºC or higher. These high temperatures are a major engineering challenge for both the thermochemical plant and the nuclear reactor that must supply the heat. In principle, inorganic membranes can be used to enhance the decomposition reaction and potentially lower temperature requirements. This would significantly reduce the engineering challenges or improve process efficiency. R&D to evaluate the potential of high-temperature membranes is recommended. Shown in Figure 6 on the left is the option of either using very high temperatures or inorganic membranes to crack the sulfur trioxide.

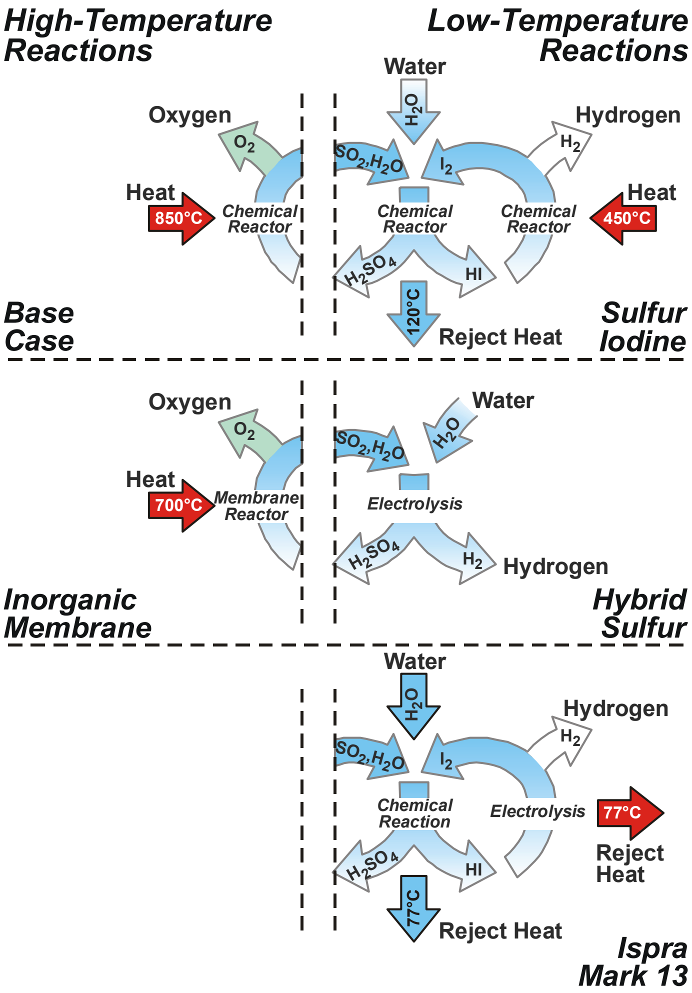


Figure 6. Sulfur family of thermochemical cycles.

The sulfur-iodine cycle is an all-liquids-and-gases cycle with three thermochemical steps.[11,12] Several organizations are developing the technology with a laboratory pilot plant in operation in Japan and one planned for the United States. Unique technical issues associated with this specific cycle include efficient separation of the hydrogen iodide, minimizing the recycle rates of chemicals within the process per unit of hydrogen produced and reducing the inventories of iodine, which, although not consumed, are expensive and somewhat toxic. Multiple alternative technical solutions (primarily using membranes) have been proposed to address these challenges.

The hybrid sulfur (also called Westinghouse, GA-22, and Ispra Mark 11) cycle is an all-liquids-and-gases cycle with a single thermochemical and a single electrolytic step. [13,14] Westinghouse Electric Corporation demonstrated it on a scale of 150 l/h and a conceptual plant design has been developed. As a two-step process, it is the simplest process that has been demonstrated, involving only sulfur compounds, water, hydrogen, and oxygen. The unique technical issues associated with this specific cycle include reducing the electrical consumption of the electrolysis step and scaleup of the electrochemical cells. The energy consumption of these electrochemical cells is a small fraction of traditional water electrolysis. The high-temperature step is the decomposition of sulfuric acid in common with the other sulfur family cycles.

The sulfur-bromide process should be considered as a backup contingency option. This all-liquids-and-gases cycle involves two thermochemical steps and one electrolysis step. It is the best developed thermochemical process (laboratory pilot plant operated for 1.5 years producing 100 l/h.) However, the projected efficiencies are slightly lower than the hybrid sulfur cycle. The hybrid-sulfur cycle is chosen relative to this hybrid cycle because 1) the process is more efficient (primarily because the electrolytic cell power consumption is less (0.6 vs. 0.8 V)), and 2) it is a simpler two step process.

7. References

1. *A Technology Roadmap for Generation IV Nuclear Energy Systems*, GIF–002-00, Generation IV International Form, (Dec. 2002).
2. *Toward a More Secure and Cleaner Energy Future for America, National Hydrogen Energy Roadmap*, U.S. Department of Energy, November 2002.
3. P. E. MacDonald et al. *NGNP preliminary Point Design – Results of the Initial Neutronics and Thermal-Hydraulic Assessments*, INEEL/EXT-03-00870, July 2003.
4. General Atomics, *Gas Turbine-Modular Helium Reactor (GT-MHR) Conceptual Design Description Report*, 910720, revision 1, July 1996.
5. "Program and Project Management Policy for the Acquisition of Capital Assets", DOE O 413.1, October 13, 2000
6. *Project Management for the Acquisition of Capital Assets*, DOE M 413.3-1, U.S. DOE Office of Management, Budget and Evaluation, June 28, 2003.
7. Advanced Gas Reactor Team, *Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program*, ORNL/TM-2002/262, April 2003.
8. D. Petti, J. Buongiorno, J. Maki, R. Hobbins, G. Miller, "Key Differences in the Fabrication, Irradiation and High-Temperature Accident Testing of U.S. and German TRISO-coated Particle Fuel, and Their Implications on Fuel Performance", *Nuclear Engineering and Design*, Vol. 222, pp. 281-297, 2003.
9. IAEA, *Hydrogen as an Energy Carrier and its Production by Nuclear Power*, IAEA-TECDOC-1085, May 1999.
10. L. C. Brown et al., *High Efficiency Generation of Hydrogen Fuels Using Nuclear Power, Final Technical Report for the Period August 1, 1999 Through September 30, 2002*, GA-A24285, June 2003.

11. G. E. Besenbruch, “General Atomic Sulfur-Iodine Thermochemical Water-Splitting Process”, American Chemical Society, Div. Pet. Chem., Prepr. 271, 48, 1982.
12. L. C. Brown, R. D. Lentsch, G. E. Besenbruch, K. R. Schultz, and J. E. Funk, "Alternative Flowsheets for the Sulfur-Iodine Thermochemical Hydrogen Cycle," 2003 Spring National Meeting, American Institute of Chemical Engineers, March 30-April 3, 2003, New Orleans.
13. L. E. Brecher et al., “Westinghouse Sulfur Cycle for the Thermochemical Decomposition of Water”, International Journal of Hydrogen Energy 21, 7, 1977.
14. G. E. Beghi, “A Decade of Research on Thermochemical Hydrogen at the Joint Research Center, Ispra”, International Journal of Hydrogen Energy 11, 761, 1986.