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NGNP with Hydrogen Production Power Level Special Study

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Record of Revisions

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001	4/18/2007	Pages 8, 41 and 42	Corrected minor typographical errors on Pages 8 and 41. Pages 41 and 42 - added paragraph at the end of Section 6.3.2 to address NGNP hydrogen process loop test configuration.

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1.0 Summary

A Special Study has been conducted to determine and justify a recommended rated thermal power for the NGNP prototype reactor and its associated demonstration hydrogen production facility. This study has been accomplished by examining a collection of topics selected to provide insight into the many aspects and perspectives from which this question can be answered.

Results of this study indicate that the goals of the NGNP project can be best met by designing, licensing, building, and successful operation of the prototype reactor at full commercial scale, that is, with a rated thermal output of 565MW. In addition, the estimated thermal power requirements of a demonstration hydrogen production facility will be approximately ten percent of this value, 60 MW.

2.0 Introduction

The Power Level Study is one of the four preconceptual design studies which the AREVA NGNP Team is performing for INL. This study will establish the recommended rated thermal power for AREVA's preconceptual HTR design based on the NGNP requirements. It will also establish the recommended fraction of this power which will be supplied to the demonstration hydrogen production facility.

This document describes the issues addressed by this study, the approach used to resolve these issues, the key criteria considered, the results of evaluation of these criteria, and final recommendations based on a synergistic assessment of the individual criteria evaluations.

This study is closely related to the NGNP Primary and Secondary Cycle Concept Study which the AREVA team is also performing. These two studies are coordinated, since the outcome of each is influenced by the other. Toward this end, close communication was maintained between the leader of the power level study and the primary-secondary study with guidance from the AREVA NGNP Systems Integration lead who provides overall coordination for all of the special studies.

3.0 Applicable NGNP Goals

The Gen IV Next Generation Nuclear Plant (NGNP) is an advanced reactor optimized to produce both hydrogen and electricity. The NGNP will generate hydrogen without emitting greenhouse gasses or other air pollutants. It will also exhibit high thermal efficiency, attractive safety aspects, minimize waste, and be proliferation resistant. It will be suitable for efficient hydrogen production utilizing, for example, water-cracking by high temperature electrolysis or thermo-chemical decomposition. For prototyping the NGNP, the DOE selected a very high temperature gas-cooled nuclear (VHTR) reactor with the capability to produce process heat, electricity and/or hydrogen.

A key design objective of the NGNP is the elimination of the need for active safety systems to prevent fuel damage in the event of loss of forced cooling. In order to prevent fuel damage, the plant must be designed to passively remove core decay heat via conduction, natural convection, and thermal radiation in this event. The requirement for passive sensible and decay heat removal under accident conditions, places a limit both on core size and on power density for a given core size in order to both limit the stored energy in the core, and facilitate passive heat removal. This results in a low power density core design. In order to achieve significant levels of energy production, the VHTR design concept favors multiple moderate size power reactor modules, typically four or more, which could share common support facilities.

In order to provide a framework within which to make the recommendations called for in this study, it is important to understand the goals of each of the key contributors and users of the NGNP project results. In the sections below are examined the goals of each of these key groups as they relate to the power level of the NGNP demonstration reactor.

3.1 DOE Expectations

The NGNP High Level Functional Requirements[1] document contains several high level functional requirements for the NGNP which must be considered in an analysis of plant power level. These requirements, and a summary of key concepts to be considered for each, are summarized below.

3.1.1 Develop and Demonstrate a Commercial-Scale Prototype VHTR

A commercial-scale prototype will be built, tested, and operated to demonstrate the performance characteristics of future advanced high-temperature reactors. The primary function of this prototype plant will be to verify both operational and safety performance of high-temperature reactors over a range of normal and transient conditions. The NGNP will also demonstrate the ability to generate efficient and reliable process heat.

3.1.2 Obtain Licenses and Permits to Construct/Operate the NGNP

The NGNP will be licensed by NRC under 10 CFR 50 or 10 CFR 52. The licensing of the NGNP by NRC will also demonstrate the effectiveness of licensing future advanced high-temperature reactor concepts for commercial applications. In particular, it is anticipated that many of the current issues associated with NRC licensing of a non-LWR and the use of nuclear power for hydrogen production will be resolved during the licensing of the NGNP.

3.1.3 Develop and Demonstrate Hydrogen Production

Hydrogen production plant(s) will be included as part of the NGNP facility to demonstrate the capability of high-temperature reactors to produce hydrogen in a cogeneration mode and demonstrate hydrogen production. Hydrogen production will be demonstrated using high-temperature water electrolysis and a thermochemical process.

3.2 Commercial (Vendor/User) Expectations

The Design Features and Technology Uncertainties for the Next Generation Nuclear Plant[2] report, developed by the Independent Technology Review Group, identifies commercial expectations as:

> *Selection of the technology and design configuration for the NGNP must consider both the cost and risk profiles to ensure that the demonstration plant establishes a sound foundation for future commercial deployments. The NGNP challenge is to achieve a significant advancement in nuclear technology while at the same time setting the stage for an economically viable deployment of the new technology in the commercial sector soon after 2020.*

4.0 Study Requirements

The "Statement of Work - Preconceptual Engineering Services for the Next Generation Nuclear Plant with Hydrogen Production,"[3] describes the following requirements for the conduct of the NGNP Prototype Power Level Study.

> *The vendor shall prepare a study that evaluates and recommends a power level for the NGNP prototype nuclear system, which is scaleable and meets all the necessary requirements as a "commercial" prototype and is licensable as a commercial prototype. In addition, the subcontractor shall evaluate and recommend minimum optimal prototype hydrogen plant size that will be scaleable to a future commercial scale plant.*

From this requirement definition, three specific, though interrelated, questions are developed to focus this study. These questions are:

- What should be the rated power level of the Nth of a Kind (NOAK) commercial VHTR module?

- Given the desired power level of the commercial VHTR module, what should be the rated power level of the NGNP prototype plant?

- In order to demonstrate commercial scalability of an associated hydrogen production plant, what is the power requirement for a demonstration plant to be associated with the NGNP reactor? The power requirements for the sulfur-iodine and high temperature electrolysis processes should be considered.

5.0 Study Process

5.1 Assumptions

The NGNP design is to be adapted from AREVA's ANTARES commercial HTR design concept, which incorporates a prismatic core, as agreed with INL. For this adaptation, the basic system configuration will remain the same for electricity production, but a separate interface for a high temperature heat transport loop to the hydrogen process will be provided. The NGNP specific power level and system operating parameters will be adjusted based on the results of the relevant special studies performed by the AREVA NGNP team.

5.2 Study Approach and Decision Process

This study has been completed utilizing the basic approach and decision process defined for all of the special studies under AREVA's scope of work. Key aspects of this process are:

- **Establish decision hierarchy** – Define the specific questions to be answered by the study, and develop a list of study criteria and supporting questions.
- **Identify range of options** – Define the range of study parameters to be considered for each of the study criteria, as applicable.
- **Get the required initial input** – Obtain sufficient information to provide a high-level assessment of each of the study criteria.
- **Prioritize decision sequence** – Identify those study criteria that provide information or insights which are critical to answering the main study questions.
- **Assess options regarding each criterion** – Identify which study criteria require additional or more detailed information to provide a complete evaluation.
- **Synthesize results for optimum solution** - Develop an overall set of recommendations based on a synthesis of the evaluations of each of the study criteria.
- **Internal expert review of draft special study results** – Utilizing the AREVA team, obtain expert review of the study and associated recommendations.
- **Finalize special study report** – Document the results of the special study.

5.3 Study Limitations

AREVA team has no scope for H_2 process development, H_2 process plant design, high temperature heat transport loop design and development, H_2 plant R&D, schedule, and risks, and H_2 plant economics (prototype or commercial). This limits the information that AREVA can use regarding these areas and their impact on the questions addressed by this study. In order to address these limitations, the AREVA team will make limited efforts to gather relevant information from available sources. Reasonable assumptions will be made where appropriate.

5.4 Study Criteria

In order to provide the necessary data to answer the three main questions defined for this special study, several study criteria were developed. For each of these criteria, focused questions were provided to guide the evaluation. Answers to these questions were pursued to the extent necessary to develop an overall understanding of the impact of the specific study criteria on the main study questions.

Market View

- What are the projected markets for the commercial VHTR module?
- For each of these markets, what is the optimum power level of the VHTR plant?
- For those applications where modularity may be advantageous, what is the optimum power level of each reactor module?

In developing the answers to these questions, end uses considered included electricity generation, hydrogen production, process heat production, and appropriate combinations of these uses.

Core Neutronics

In order to fulfill the top-level requirement that the VHTR plant being developed meets the passive safety goals of a Generation IV reactor, operating core power densities will be limited and rated reactor power changes will require changes in core size and geometry. Given this:

- What are the practical limits on core geometry (diameter, height, configuration – cylindrical vs. annular) from a neutronics/reactor physics standpoint?
- Considering these limits and representative power density limits, what are the practical power limits of a VHTR core?

Licensing Issues

It is a top-level goal of the NGNP program that the prototype NGNP reactor will be licensed by the NRC using a process consistent with that used to license commercial nuclear power plants.

- What is the optimum power level for the prototype NGNP module, as a fraction of the desired commercial VHTR module power level, to maximize the portability of the NGNP prototype licensing experience to the commercial plant?
- As this power fraction changes, what is the expected impact on the portability of the licensing experience in key licensing areas? What areas are most and least impacted?

Demonstration of Passive Safety Features

One of the primary purposes for constructing the NGNP prototype is to provide an opportunity to demonstrate, and generate data regarding, the passive safety features of this reactor type.

- What are the key plant power-related operational parameters that influence the performance of the reactor passive safety features?
- What is the optimum value of these parameters for the prototype NGNP module, as a fraction of those of the commercial VHTR module, to generate useful and applicable data and operational experience with these safety features?
- As this power fraction changes, what is the expected impact on the usefulness and applicability of the data generated for each of these key parameters?

Fabrication Issues

- Which major reactor components present challenging fabrication issues?

- For those components and associated issues, which are functions of rated reactor module power and what is the nature of that functionality?

Component Feasibility

There are several reactor components, the performance of which may limit the power of a VHTR module. These components include the reactor vessel, the intermediate heat exchanger, and the helium circulator.

- What other components fit into this category?
- For each component, what is the limiting consideration and how is it related to rated reactor power?
- Must this component be unique within a reactor module, as with the reactor vessel, or may separate trains be utilized to mitigate the performance issues?

Plant Flexibility and Operability

- For those applications that utilize multiple power output types (i.e., production of electric power and hydrogen) what is the optimum relationship between the outputs to achieve acceptable operational flexibility and plant availability?
- For any power output type or combination, are there module rated power levels which present particular operational flexibility or availability challenges, for example plant startup or load following operations?

Plant Safety Limits

Several plant safety limits and related operational parameters are directly related to the rated power of the reactor. These limits include conduction cooldown limits, fuel temperature limits, core flow and flow bypass limits, and core mechanical performance limits.

- How does the reactor module rated power influence these operational and off-normal limits?
- In each case, what are the key parameters which relate the reactor power to the limits?
- Are there any threshold powers above which it is impractical to meet these limits?

Economic Considerations

One of the benefits of constructing the NGNP prototype is to provide an opportunity to benchmark key cost data for this reactor type, including construction costs, capital equipment costs, fuel costs, and operation and maintenance costs.

- What are the key plant operational parameters that influence the usefulness of this economic benchmark data?
- How are these parameters related to the commercial VHTR module rated power, the NGNP prototype module power, and the difference between these power levels?

Hydrogen Plant Process Heat Requirements

One of the top-level requirements for the NGNP prototype reactor is to support the operation of a hydrogen production plant. The design of this plant is to be sufficient to demonstrate scalability of the process to commercial size. For the purposes of this evaluation, the hydrogen production process is assumed to be either the sulfur-iodine chemical process or the high temperature electrolysis process.

- What are the expected power requirements for the commercial scale processes.
- What are the expected power requirements for the demonstration scale processes that must be supported by the NGNP prototype reactor?
- What is the current state of development of each of these processes, with respect to power requirements, and what is the prognosis for development to the required demonstration scale on a schedule consistent with deployment of the NGNP prototype reactor in 2018?

Research and Development

- What impediments exist to successful design, fabrication, and operation of the NGNP at the chosen power level?
- What R&D opportunities are presented by design, fabrication, and operation of the NGNP at the chosen power level?

6.0 Evaluation of Study Criteria

Upon review of the initial evaluations of each of the study criteria, several were identified as being critical to the establishment of the recommended commercial reactor and NGNP prototype reactor power levels. These are designated Key Discriminating Criteria and were subject to additional study and evaluation. The results of these evaluations are presented first in the following sections. The evaluation results for the remaining study criteria are presented following the Key Discriminating Criteria. The results of the Hydrogen Plant Process Heat Requirements evaluation are presented separately because it was determined that, while the relatively small power requirements for the demonstration hydrogen plant were not critical to determination of the NGNP power level, the results of the evaluation are required to answer the third of the power level special study questions.

6.1 Key Discriminating Criteria

6.1.1 Market View

The most likely commercial applications for the VHTR will entail the use of process heat and electricity in various combinations. A principle anticipated commercial use of the energy from the VHTR will be the production of hydrogen. However, AREVA internal studies have also identified a number of other potential industrial applications for the energy products from the VHTR. These applications are introduced below and more fully developed in following sections.

6.1.1.1 Hydrogen Production

The long-term vision for the VHTR is to be an integral part of the Hydrogen Economy. The primary reason for the US DOE sponsorship of the Next Generation Nuclear Plant Initiative is to support this vision. From a market standpoint, government funded initiatives will be the primary market driver in the near-term.

In framing the commercial VHTR's market potential, there is a need to gain a better understanding of its potential role in a hydrogen economy. A part of this task is to ascertain which hydrogen production technologies show the most promise. As the most potentially promising methods are currently at the research/development stage, this assessment, of necessity, remains somewhat speculative. However, it is possible to report the favored production processes and project the required energy characteristics, particularly temperature, to drive these processes. From this information, energy production requirements for hydrogen generation utilizing the VHTR can be postulated.

Power and Production Process Configurations for Hydrogen Production[4]

Hydrogen can be produced by thermo-chemical, electro-chemical, and hybrid (electro-thermo-chemical) processes using nuclear energy as the primary thermal energy source. The hydrogen production process properties determine the types of reactors that can appropriately be coupled to the relevant hydrogen production technology. Some processes require both electrical and thermal energy, and, therefore, for such applications, plants readily configured for co-generation are attractive.

An important design requirement for both thermo-chemical and electrochemical hydrogen production is the relatively *high temperature* needed for achieving high thermal-to-hydrogen energy efficiency. This is an important factor in the economics of the technologies. Furthermore, each hydrogen production process, and the nuclear system supporting it, has unique technological features that can significantly influence the economic compatibility of the system with the projected hydrogen markets.

Energy from the VHTR can be used in hydrogen production mainly in three ways:

- By using the electricity from the nuclear plant for conventional *liquid water electrolysis*.
- By using both the high-temperature heat and electricity from the nuclear plant for *steam electrolysis*.
- By using the heat from the nuclear plant for pure *thermochemical processes*.

Water electrolysis is already commercialized, however, is comparatively inefficient. It is unlikely that water electrolysis will become a favored commercial application of the VHTR for hydrogen production. However, high temperature steam electrolysis shows promise in that it has comparatively high efficiency and requires only intermediate range temperature –temperatures achievable by the VHTR. Large scale production capabilities, however, remain to be demonstrated.

Thermo-chemical water splitting is the principal process under study for a nuclear powered thermo-chemical hydrogen production.   Hydrogen can be produced from nuclear power by thermo-chemical water splitting. (Heat plus water yields H_2 and oxygen.) Thermochemical processes have potentially higher efficiencies and lower costs than the electrolysis of water with electricity. High temperatures, in the range of 750-1000 C, potentially achievable by the VHTR, are required for economically viable production.

6.1.1.2 Industrial Applications Utilizing the VHTR

Commercializing the VHTR requires the identification of potential industrial applications that could utilize the energy output from the VHTR either in the form of process heat, electricity, or various combinations of both. AREVA NP studies have identified a number of such potential industrial applications for the VHTR. These applications (see below) utilize process heat and electricity in various combinations. The first few are ordered by the approximate timeframe of likely implementation, earliest first.

Hydrogen production, already discussed above, is included in this listing in order to suggest the time frame of likely implementation relative to the other industrial applications. (Note also that hydrogen generation may be a significant component of several of these industries.)

Potential Industrial Applications of the VHTR

1. Coal to Liquids

2. Oil Sands
3. Oil Shale
4. Coal Gasification – “Clean Coal”
5. Hydrogen Production
6. Petroleum Refineries
7. Electricity Production
8. Industrial Process Heat Applications
    8.1 Steel
    8.2 Alumina and Aluminum
    8.3 Chlorine VCM and PVC
    8.4 Ammonia and Fertilizers
    8.5 Chemical Platforms
9. Biomass
10. Water Desalination

A discussion of each of these potential applications for the VHTR is provided below. This material represents a summarized composite of AREVA and industry research. Hence, individual citations may not always be provided.

Assessment of Industrial Applications

Coal-to-Liquids

Coal-to-Liquids (CTL) is a promising concept for converting existing large supplies of coal to forms that can be substituted for current petroleum products. Coal is one of the most abundant sources of energy on earth but it suffers from a high cost for transporting it to needed locations, high environmental impact from burning coal and the difficulty of using coal to meet transportation energy needs. A CTL process addresses all of these issues.

A strategy for using nuclear heat in the CTL process is to identify conceptual approaches to using that energy, then to identify specific points in the process where those approaches could be applied. It was determined that the optimum application for the VHTR would be to displace chemical energy. One way is to use the VHTR to produce hydrogen. This offers the following CTL process improvements:

- The water-gas shifter reactors are eliminated
- The carbon monoxide that had been converted to carbon dioxide is now available to make more Fischer-Tropsch feedstock
- The size of the CO_2 removal equipment is reduced

For the purpose of this assessment, the process for producing hydrogen was assumed to be electrolysis which also produces oxygen. This assumption results in a further process simplification in that the oxygen producing equipment otherwise required in the CTL process can be eliminated.

The second nuclear heat application is to recover the tail-gas from the Fischer-Tropsch synthesis rather than to burn it for process heat. Also, the CO_2 can be recovered and converted to carbon monoxide for use in the reaction. These process changes increase the carbon utilization to 95.7%.

Plant sizes consistent with current plans would require approximately 3,000 WMth of nuclear generated heat.

At present, it appears that the nuclear heat option would be competitive with the fossil heat source at a CO_2 penalty of about $100/ton.

Oil Sands

The oil sands in Canada present a sound potential application for the VHTR. Production is expected to increase from today's level of about 1 million barrels per day to a level between 4 and 6 million barrels over the next few decades. The current in-situ methods require about 1,000 standard cubic feet (scf) of natural gas per barrel of bitumen. This natural gas is used only for process heat. An additional 80scf/barrel is used for processing and 250scf/barrel is used for hydrogen production for refining. Using the heating requirements only, one 600 MWth VHTR module could supply the requirements for a 40,000 to 50,000 barrel per day facility. The current oil sands production facilities are being built in 35,000 to 50,000 increments so this matches well with the VHTR capability. Most current oil sands facilities transport steam for heating about 10 km but two transport steam up to 17 km to support a single field. With this range, an oil sands field is expected to be productive for 40 to 60 years. Each of these characteristics matches well with VHTR conceptual design characteristics. The Canadian oil sands could possibly support a large number of VHTRs, providing significant environmental benefits by displacing the use of natural gas, the current plan.

Oil Shale

Current estimates indicate the oil shale deposits in the United States have 800 billion barrels of recoverable oil. While oil shale is found in many places worldwide, by far the largest deposits in the world are found in the United States in the Green River Formation, which covers portions of Colorado, Utah, and Wyoming. The oil resources in place within the Green River Formation are estimated to range from 1.2 to 1.8 trillion barrels. Not all resources in place are recoverable; however, even a moderate estimate of 800 billion barrels of recoverable oil from oil shale in the Green River Formation is three times greater than the proven oil reserves of Saudi Arabia.

Studies have shown that the heat from one 600 MWth VHTR unit can provide the needs of a 100,000 barrel/day facility for 40 years with heat transport no greater than 1,200 m. The oil shale is heated to 370°C which requires a heat source of 450° to 500° C. These requirements match the design profile for the VHTR.

Oil shale production is a significant potential industrial application for the VHTR.

Coal Gasification-"Clean Coal"

Power generation from coal emits significant amounts of sulfur dioxide (SO_2), nitrogen oxides (NOx), mercury and carbon, contributing to numerous health and environmental concerns. The Clean Air Act of 1970 set emission standards, but existing plants were grandfathered. Today, 850 of those plants are still operating, exempt from the 1970 emission standards. Clean coal initiatives will boost businesses involved in efforts to reduce emissions from coal.

Using heat, steam, pressure, and oxygen, coal can be broken down into a relatively clean gas, and a handful of other chemical byproducts. Coal gasification offers one of the cleanest, most versatile ways to convert coal into electricity and other forms of energy. Rather than burning coal directly, gasification breaks down the coal into its basic chemical components. The gasification facility can then co-produce a wide range of products, including electricity, high-value chemicals, and synthetic fuels. It is also important to note that Hydrogen can be produced in the coal gasification process.

The use of the VHTR for the coal gasification process is similar to that described above in the Coal-to-Liquids application above. The CTL process produces a fluid output that is more easily transported than bulk coal. A gaseous product can also be produced and transported but is more likely to be used at the source to generate, for example, "clean coal" electricity. For this reason, initial projects would be more likely to be CTL. A successful CTL application would also lead to interest in using VHTR for coal gasification. It is likely that these facilities would be sized similar to the CLT facilities, requiring on the order of 3,000 MWth for each installation.

If the trend to limit the production of green house gases both continues and, likely accelerates, coal gasification is viewed as a strong potential future market for the VHTR.

Hydrogen Production

One energy vision for the future is to create a stable, non-polluting hydrogen economy. The nuclear role in this economy is to produce the hydrogen that will then be used to fuel the transportation industry. The time scale for achieving this economy is debated but, with a finite hydro-carbon supply and no viable alternatives, a hydrogen economy will come into being someday. The timing will be based on the relative economics of using current petroleum resources compared to hydrogen production costs.

At present, Hydrogen demand is expected to grow at a rate of 4-10% annually for the foreseeable future. The current and future hydrogen market can be characterized as follows:

Current and near-term

- Oil Refining
- Ammonia (fertilizer) industries

  - Methanol industry
  - Merchant H_2 Customers
  - Oil Sands
- Mid-term
  - Oil Shale
  - Coal-to-Liquid
  - Electricity Power Peaking
- Far-term
  - Transportation
  - Remote electricity production

The most likely hydrogen production applications for the VHTR in the near term (next few decades) are as a supplement to coal-to-liquids, oil sands or oil shale production. In each of these processes, the crude product needs to be refined which requires hydrogen.

The demand for "stand alone" hydrogen production, e.g. for the transportation market, is more difficult to predict. This market is unlikely to develop a substantial demand until beyond 2030, which suggest it will not present a significant near term application for the VHTR, but may present a significant industrial application in the long term.

A recent study by Savannah River National Laboratory[5] demonstrated the feasibility of stand-alone nuclear hydrogen production facilities utilizing 600 MWth of process heat with an additional electric demand of approximately 192 MWe from either an additional reactor of from the electric grid.

Electric Production

Historically, economy of scale advantage has generally favored larger plants for production of electricity. However, the VHTR has several attributes that could make it attractive for electric power generation:

- Modular construction leading to shorter construction schedules and reduced construction costs

- Greater inherent safety permitting siting closer to load demand

- Smaller added increments of power to better match load growth and minimize capital outlay

An outline of the market potential based on each of the primary benefits follows:

<u>Short Construction Schedules</u>

The benefits from short construction cycles come from two sources:

1. Reduced interest during construction and

2. Delayed decisions on capital investment.

Scoping calculations suggest that a modular VHTR can compete with a large Gen III plant, on construction costs alone, provided the over-night construction costs do not exceed the costs for the Gen III plant by more than about 10%.

The second benefit of short construction schedules is to provide utilities the ability to delay capital investment decisions. Capital decisions made close to the need date are more likely to closely match generation with demand than decisions with a longer time horizon.

Location Close to Demand

Finding routes for transmission lines is becoming increasingly difficult. This is especially true in densely populated areas. One strategy currently employed is to construct the power generator as close as possible to the demand in order to reduce the need for new transmission lines. The inherent safety of the VHTR could facilitate such siting.

Smaller Increments of Power

One of the advantages of modular VHTR is that power can be added to the grid in smaller increments than with a larger base load plant. These smaller increments better match the load growth.

Modular construction also contributes to the option of progressing incremental capital investment to match electricity demand, i.e, adding individual power modules only when justified by demand. In fact, the market may even be willing to pay a premium for this flexibility.

For the purposes of this study, it is assumed that most electric generation facilities will be constructed in the range of 1000 MWe.

Industrial Process Heat Applications

Five industrial applications that use significant amounts of process heat were identified as potential applications for the VHTR: Steel; Aluminum and Alumina; Chlorine, VCM and PVC; Ammonium and Fertilizers; and Chemical Platforms.
A summary of each potential application is provided below.

Steel

The most viable concept for applying nuclear energy to steel making combines two well-known processes: direct reduction in a shaft furnace and refining in an electric furnace. In this process, iron ore is reduced in the solid condition by a synthesis gas ($CO+ H_2$) derived from steam reforming of natural gas to a product known as sponge iron. The reaction requires high temperatures and heat. The VHTR could he used to provide the heat needed to produce the reducing as for the direct reduction of iron ore and the electricity needed to refine the resulting sponge iron to steel in an electric-arc furnace. Production of steel by electric-arc furnaces is a long-established commercial technology. Electric-arc refining uses about 650 KWH/ton of steel. In a steel making system involving direct reduction and refining in an electric-arc furnace, nuclear energy can be used to:

a. Provide high-temperature heat for the production of a gas suitable for the reduction of iron ore to iron.

b. Produce electricity for operation of electric-arc furnaces to refine the sponge iron.

The most serious competition for the VHTR in this application is presented by fossil fuel. Absent strong pressure to reduce green house gases, if low cost fossil fuel is available close to iron ore reserves, supplying heat from the VHTR may not prove cost effective.

However, it is anticipated that a potential market may well exist in countries which take steps to limit the generation and release of green house gases.

Recent work by the Japan Nuclear Steelmaking Project[6] has focused on a nuclear reactor with a 500 MWth thermal output as a base case.

<u>Alumina and Aluminum</u>

The comparatively low temperature requirement (150°C) for the aluminum production process suggests heat sources used in alumina facilities will based on technologies less sophisticated than VHTR. Therefore, at present, aluminum and alumina manufacturing and processing facilities are not viewed as a strong potential market for VHTR.

However, economic pressure to reduce the generational of green house gases in industrial production processes would likely alter this conclusion. It is estimated that a 600 MWth facility, supporting a 1.2 Mt/y output may be feasible in this case.

<u>Chlorine VCM and PVC</u>

Chlorine is produced from the electrolysis of sodium chloride, using three methods: the mercury cell, the membrane cell (Best Available Technology) and the diaphragm cell. Vinyl Chloride Monomer is produced in two steps by chlorinating ethylene and by its oxychlorination (250°C) into dichloroethane, which is decomposed at 500°C into VCM. VCM is polymerized into PVC, mainly in suspension in water (50-70°C).

These process energy requirements would not fully utilize the capabilities of the VHTR. There may prove to be some advantage if the production of Chlorine-VCM-PVC is part of an integrated chemical platform. However, it is not clear that production of chlorine VCM and PVC presents a significant future commercial application.

Economic pressure to reduce the generational of green house gases in industrial production processes may alter this conclusion.

In order to support a 600 MWth VHTR facility, many related functions would have to be consolidated onto one site.

<u>Ammonia and Fertilizers</u>

Most ammonia is produced by the steam reforming of natural gas. However, it may also be produced by steam reforming of other hydrocarbons. For example, China produces 80% of its ammonia from coal, naphtha and refinery gas through reforming.

About 80% of the manufacturing plants use the catalytic steam reforming of natural gas. Primary methane reforming is highly endothermic and takes place at between 750 and 800°C in the presence of steam. It is fueled with natural gas. The secondary reforming is autogenic and takes place in the presence of air at around 1000°C. This eliminates the remaining methane and introduces into the system the nitrogen necessary for ammonia synthesis. The ammonia is synthesized from the catalytic conversion of hydrogen and nitrogen in an exothermic reaction at temperatures of between 350°C and 550°C.

Even though there is a reasonable match with the process energy requirements, the limited market size suggests that the production of ammonia and fertilizers will not present an attractive opportunity for the VHTR. It is estimated that facility requirements would limit feasible reactor outputs to 200 MWth.

The conclusion may be altered should production of these products be integrated as part of a chemical platform or if there is economic pressure to reduce the production of greenhouse gases.

<u>Chemical Platforms</u>

Base chemical production is generally endothermic whereas complex chemical syntheses are exothermic. Ethane and naphtha supplied from oil refineries are the source of major intermediates such as ethylene and propylene, which are produced in steam crackers using large amount of heat but also produce large amounts of steam. Natural gas is also a major feedstock to produce hydrogen and syngas.

The process heat demand is driven by the accumulation of processes which allow energy optimization and by-product recycling, as well as improved risk management in a given location. Most of the chemical platforms which will develop will be built in transition economies, some in OECD countries, but they will not all reach a demand in the region of 600 MWth.

Absent economic pressure to reduce processes that produce green house gases, chemical platforms appear to present a limited future market for the VHTR.

Biomass

Biomass, in the energy production industry, refers to living and recently living biological material (lignocellulosics) which, after some level of processing can be used as “bio” fuel or for industrial production. Biofuels include bioethanol, biobutanol, biodiesel & biogas. Biodiesel and biobutanol are direct biofuels and can be used in petroleum engines.

The most promising possibility for integration of the VHTR may be through indirect biomass-to-liquids approaches utilizing gasification. Thermochemical processes, including pyrolyis and gasification, employed in processing lignocellulose utilize heat in the range 400 - 850°C and are the best candidates for such integration.

It should be noted that the general economic viability of biomass fuel is controversial with experts in disagreement. For example, some believe that biomass-to-ethanol via processing lignocellulose results in a net energy deficit for the conversion process.

Government incentives may be necessary to attract business investment if there is, in fact, a net energy deficit in converting biomass-to-ethanol for fuel. This application, absent other incentives, appears to afford little opportunity for the VHTR.

However, should such incentives develop the most likely potential commercial application of the VHTR is that of indirect biomass-to-liquids approaches utilizing gasification. Other options include nuclear energy-supported integrated bio-refineries that utilize reduction of the byproduct CO_2 to liquid fuels to displace petroleum and generate additional carbon credits. Future developments in energy densification of the feedstock that allow larger processing facilities will improve the options for efficient integration of a 600 MWth VHTR with biomass conversion processes.

Water Desalination

Desalination technologies have achieved commercial, world wide application. While many are fossil powered, there are numerous nuclear powered desalination applications as well.

The International Atomic Energy Agency (IAEA) has studied, and continues to study, the nuclear desalination option. The IAEA results generally show that nuclear seawater desalination yields costs in the same range as fossil options. However, this conclusion is generally derived from data for large base loaded nuclear plants.

Large-scale deployment of nuclear desalination on a commercial basis will depend primarily on economic factors. Such economic factors may be very much region specific. For example a market may exist in an arid region with high water demand but with limited access to low cost fossil fuel.

Perhaps a water starved region enjoys (1) plentiful sunshine, (2) a high electricity demand during day light hours and (3) low electricity demand at night. In this instance, solar conversion systems could provide fresh water during the day, with the nuclear plant providing electricity in the same period. However, in darkness the “off-peak” (excess) electrical power could flow to the desalination plant during the night when the solar desalinization plant would otherwise be idle.

The modularity of the VHTR would favor this design for construction in certain remote locations, though required modules would likely be in the rage of 100-400 MWth. The high thermal efficiency of the plant, particularly in the co-generation configuration, would also favor the VHTR in arid regions with its reduced cooling water requirements over the Gen III plant designs. However, unless it were possible to uniquely match the advanced design capabilities of the VHTR (particularly the high temperature outputs) to a unique combination of electrical and thermal demands, it is improbable that it would prove cost effective for water desalination.

6.1.1.3 Market View Summary

The Gen III commercial impetus for very large individual reactors to optimize the investment in plant and fuel, and minimize electric power production cost is substantially altered by the Gen IV objective of passive core cooling post accident. Even given the improved thermal efficiency of the VHTR, the passively safe design may compromise the cost of electric power production when contrasted with the Gen III water cooled reactors. Thus cost optimization for the VHTR must take a different path -modularity.

The Gen IV safety objectives encourage the development of multiple “modular” reactors within a single physical facility. An important ancillary benefit of the modular concept is a reduction in the high initial capital investment typically demanded for the large Gen III units. With the VHTR, individual reactor modules can be added to match energy demand, pacing the capital outlays.

Modular construction can also take advantage of the economies of production, relying less on the economies of scale to reduce costs. It is envisioned by some that a large contribution to the cost effectiveness of modular facilities is the ability to manufacture the major component parts in a “factory” environment, shipping these subassemblies to the site to be assembled. The factory environment facilitates both careful control of the manufacturing process and reduction of production cost.

Commercial applications thus far identified for the VHTR do not appear to establish constraints on reactor module size. That is, there does not appear to be a significant advantage to producing modules with power levels below that which is limiting based upon other criteria. Thus the optimal size for a commercial module is the largest capacity permitted within the design constraint of passive safety and, if “factory built,” it is also constrained by the largest pre-assembly structures that can be cost-effectively transported to the plant site. There is an additional assumption built into this conclusion, namely, that existing experience regarding economies of scale are applicable and it is not cheaper to build many smaller units than one large unit of comparable size.

Table 6.1 – Summary of Market View Evaluation

Market	Standard Plant Heat Input MWth	Output	Comments
Coal to Liquids	3000	26,000 b/d	Competitive with fossil fuel options at approximately $100/ton carbon credit
Oil Sands	600	40,000 /d	Study configuration for 1 VHTR module
Oil Shale	600	100,000 b/d	Study configuration for 1 VHTR module
Coal Gasification	3000		Based on coal to liquid results
Hydrogen	600	100,000 t/y	SRNL study configuration for 1 VHTR
Petroleum Refineries	1800	15 Mt/y	
Electricity	2400	1000 MWe	Assumed default configuration
Steel	500		Japan Nuclear Steelmaking Project
Alumina/Aluminum	600	1.2 Mt/y	Low temperatures limit VHTR market
Chlorine/VCM/PVC	600	1 Mt/y PVC and 0.6 Mt/y Cl	Marketability requires consolidation of multiple functions on one site
Ammonia	200	0.75 Mt/y	
Chemical Platforms	200-600		Based on combination of processes to gain efficiency advantages
Biomass	600	1 Mt/y feed	Market depends on Carbon credit
Water Desalinazation	100-400		Low temperatures limit VHTR market

6.1.2 Economic Considerations

It is argued in the preceding section of this study that the optimum size VHTR module from an applications view point is the maximum module size imposed by design constraints (passive cooling, for example) not the size of the industrial facility that it is intended to supply with electricity or heat. The demand size can always be scaled so as to fully utilize the supply size.

There are several additional economic considerations that apply specifically to the planned size of the NGNP reactor. These considerations can be viewed from the perspective of the reactor vendors who will eventually participate in the NGNP project and the end-users who will purchase the commercial units built using the NGNP experience.

From a reactor vendor perspective, participation in the NGNP project, particularly the latter stages where significant sharing of the costs is anticipated, depends on a favorable balance of these cost with the benefits gained through such participation. Some of these benefits are difficult to assess from an economics standpoint, such as the perception of industry leadership gained through participation. Others are easier, particularly those related to the applicability of costs incurred for the NGNP that are directly transferable to the commercial fleet. Chief amongst these benefits is the ability to complete first-of-a-kind engineering tasks in a cost share manner. This benefit is maximized if the power level of the NGNP reactor is equal to the power level of the eventual commercial plant.

Any difference in power level will reduce this benefit. The reduction in benefit will increase dramatically as the power levels diverge. Thus, from a reactor vendor standpoint, there is considerable incentive to have the NGNP built as a full size demonstration plant.

Deployment of the NGNP provides an opportunity for eventual end-users to benchmark key cost data that will aid the decision making process. These costs may include capital cost data, construction costs, costs of operation and maintenance, and fuel cycle costs. Design of the NGNP at any power level other than 100 percent of the commercial plant will make these benchmarks less directly applicable, thus less useful.

From this argument, it follows that the NGNP prototype should be a full-rated design, though it may initially be licensed to some fraction of that design capability. While distortions in pricing may result from a first of a kind vs. N^{th} of a kind installation, this approach will nonetheless present the best opportunity of achieving these cost benchmarks. These benchmarks will play a key role in assuring the eventual commercial acceptability of this reactor technology.

Note that any first-of-a-kind prototype will not be able to capture the potential benefits that could accrue from some form of "mass production" of modular components in a factory environment – for subsequent shipment and assembly a plant site. It has been argued[7] that it is modularity of component construction that will encourage the acceptance and commercial utilization of the GEN IV nuclear plant designs. In this conceptual model, modularity takes advantage of economies of production, not the economy of scale (i.e., the GEN III very large base loaded plants) to both reduce construction capital at risk, and to reduce overall costs, thereby encouraging commercial acceptance.

In summary, economic considerations from both the reactor vendor and end user standpoints support the construction of the NGNP as a full sized demonstration plant.

6.1.3 Plant Safety Limits

The key parameters that influence the performance of reactor passive safety features (in order of importance) are the

- power level (including the axial profile),
- decay heat,
- thermal conductivity of graphite (especially including the effects of irradiation on the conductivity and the effects of annealing at higher temperatures),
- amount of bypass flow and its effect of cooling the reflector graphite,
- amount of power generated outside the active core, which has an influence that is similar to, but opposite in effect of, the bypass flow,
- inlet temperature, and
- outlet temperature.

The power level and inlet and outlet temperatures are project influenced parameters and are set by the particular design. Similarly, design decisions can be used to control the amount of bypass flow to within certain limits. It is possible that uncertainties in the graphite conductivity and uncertainties in the effect of annealing can be reduced through additional materials R&D.

The effect of bypass on cooling the reflector graphite has a rather large influence on the peak temperature during depressurized conduction cooldown (DCC) events. Parametric calculations, internal to AREVA, with the unrealistic assumption of no bypass flow had peak fuel temperatures during DCC that were approximately 77 °C higher than the corresponding reference cases. Other parametric cases show that the bypass flow through the central reflectors has a larger effect than bypass flow in any other region of the core. Nevertheless, beyond a minimum amount (a few percent of the total flow) required to cool the reflectors, additional bypass flow has little effect on the peak temperatures.

Modular HTR's rely on conduction and thermal radiation in their passive safety features for decay heat removal. Therefore, the selection of geometry, materials, and power level are all direct factors in the ability of the design to avoid exceeding limits after a loss of active cooling. This differs significantly from LWR's for which these plant-level decisions primarily influence the size of supporting safety systems.

It is difficult to assign an "optimum value" for the specific parameters without sufficient consideration of the savings in cost of the NGNP prototype resulting from these design decisions and an equal consideration of the costs of additional R&D that would be required to scale the data acquired from the prototype to the level of a full-size commercial plant. Nevertheless, the following comments can be made.

The thermal performance of the plant during a loss of active cooling is dominated by four items: the geometry of the plant, the thermal energy stored in the core at the beginning of the event, and energy (the decay heat) that is generated inside the core, and the heat transfer properties of the core (graphite). In the case of Pressurized Conduction Cooldown, which is less challenging for the fuel, the movement of heat through natural circulation of the helium coolant is also important. These four items are influenced by the operating parameters listed above as follows:

> **Power level and decay heat** - The decay heat is directly related to the power level and is a strong factor in determining the peak temperatures reached during a DCC transient. Thus, reducing the linear power level (thermal power per unit height) would result in lower temperatures and is less challenging to the passive heat removal features of the design, but could still provide some useful data and experience. One possibility to compensate for the reduced power would be to decrease the reactor's physical size; however, this has serious consequences for other data and operational experience provided by the prototype -- such as core layout, (perhaps) block size, control rod locations, and neutronics.
>
> **Outlet temperature** - The outlet temperature influences the maximum temperature of the fuel during normal operation, but has a much smaller effect on the safety features for decay heat removal and the peak temperatures during DCC.

Furthermore, the selection of outlet temperature is primarily determined by the target application of the nuclear heat source. All other considerations being equal, the higher the outlet temperature the more power is stored in the core and the more severe the impact of events that either increase the power level, locally or globally, or decrease the coolant flow either locally or globally.

Inlet temperature - Assuming sufficient bypass flow, the inlet temperature determines the temperature of the majority of the reflector graphite in the core and thus most of the thermal energy stored in the core at the beginning of the event. This has a large effect on the ability of the reflector graphite to absorb additional energy during a DCC event and thus a relatively large effect on the peak fuel temperature.

A change in linear power level for the prototype would have the following effects on the key parameters listed above:

The thermal properties of graphite - A reduction in linear power level will result in lower temperatures in the core during a DCC event. Thus, any data obtained for the thermal response of the core during conduction cooldown will be for a temperature regime that is lower than the temperatures that would occur in a full-scale reactor.

Bypass flow - A reduced power level will result in a lower mass flow (assuming that T_{out} - T_{in} is unchanged), which would result in a change in the pressure drop across the core and a change in the amount and distribution of the bypass flow for a given core geometry. The effect of this change in bypass flow on passive decay heat removal would most likely be small or negligible, however.

Power generated outside the active core - To first approximation, this should vary directly with the core power.

Inlet temperature / Outlet temperature - These are additional design parameters of the reactor, which can be altered independently of the core power and which could potentially be adjusted to compensate for the effects of a power reduction.

From the results of the parametric studies above, it is possible to quantify the sensitivity of the DCC results to these key parameters in terms of an equivalent change in reactor power. The impact of the graphite thermal conductivity on decay heat removal is very non-linear and depends greatly, not only on the temperature of the graphite, but its irradiation history as well. The results given here were obtained from calculations that used conductivity values that differed by ±25% from the thermal conductivity data for irradiated graphite, such as would be found in the core blocks at end of life.

These results are expressed in terms of an equivalent increase in reactor power level required to achieve the same peak fuel temperature during a DCC event.

- -5.9 MWt / % increase in residual power

- 1.0 MWt / % change in graphite conductivity - 27.7 MWt if power generated outside the active core is included in the calculation
- -0.23 MWt / °C increase in inlet temperature
- -0.11 MWt / °C increase in outlet temperature

Sensitivity to the initial power level of the peak temperatures during normal operation and during DCC were determined for conditions that were limiting for the fuel and for conditions that were limiting for the reactor vessel. Taking an average of the two results, these calculations indicate that the sensitivity of the maximum temperature during normal operation is 0.229 °C per MWt core power and the sensitivity of the peak temperature during DCC is 1.771 °C per MWt core power.

The mass flow through the core varies directly with the core power, assuming that T_{out} - T_{in} remains the same. The relationship between the mass flow, the amount of bypass flow, and its distribution in the core is non-trivial and requires further study.

The answer to the question, "Are there any threshold powers above which it is impractical to meet the applicable DCC limits?" depends on the safety philosophy that is used and how one combines uncertainties. Best estimate calculations, conducted internally by AREVA, remain below the 1600 °C guideline for a core power of 600 MWt. If uncertainties are "stacked", that is, if the most conservative value is assumed for every parameter influencing the peak fuel temperature, then a core power of 400 MWt (and a reduction in both inlet and outlet temperatures) is required to remain below the 1600 °C guideline. However, this approach is extremely conservative.

A less conservative calculation was conducted internally by AREVA eliminating the uncertainties in some of the less important parameters and choosing "reasonable values" for the rest. The results demonstrated that a power level of 540 MWt is sustainable without exceeding the 1600°C fuel-temperature guideline during DCC.

A more recent AREVA internal attempt to combine the uncertainties that contribute to this safety calculation, which has taken a more realistic approach for combining uncertainties, while maintaining a reasonable level of conservatism, has suggested that 565 MWt is a more accurate limit for the power level that is able to keep the fuel temperature below the safety guideline. Figure 6.1 presents the calculated reactor power level limits as a function of core inlet temperature for a 102 column prismatic core with an outlet temperature of 900°C and a limiting accident fuel temperature of 1600°C.

It should be noted that these results are very preliminary in nature, based upon the current level of understanding of the NGNP reactor core configuration and operational parameters. The uncertainties included in these analyses include both real calculational uncertainties and added margins due to our current lack of detailed information. It was designed to provide for a realistic approach to combination of appropriate uncertainties while maintaining a reasonable level of conservatism. Once more concrete input parameters are available, addressing many of the concepts briefly discussed above such as graphite thermal response and core bypass flow values, a more refined analysis can be conducted. Such a reanalysis may allow some increase in rated reactor power.

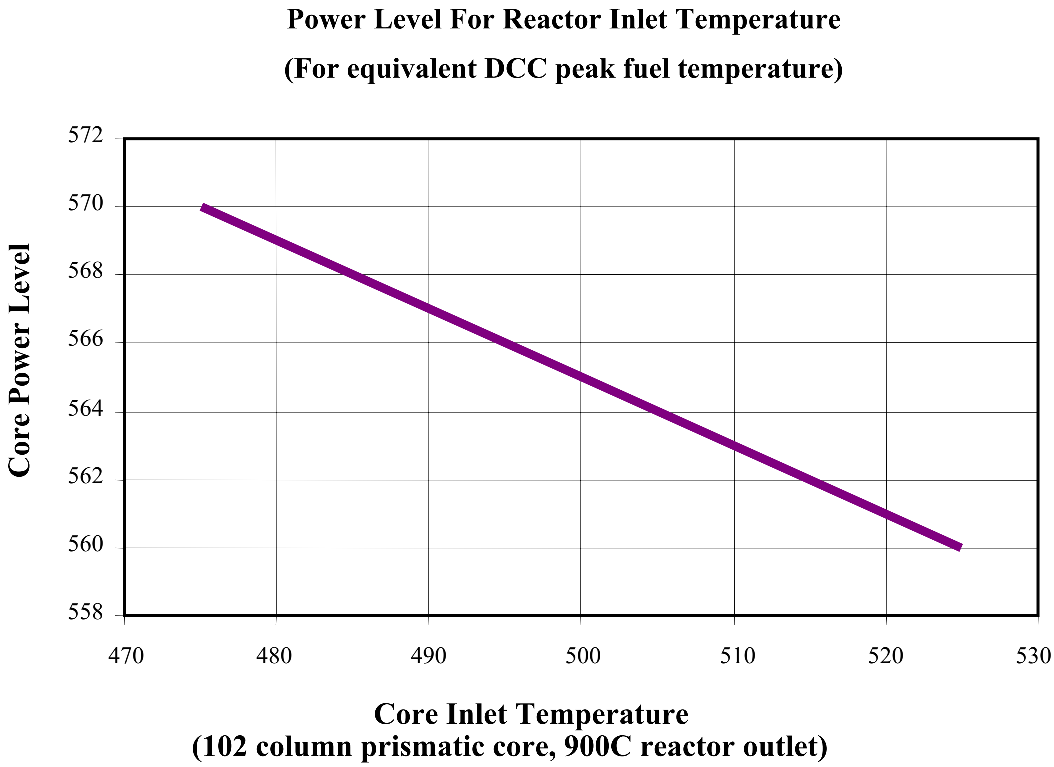

Figure 6.1 Depressurized Conduction Cooldown Analysis Results

Based on the considerations presented here, a maximum reactor thermal power rating of 565 MWth should be considered for NGNP the preconceptual design. This power level will allow some margin for uncertainties as the reactor design process continues.

6.1.4 Licensing Issues

The current commercial; nuclear plant licensing rules in the United States have created and evolved over the past 40 years to license light water reactor (LWR) technology. These regulations are generally ad-hoc, prescriptive, and deterministic. The regulations have generally evolved as operational experience level increased.

Thus all currently operating nuclear power reactors in the United States were licensed using the two-step licensing process of 10 CFR Part 50 where a construction permit (CP) is granted based on preliminary reactor design and site environmental impact statement. The license to operate the plant (OL) is later granted after years of review during the plant construction phase. This process naturally leads to regulatory delays and potential expensive construction rework.

The uncertainty associated with this licensing process was among the key factors that practically stopped the construction of nuclear plants in the United States in the last 25 years. The Nuclear Regulatory Commission (NRC) recently provided an alternative to the Part 50 licensing to remove this uncertainty. The so call 10 CFR 52 one-step licensing process, was created to grant a combined construction and operating license

(COL) to an applicant before the plant construction began. Of course, the COL application must include a plant design and site environmental impact statement or reference a previously reviewed and approved early site permit (ESP) and certified design (DC). The new Part 52 COL process has yet to be fully exercised. It is now undergoing trail usage by several applicants. However, the ESP and the DC portion of this licensing process have been tested by several utilities and reactor designers. Nevertheless, the basic nuclear plant regulations still reside in old and evolving 10CFR Part 50 and they are for the most part specific to light water reactor technologies.

The gas cooled reactor technology being considered for the NGNP prototype reactor is conceptually different from the traditional LWR technologies in most aspects of reactor design, safety, and operations. Both the pebble bed and the prismatic technology being contemplated for the NGNP prototype are specifically designed to include passive safety and inherent characteristics that are required by the Generation IV reactor requirements. Therefore, the deterministic licensing regulations developed for the LWRs do not directly apply to the modern gas cooled reactor technologies being considered for the NGNP prototype.

Through various gas cooled reactor licensing attempts in the recent history starting from DOE's efforts in 1990s to licenses the MVHTR, GA's application to license the GT-MHR, Exelon's interactions with the NRC on the pebble bed design, and the current Westinghouse efforts seeking certification for their PBMR, the US-NRC has recognized that new regulatory framework and subsequent licensing regulations are necessary to license non-LWR reactor technologies in the United States. The NGNP will most likely be a candidate that will utilize this new regulatory framework and it could be one of the first test cases that will exercise the new regulations.

In order to efficiently commercialize the VHTR, it would be clearly advantageous that a full scale NGNP prototype reactor is designed and reviewed by the NRC. This would assure that all aspects of the framework including the technology neutral and the subsequent technology specific regulatory guidance portion of the regulation are exercised such that most if not all safety issues have been reviewed and resolved through this prototype licensing effort.

Under the new regulatory framework a design phase PRA will be prepared and utilized to determine the licensing bases events (LBEs) and a subsequent design bases and beyond design bases events (DBEs) and (BDBEs). These event families and the subsequent design bases accidents (DBAs) must be deterministically analyzed with approved safety analyses computer codes. These analyses performed for the prototype are most useful for future commercial application if they are performed for a full scale plant design.

The risk informed regulator nature of the new licensing framework requires that the design phase PRA should evolve into the plant as built PRA and will subsequently become the living plant PRA. As a living PRA, it will serve as a tool that the plant designer, utility/operator, and the regulator can utilize to assess plant performances and sensitivities. The value of such a tool is most beneficial if it is developed full scale where many semi-scale plant performance characteristics of a commercial reactor designed with passive safety features may not be readily relevant.

Therefore, from the licensing point of view it is recommended that the power level of the NGNP prototype plant should at the commercial scale NOAK plant.

6.1.5 Demonstration of Passive Safety Features

Modular gas cooled reactors are designed for safety. This results in specific design decisions that provide such reactor characteristics. The NGNP, as a prototype of such reactor design for subsequent commercialization, must be capable of providing technical evidence of the performance of such features as they were postulated by the designers. The following are major design decisions for any modular gas cooled reactor type which must be demonstrated:

1. Annular core performance characteristics
    a. Neutronic
    b. Thermal
2. TRISO particle fuel performance characteristics
    a. Neutronic
    b. Thermal
3. Graphite characteristics
    a. Moderator and reflector neutronics
    b. Heat transfer properties
    c. Large stored heat capacity
4. Large negative reactivity coefficient
5. Passive residual (decay and stored) heat removal characteristics

The path to commercialization of modular gas cooled reactor is through the NGNP prototype demonstrating passive safety features to the licensing authorities in addition to the potential customers. The performance-based component of the new regulatory framework demands technical evidence of the performance and safety claims assumed or postulated by the design. The data necessary to provide this proof can only be provided by individual full scale test facilities or an integrated test facility. For passive features the dynamics of the required proof test demand full scale models. Extrapolation from scaled test facility is possible but the true dynamics of the system interactions can only be demonstrated with a full scale facility.

In consideration of these observations, the NRC, in 10 CFR 52.47(b)(2)(i)(B), promulgated the following requirement.

> *(2)(i) Certification of a standard design which differs significantly from the light water reactor designs described in paragraph (b)(1) of this section or utilizes simplified, inherent, passive, or other innovative means to accomplish its safety functions will be granted only if:*

> *(B) There has been acceptable testing of an appropriately sited, full-size, prototype of the design over a sufficient range of normal operating conditions, transient conditions, and specified accident sequences, including equilibrium core conditions. If the criterion in paragraph (b)(2)(i)(A)(4) of this section is not met, the testing of the prototype must demonstrate that the non-certified portion of the plant cannot significantly affect the safe operation of the plant.*

In other words, successful licensing of a commercial VHTR reactor depends on the successful safety testing of a full-scale prototype reactor. This is a critical role for the NGNP to fulfill.

Beyond the technical, regulatory, and licensing considerations which drive a full scale safety demonstration test, acceptance of this technology by reactor vendors, potential end users, and the general public would be greatly enhanced by a full-scale, integrated demonstration of the plant passive safety features.

6.2 Remaining Study Criteria

6.2.1 Core Neutronics

In order to maintain passive cooling capability, which typically limits the power density of the core, increases in core power level typically result in changes in core geometry, either increasing core diameter or height. These geometric changes will change the neutronic behavior of the core, particularly with respect to xenon stability at larger core sizes.

The diameter of current reactor designs in the 600 MWth range are well within the acceptable range of core widths from a neutronic stability standpoint. However, increases in core diameter are precluded by other considerations, particularly related to reactor vessel feasibility. The 600 MWth plant designs are essentially at the vessel diameter limit for all practical purposes.

Previous work by GA and INL[8] indicates that a core height of 10 blocks or less, consistent with current 600 MWth plant designs, are neutronically stable and require no active Xenon control measures. There are preliminary indications that it may be possible to utilize 11 and possible 12 block core heights without active xenon control, but no decisive studies have been conducted to date. Beyond these heights, at some point, there is a need for active control measures, which result in significant complication in rod movement strategy, particularly considering the large temperature variation along the core and the impact that has on neutronics. One of the reasons that no significant work has been done on these higher cores is that other considerations, including higher core pressure drops requiring greater circulator power requirements and reactor vessel embedment issues have supported a core height of no more than 10 blocks.

Based on these observations, it is concluded that neutronics concerns will not be a limiting factor in the determination of the recommended power level for the commercial and NGNP reactors.

6.2.2 Fabrication Issues

One of the advantages of the modular VHTR design is the ability to fabricate major components within a factory setting and ship the completed components to the plant site. The one component which presents some logistical issues is the reactor vessel. It must be a single component within each module, where other large components can be split into multiple trains should field fabrication be not feasible. The reactor vessel fabrication question can be divided into two groups: Fabrication of the reactor vessel for sites with barge access, and for those sites restricted to land access.

Table 6.2 – Representative Reactor Vessel Parameters

	MVHTR 350 MWth[9]	**MVHTR 450 MWth**[10]	**Antares 600 MWth**
Outside diameter at the flange level	7.36 m (24.1 ft)	≈ 9 m (29.5 ft)	8.24 m (27.0 ft)
Outside diameter in the cylindrical part	6.8 m (22.4 ft) upper 7.0 m (22.9 ft) lower	7.55 m (24.8 ft) upper 7.64 m (25.1 ft) lower	7.54 m (24.7 ft) upper 7.74 m (25.4 ft) lower
Reactor vessel height	22 m (72.0 ft)	23.5m (77 ft)	25 m (82 ft)
Core inlet temperature	259°C (497°F)	288°C (550°F)	400°C (752°F)
Core outlet temperature	687°C (1268°F)	704°C (1300°F)	850°C (1562°F)
Primary pressure	6.4 MPa	7.07 MPa	6 MPa
Core concept	annular	Annular	annular
Active core equivalent outer diameter	≈ 3.5 m (11.5 ft)	4.17 m (13.7 ft)	4.84 m (15.9 ft)
Minimum reflector thickness	≈ 1.1 m (3.6 ft)	1.0 m (3.3 ft)	≈ 0.82 m (2.7 ft)
Number of fuel element columns	66	84	102
Average power density	5.9 MW / m^3	6.0 MW / m^3	6.5 MW / m^3
Material	LWR steel	LWR steel SA533, Grade B Class 1 and SA508 Class 3	Mod 9 Cr 1 Mo

Table 6.2 presents representative parameters for various reactor sizes. It should be noted that the active core outer diameter is a function of the power and also of the fuel element size. The increases from 350 to 450 then from 450 to 600 are each accompanied with the translation of the annular core by one fuel element outward.

The ANTARES design (based on GT-MHR) corresponds to a larger active core outer diameter. At the same time the outer diameter of the reactor vessel remains the same as that of MVHTR 450 MWth in the upper cylindrical part which means that internals design has been optimized. The ANTARES design is also based on modified 9 Cr 1 Mo as reference material which is more creep and irradiation resistant compared to conventional LWR vessel steel.

Sites With Barge Access

Many of the sites that are likely to support initial deployments of NGNP technology, particularly those related to existing hydrogen usage or petrochemical refining, are located in areas that support barge shipment of the reactor vessel to the plant site, such as the Gulf Coast of Texas and Louisiana. There is at least one domestic vendor capable of fabricating and barge shipping vessels of a size that approximates the size of the ANTARES reactor vessel to these locations[11]. This situation will likely prove the most cost effective method for delivering a completed reactor vessel.

Sites Without Barge Access

Both the proposed NGNP site and many sites that represent the largest potential deployment of VHTR technology, including tar sands and oil shale extraction, are located in areas that preclude shipment of a large reactor vessel by barge. Representative railroad size and weight limits[12] in the United States of 4.6 m wide and 5.6 m high with a weight limit of 800 tons clearly preclude shipment of any of the reactor vessels listed on Table 6.2. As such, deployment of an NGNP reactor of any reasonable size will require on-site fabrication of the reactor vessel. This situation may prove advantageous, in that the required techniques can be developed and demonstrated before commercial use.

Experience indicates that final assembly of the reactor vessel can be performed on site. There are questions as to whether the best option would be to perform the welding in the reactor cavity or in a dedicated on-site workshop. The major determinant will be the cost. Workshop fabrication is probably reasonable when the intent is to built 4 modules or more. It is probably an expensive option for one unique module. The final assembly in the reactor cavity is probably also technically possible. However, difficulty will be linked to the qualification of the processes (welding, etc) on site. Local Post Weld Heat Treatment will also have to be performed. In addition, radiographic examinations and final machining of the vessel are significant field fabrication issues. The radiographic examinations are an important schedule issue in that a wide range of surrounding activities can be affected due to personnel protection. Field final machining of the large diameters can also be challenging.

Based on this information, the fabrication method for the reactor vessel will not be a determining factor for the selection of the commercial or NGNP reactor power level, in that sites will be either capable of receiving a full sized reactor vessel or will require on-site fabrication of reactor vessels for any reasonable reactor power.

6.2.3 Component Feasibility

With respect to reactor power level, the component of interest is the reactor vessel, and the issue of interest is the material from which it is constructed. There are two material choices which are typically considered, modified 9 Cr 1Mo or LWR vessel materials. Each has potential benefits and drawbacks.

Modified 9 Cr 1 Mo Material

The availability of modified 9 Cr 1 Mo heavy section forgings in the dimensions required for HTRs is in question, more so even than LWR vessel materials which also have some schedule issues in this area. So far, the capabilities of Japan Steel Works for instance are not compatible with the required ingot size. A back-up solution would be to use plates instead of forgings. This is the current practice for BWRs (even modern ones) which reactor sizes and pressure conditions are close to those of HTRs. It is however to be noted that BWR vessels operate under fluences even lower than those of HTRs (which are already reduced compared to those met in LWRs). In any case, due to NGNP schedule limitation of 2018, it is likely that recommendations will be made to base the design on plates and to keep the forging option as a target for the N^{th} of a kind commercial reactor.

This material is also more costly than the alternate LWR material.

LWR Vessel Materials

The other alternative would be to select LWR material (SA 508 grade3 class1 for forgings and SA 533 grade B class1 for plates) instead of mod 9 Cr 1 Mo. This solution would have two drawbacks:

1. Need to decrease the core inlet temperature so that the temperature of the vessel would fall under the current limits of ASME Code Case N-499 defined as follows:
   - Normal service temperature < 371°C
   - Limitation on transients:
     - 3000 hours maximum duration between 371 and 427°C
     - 1000 hours and no more than 3 events between 427 and 538°C

   The reduction of the core inlet temperature would increase the temperature rise of the coolant through the core and this combined with the increase of the core outlet temperature envisioned for the NGNP is likely to be unacceptable for the fuel under normal operation

2. Need to operate at a power that supports acceptable conditions for the vessel under conduction cooldown situations. Table 6.3 indicates that all the cases from Ref. 14 that are conservative for the vessel give temperatures in DCC greater than the 538°C limit of Code Case N499. The maximum vessel temperature during DCC is slightly dependent on the core inlet temperature and core outlet temperature. The comparison of cases (1) and (2) on the one side and (1) and (3) on the other side show a decrease of the maximum vessel temperature by 2.4% when the core inlet temperature is decreased by 100°C and an increase by 0.9% when the core outlet temperature is increased by 100°C. Cases (1) and (4) can therefore be used to show the influence of power level for the NGNP base line. Assuming that the effect would be linear, the temperature achieved for a power of 550 MW would be 535°C. This would be theoretically acceptable in meeting this one limit, but does not consider other, time at temperature related limits that are also part of this code section, for example, it is also necessary to check that the cumulative duration

spent above 427°C is below the maximum allowed duration of 1000 hours. The consequence is therefore that the power level below which LWR material could be envisioned, subject that the temperature of the vessel can be reduced enough during normal operation (by implementation of a thermal insulation or by the modification of the flow path) would more likely be in the 450 MW range to provide some margin to these limits and assure some degree of operational success.

Table 6.3 – Key DCC Temperatures

Event	DCC	PCC	DCC	DCC	DCC	DCC
Assumption	Best estimate	Best estimate	Conserv. Vessel (1)	Conserv. Vessel (2)	Conserv. Vessel (3)	Conserv. Vessel (4)
Power (MW)	600	600	660	660	660	612
Core inlet	400°C	400°C	480°C	380°C	480°C	480°C
Core outlet	850°C	850°C	880◦C	880◦C	980◦C	880◦C
ΔT core	450°C	450°C	400°C	500°C	500°C	400°C
Mass flow (kg/s)	256.9	256.9	317	317	317	317
Pressure (MPa)	6	6	5	5	5	5
Bypass flow (%)	10	10	5	5	5	5
Fuel	1475°C	1374°C	1574	1527	1599	1494
Core barrel	710°C	627°C				
Main vessel	477°C	402°C	574	560	579	557
Core support structure	612°C	661°C				

Based on this data, operation of the NGNP at 565 MWth will require the adoption of a vessel made of modified 9 Cr 1 Mo material. This does not present a limitation on the reactor power level selected.

6.2.4 Plant Flexibility and Operability

The flexibility and operability characteristics of a particular reactor/production plant system are a strong function of the specific processes to which the reactor supplies power, the power split amongst multiple uses, and the fraction of reactor power supplying each individual process train. Overall system configurations will determine allowable power change rates and will dictate optimum operational strategies.

One area that will need to be addressed for each operational scenario is the safety impact of the load characteristics of the secondary systems. Operation of the NGNP hydrogen process plant at only 10% of the total reactor power may not fully reflect some of the system feedback effects that may impact both operational and accident performance in plants that utilize a significant fraction of reactor power for hydrogen production or other process heat. Such feedback effects will need to be investigated for configurations representative of various commercial applications. The potential transient power behavior of the system must be reviewed to ensure that the most limiting cases are addressed in the plant safety analyses, including any potential power feedback effects that may exist. It is not the purpose of this study to attempt to answer these questions, but only to document them as important to ask at some point.

Though various power and temperature control strategies may need to be implemented within the process loops to reduce reactor fluctuations, these characteristics do not appear to be strongly impacted by the overall power of the reactor module, and, therefore, have little impact on the decision regarding the power level of the NGNP and commercial reactor units.

Preliminary research activities on VHTR-based hydrogen generation systems[13] indicates that, if the power requirements of the hydrogen plant are a significant fraction of the reactor thermal output, a "thermal absorber" device is needed in the secondary power system to minimize the impact of process temperature fluctuations on the reactor. In the referenced research, a small steam generator is used to perform this function. Since the demonstration hydrogen production plant associated with the NGNP reactor will only utilize approximately ten percent of the total reactor power output, it is not anticipated that such a system would be required.

6.2.6 Research and Development

The investigations conducted in the course of completing this special study have identified three areas that require additional development activities to support the conclusions reached. These areas are:

1. Development of large-scale forging capabilities for modified 9 Cr 1 Mo vessel material.

2. Improvement of the ASME Boiler and Pressure Vessel Code to incorporate all of the required operational conditions anticipated for the modified 9 Cr 1 Mo vessel material.

3. Development and qualification of fuel designs to allow operation at the desired power level for the desired durations. (Current fuel designs should support operation at the desired power level, though for shorter cycles or larger reload batch sizes.)

There does not appear to be sufficient risk associated with these activities, in terms of schedule or cost impacts, to change the recommendations made by this special study.

6.3 Hydrogen Plant Process Heat Requirements

6.3.1 Hydrogen Production Systems

The purpose of this section is to provide a high-level description of the hydrogen process options considered in the determination of process heat power requirements since the AREVA scope of work does not include design or detailed analysis of the hydrogen processes. The candidate hydrogen processes to be considered include the sulfur iodine (S-I) thermochemical process and the high temperature electrolysis process.

Sulfur Iodine Thermochemical Process

The Sulfur-Iodine (SI) process is a classic thermochemical cycle. Thermochemical cycles combine a net endothermic series of linked chemical reactions to achieve a desired overall reaction while regenerating all intermediate reactants. Thermochemical hydrogen cycles split water into hydrogen and oxygen with heat and water as the only system inputs.

The SI cycle consists of three chemical reactions, coupled in two process loops. The process involves thermal decomposition of sulfuric acid and hydrogen iodide, followed by regeneration of these reagents using the exothermic Bunsen reaction. Process heat is supplied at temperatures greater than 800°C to concentrate and decompose sulfuric acid. The exothermic Bunsen reaction is performed at temperatures below 120°C and releases waste heat to the environment. Hydrogen is generated during the decomposition of hydrogen iodide, using process heat at temperatures greater than 300°C. The General Atomics SI process flowsheet with reactive distillation of hydrogen iodide as the third step is assumed for illustrative purposes.

Section 1 carries out the exothermic Bunsen reaction,

$$I_2 + SO_2 + 2\ H_2O \rightarrow H_2SO_4 + 2\ HI$$

This primarily takes place around 120°C in a heat exchange reactor and, to a lesser extent, in two oxygen scrubbers and a sulfuric acid boost reactor. The output from the heat exchange reactor consists of three phases, which are separated and processed separately. The gas phase contains primarily O_2, which is scrubbed to remove residual SO_2 and withdrawn as a co-product. The sulfuric and hydroiodic acids split nearly completely into two, distinct liquid phases. The lighter of the two liquid phases contains sulfuric acid, which is concentrated in a boost reactor to about 20 mole % and passed on to Section 2 for decomposition. An aqueous solution of hydroiodic acid and iodine comprises the heavier phase, which is passed on to Section 3.

Section 2 carries out the high temperature, endothermic decomposition of sulfuric acid into water, SO_2, and O_2,

$$H_2SO_4 \rightarrow H_2O + SO_2 + \tfrac{1}{2}\ O_2$$

The sulfuric acid stream from Section 1 is heated to about 550°C, pressurized to about 70 bar, and concentrated to about 50 mole % H_2SO_4 in a series of flash steps, after which it is vaporized (550-700°C) and decomposed (700-850°C) in a catalytic reactor using high temperature heat provided by the intermediate heat transfer loop. The 850°C decomposition products are cooled by interchange with the sulfuric acid being concentrated as well as by interchange with process streams in Section 3. Cooled and partially condensed product from Section 2 (40-120°C) is returned to Section 1 to close the sulfuric acid loop of the SI cycle.

Section 3 carries out the intermediate temperature decomposition of hydroiodic acid into hydrogen and iodine,

$$2\ HI \rightarrow H_2 + I_2$$

The aqueous solution of hydroiodic acid and iodine from Section 1 is heated by interchange with other process streams and fed to a reactive distillation column in which hydrogen iodide is taken overhead along with water and simultaneously decomposed to hydrogen and iodine. This column is operated at 40 bar and 265-290°C. The vapor overhead product is primarily water, hydrogen, and some unreacted hydrogen iodide, while the bottoms are mostly iodine and water. Since much of the water that comes with the aqueous solution of hydroiodic acid and iodine from Section 1 is vaporized, the heat of vaporization must be recovered for the process to be efficient. Heat pumps, with steam as the working fluid, are used to recover heat from water condensation. A novel feature of this process is that the heat of solution obtained by mixing the overhead and bottoms products is also recovered using a heat pump. Hydrogen is separated from the reactive distillation effluents and removed as product, while all of the remaining streams are cooled by interchange and returned to Section 1 to close the hydroiodic acid loop.A simplified SI process flowsheet is shown in Figure 6.2 below.

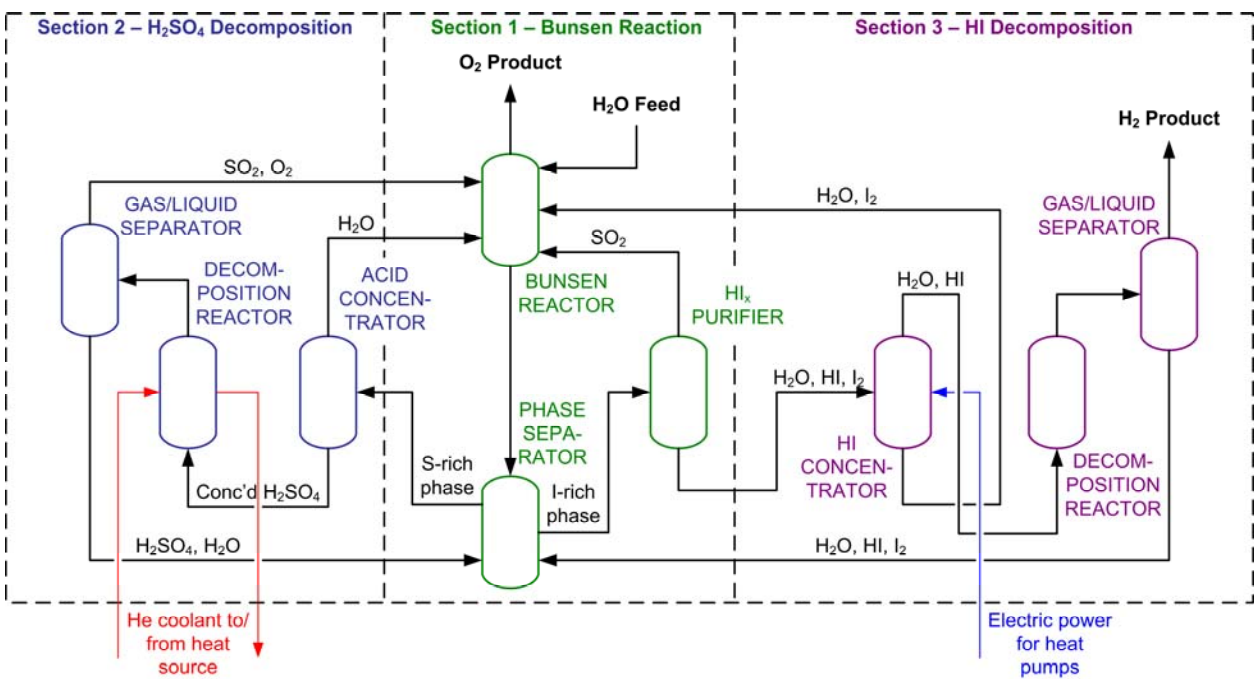

Figure 6.2 - Simplified Sulfur-Iodine Process Flowsheet

High Temperature Electrolysis

High Temperature Electrolysis (HTE) refers to the process of electrolyzing water (actually steam) at elevated temperature in a ceramic-type electrolyzer. The process is essentially the reverse of solid oxide fuel cell operation, in which hydrogen and oxygen (from air) are electrochemically reacted to produce water, heat and electric power. In the case of HTE, steam is reacted over a catalyst in a solid oxide electrolyzer at 800-1000 °C to produce hydrogen at the cathode of the cell and oxygen at the anode of the cell. The advantage of a high temperature HTE versus conventional low temperature water electrolysis is that a portion of the energy can be supplied as heat rather than electricity. This results in a substantial improvement in overall plant efficiency. Figure 6.3 shows how the thermal and electrical requirements vary for water electrolysis as a function of temperature.

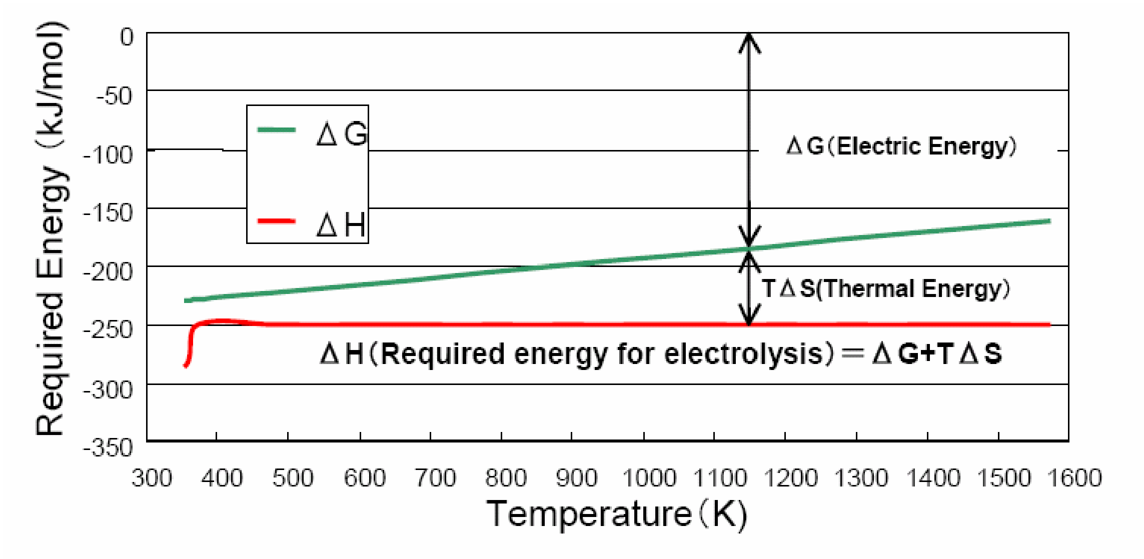

Figure 6.3 - Energy Requirements for High Temperature Electrolysis

The solid oxide electrolyzer operates by the conduction of oxygen ions through a ceramic electrolyte, typically yittria-doped zirconia. In order to obtain sufficient electrolyte conductivity, the cells must be operated at temperatures 800 °C. At the HTE operating temperature of 800-900 °C approximately 80% of the energy needs to be supplied as electricity and 20% as thermal energy in the form of superheated steam.

In actual operation, the HTE also requires a steam sweep gas be supplied to the anode portion of the electrolyzer in addition to the steam/hydrogen mixture supplied to the cathode. The cathode feed is expected to consist of 90% steam and 10% hydrogen. Heat from the nuclear reactor (via a helium heat transport loop) is used to generate steam, superheat the cathode steam/hydrogen mixture, and preheat the anode steam sweep gas. A hydrogen production efficiency of 55.5% (HHV basis) has been estimated for an HTE plant using heat from a modular helium reactor[14].

Since the HTE process is based on an electrochemical reaction, it is modular in nature due to limitations on scaling-up the electrochemical cell. A recent paper by General

Atomics, Idaho National Laboratory and others[14] proposed that a four reactor plant based on 600 MWth MHRs with an HTE hydrogen process plant would require 300 trailer-size HTE units containing 8 modules per trailer. Each HTE trailer unit would require 4.0 MWe of power to drive the electrolyzers. An additional 1.0 MWth of thermal energy would be required for the heat duty requirements of each trailer unit. The module HTE concept is shown in Figure 6.4.

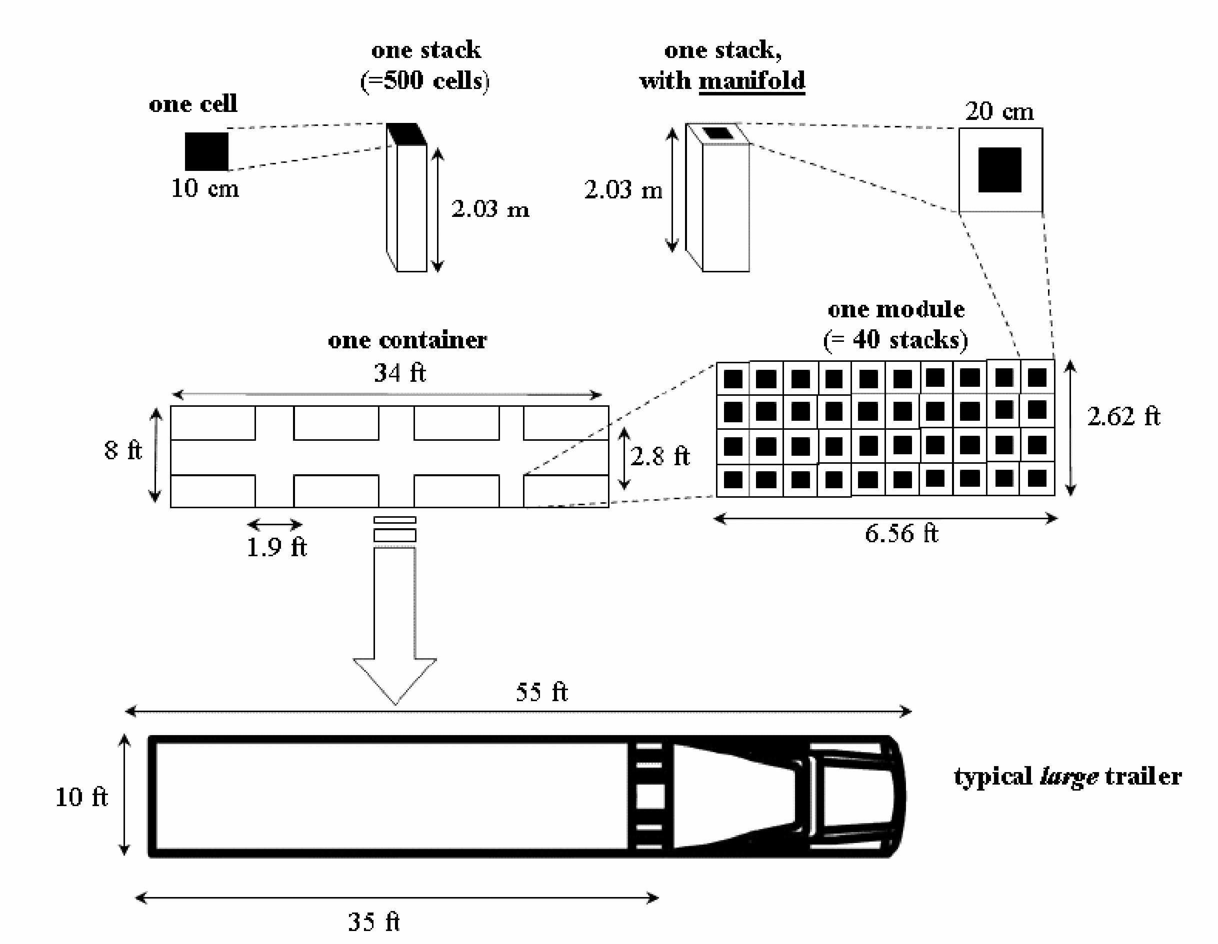

Figure 6.4 - Potential HTE Module Concept[14]

6.3.2 Hydrogen Production System Power Requirements

The hydrogen process requirements impact the power level trade study by establishing the thermal and electrical needs for the hydrogen engineering demonstration. In order to determine these requirements, an assessment was made of the expected power requirements for a commercial-scale hydrogen process. By considering the likely modular design of such a plant, and well-known chemical engineering scaling procedures, one can then determine the necessary power requirements for the NGNP demonstration scale hydrogen process.

Expected Power Requirements for Commercial-scale hydrogen process

A commercial-scale nuclear hydrogen plant will likely utilize the entire reactor thermal output for hydrogen production. A recent study by Savannah River National Laboratory[5] determines that a 600 MWth helium-cooled nuclear reactor combined with a sulfur iodine hydrogen production process could produce approximately 280 metric tonnes per day of hydrogen, which is sufficient for a large ammonia plant or oil refinery. This design used a total of 192 MWe from the grid. If the plant were self-sufficient, generating both thermal and process electric power, the hydrogen output per reactor would be less.

The 280 TPD SI plant described in the referenced report utilizes three process trains for Section 1 (Bunsen reaction), a single large train for Section 2 (sulfuric acid decomposition) and ten process trains for Section 3 (HI decomposition). The Section 3 units were based on the largest shippable components.

Since the HTE process is based on an electrochemical reaction, it is modular in nature due to limitations on scaling-up the electrochemical cell. Commercial applications would thus be scalable to the required size by adding modules.

Expected Power Requirements for Demonstration-scale Hydrogen Process

Well-known chemical process design requirements permit scale-up from smaller equipment sizes to full-size commercial units. A scale-up factor of 10:1 is usually achieveable, and larger scale-up factors are possible in many cases. For new equipment with several materials and design features that have not been demonstrated previously at large scale, it is often advisable to demonstrate a full-scale unit. For the S-I Process the most developmental and challenging portion of the process is the HI Decomposition (Section 3). It is therefore recommended that a full-size Section 3 process train (one of ten in a commercial plant) be demonstrated. Sizing the balance of the SI Process to this capacity would result in a hydrogen process energy requirement of 60 MWth and 20 MWe. Since the Section 3 process train for the commercial plant was based on the largest shippable unit size, it would also be permissible to test this unit at a slightly reduced size and still be large enough such that the key engineering questions can be answered. In this case, the SI hydrogen plant would require thermal input in the 30-60 MWth range and electric power of 10-20 MWe.

It is anticipated that the HTE process demonstration would consist of one train of modules, requiring 4 MWe and 1 MWth of process heat.

NGNP Hydrogen Process Test Configuration

It is assumed that hydrogen process testing would be conducted sequentially; nevertheless, given the fairly low power requirements of the HTE process, both HTE and SI processes could be run in parallel.

The power level chosen for the HTE process was chosen to permit deployment of a commercial scale module, including associated systems that could be tested using nuclear heat. Should it be desired to test the HTE process on a scale similar to that of the SI demonstration process, additional HTE modules could be added; however, doing so may impact the ability to run both SI and HTE hydrogen production systems in parallel due equipment limitations (i.e., IHX sized for 60 MWth).

While the development of the final operating strategy of the hydrogen process loop is beyond the scope of this study, it is important to note the level of testing flexibility that could be accommodated in the final design configuration.

6.3.3 Current State-Of-The-Art and Prognosis for Development

The SI thermochemical process has been demonstrated in an integrated system at the small scale of 100 liters by the Japanese Nuclear Energy Agency. A somewhat larger 200 lph SI plant is under construction in the United States as part of the DOE-NE Nuclear Hydrogen Initiative (NHI). It is being constructed by General Atomics in La Jolla, CA in conjunction with Sandia National Laboratory and the French national laboratory CEA. The 200 lph hydrogen output will have an energy content of approximately 600 watt(th). Assuming a process efficiency of 45% (not possible for such a small plant but representative of a commercial-scale unit), the equivalent hydrogen process thermal requirement is 1.3 kWth. This is obviously a long way from the 30-60 MWth required for the NGNP engineering demonstration.

The DOE's NHI program plan calls for the next stage of development of the hydrogen process to be a MW-scale pilot plant beginning in FY11. If a pilot plant of this scale can be built and operated in the 2011-2015 timeframe, it should be feasible to scale-up to the NGNP size of 30-60 MWth by 2018. The biggest challenge is perhaps the design and construction of the MW-scale pilot plant beginning in FY11.

The HTE process has been demonstrated at the component level for 2000 hours with a hydrogen output of 900 liters per hour[15]. This is equivalent to an electrolyzer electrical input of approximately 3 kW(e). The INL program plans for the HTE include completing an integrated lab-scale model at a nominal power level of 15 kW(e) by 2008; a pilot scale module of 50 kW(e) by 2010; a multi-module experiment at 200 kW(e) by 2012; and an engineering scale demonstration of a 5 MW section by 2015. Based on achieving this plan, the HTE development should be sufficiently advanced to meet the NGNP requirements in 2018. One of the major challenges will be the design and operation of a pressurized electrolzyer, since all the current and planned near-term development work has been with atmospheric pressure units.

7.0 Integrated Study Results and Recommendations

Table 7.1 presents a summary of the evaluations documented in the preceding sections. For each study criteria, an indication of the recommended commercial and/or NGNP reactor powers is stated based on the evaluation results. In addition, a qualitative assessment is provided of the potential impacts of a reduction in the NGNP rated power as a fraction of the projected commercial plant. These assessments are based largely on the expertise of the personnel involved in the evaluations. Comments are also provided which summarize the key findings of the individual evaluations.

Results of the evaluations of the key discriminating criteria indicate the following answers to the three study questions:

1. What should be the rated power level of the NOAK commercial VHTR module?

   The commercial VHTR module should be designed to operate at 565MWth.

This recommendation is based on commercial applications that are expected to support large module sizes and an evaluation of plant safety limits which indicate that the maximum power for NGNP initial conditions that provides acceptable results for the DCC accident is 565MWth.

2. Given the desired power level of the commercial VHTR module, what should be the rated power level of the NGNP prototype plant?

   The NGNP prototype plant should be designed and operated at 100% of the planned commercial power level, that is, 565MWth.

   This recommendation is made to support demonstration of plant passive safety features, portability of licensing experience, and sharing of first-of-a-kind engineering costs.

3. In order to demonstrate commercial scalability of an associated hydrogen production plant, what is the power requirement for a demonstration plant to be associated with the NGNP reactor?

   The demonstration Sulfur-Iodine plant will require 60MWth of process heat and 20MWe from the power conversion system.

   The demonstration High Temperature Electrolysis plant will require 1.2 MWth of process heat and 5MWe from the power conversion system.

   These recommendations are based on an examination of the current state of the art for these tow systems and the expected development progress between now and NGNP plant startup in 2018.

Evaluations of the remaining study criteria identified no concerns which would preclude or challenge the use of these recommendations.

Table 7.1 – Summary of NGNP Power Level Special Study

	Study Criteria	Recommended Power Level	Impact of NGNP as a Fraction of Full Size					Comments
			100%	75%	50%	25%	20MW	
Key Discriminating Criteria	Market View	Max. Practical	Base	Moderate	Major	Major	Major	Markets can support module powers as high as achievable within Gen IV constraints.
	Economic Considerations	100%	Base	Major	Moderate	Major	Major	100% power NGNP provides best commercial demonstration.
	Plant Safety Limits	Max. of 565MW	Base	Minor	Minor	Minor	Minor	The coupled limits imposed by Gen IV concerns and nuclear design constraints make this the practical upper power limit.
	Licensing Issues	100%	Base	Moderate	Major	Major	Major	Applicability of licensing experience and techniques will decrease significantly as the power fraction decreases.
	Demonstration of Passive Safety Features	100%	Base	Major	Major	Major	Major	Effective demonstration of the systematic response of the passive safety features requires a full-size test.
Remaining Criteria	Core Neutronics	No Limitations	Base	Minor	Minor	Minor	Minor	Neutronics impacts occur at plant sizes beyond those which would impact the practical upper power limit.
	Fabrication Issues	>50%	Base	Minor	Minor	Moderate	Moderate	Reasonable powers will require on-site reactor vessel fabrication for INL site. Though many commercial sites allow shipment, on-site fabrication experience may be beneficial.
	Component Feasibility	No Limitations	Base	Minor	Minor	Minor	Moderate	Key variables, including temperature and neutron exposure are not directly controlled by power level.
	Plant Flexibility and Operability	No Limitations	Base	Moderate	Major	Major	Major	Operational lessons learned from the NGNP will be applicable only at power levels near that of the commercial plant.
	Research and Development	100%	Base	Minor	Minor	Minor	Moderate	As stated above, key component limits, thus R&D opportunities, are not directly power related. As an overall R&D project, an NGNP plant of 100% power would provide most R&D return.
	Hydrogen Plant Process Heat Requirements	No Limitations	Base	Minor	Minor	Moderate	Major	This topic not directly related to NGNP power at expected power requirements of 60 MW or so, unless it becomes a significant fraction of total plant power.

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