INFORMATION KIT

March 2014

AREVA HTGR

High Temperature Gas-cooled Reactor

AREVA

Contents

Abstract

In the U.S., the focus for commercializing the modular High Temperature Gas-Cooled Reactor (HTGR) technology has shifted from a DOE-based Next Generation Nuclear Plant (NGNP) Project to an industry-based effort led by the NGNP Industry Alliance Limited. However, DOE support continues for completing the critical technology development programs, particularly for fuel and graphite qualification, and the pre-application licensing program with the NRC. The Alliance recognizes the critical role that this technology will serve in the meeting growing environmental challenges while providing price stability in the face of increasing competition for fossil fuels. The Alliance near-term goals are to broaden the base of industry and government participants and supporters and establish an international enterprise that will complete the overall development, plus the deployment of an initial fleet of commercial plants.

Toward that end, the Alliance has selected Areva's prismatic core modular HTGR with a conventional steam cycle for process steam and/or electricity as the reference design for near-term development and deployment. The nuclear steam supply system is based on a nominal 625 MWt annular reactor core in a large steel reactor vessel. It is a two loop system with the reactor connected to two parallel steam generators and helium circulators. Overall, this concept provides the best match to near-term energy needs for targeted industrial applications with competitive economics and acceptable risks for investment readiness. The Areva design provides a foundation for more advanced, higher temperature modular HTGR designs beyond 2050 (or later in this century).

During 2012, the key activities being advanced by the Alliance include the identification and characterization of candidate applications and sites in multiple countries for an initial fleet of modular HTGR plants; the update of a related Plant Parameter siting envelope, Plant Requirements document and Point Design parameters; the establishment of direct interactions with the NRC in support of the ongoing pre-application program, including review of the NRC assessment reports expected from the initial round of licensing white papers, and establishing the framework for the demonstration plant construction and operating license application; and the development of an overall enterprise Business Plan as a means of engaging and broadening investor support and participation.

AREVA HTGR – Questions/Answers

Background

The Next Generation Nuclear Plant Project was authorized by Energy Policy Act of 2005 and sets the stage for a collaborative effort between government and industry to bring high temperature gas-cooled reactor (HTGR) technology to a commercial reality. The industry as represented by the Alliance seeks to partner with the US Government to complete design, development and licensing activities and build a first-of-a-kind HTGR reactor. Participants in this partnership will establish a leadership position with this new nuclear energy source – to ensure that it meets U.S. long term needs with respect to energy security, emissions free generation and cost effective energy supply.

History

AREVA has a long history of involvement in HTR development. AREVA and its predecessor companies have been involved in various ways with past and present European HTR programs and the international Gas Turbine – Modular Helium Reactor program. Recently, AREVA completed a four-year evaluation of the ARE-VA New Technology Advance Reactor Energy System (ANTARES) concept. Currently AREVA is supporting the US Department of Energy's Next Generation Nuclear Plant program

AREVA has over thirty years of internal investment in pebble-bed HTGRs, and for the past ten years has significantly invested in the prismatic HTGR. The preference for the prismatic design concept as the basis for pursuing a high temperature reactor design was selected for near-term industrial deployment. AREVA has indicated a willingness to bring their background intellectual property in both pebble-bed and prismatic HTGRs to the Alliance for further development. In addition to AREVA, other Alliance members including Westinghouse, SGL Group, and Technology Insights bring a wealth of technical and business experience to this development effort.

Talking Points

- AREVA's 625 MWt steam cycle high temperature gas-cooled reactor (SC-HTGR) has been selected by the Next Generation Nuclear Plant (NGNP) Industry Alliance as the reactor design concept of choice to provide high temperature process steam for industrial applications.
- Nuclear power currently only supports electricity generation. The process heat and transportation fuel sectors are completely dependent on fossil fuel. With the potential of HTRs to supply high temperature process heat many different applications exist such as: oil refining, chemical processing, heavy oil recovery, tar sands oil recovery, hydrogen production, etc.
- AREVA's steam cycle high temperature gas-cooled reactor (SC-HTGR) is one of AREVA's Generation IV reactor concepts that offers excellent inherent safety features including passive nuclear safety and unique high temperature performance capabilities that are well suited for a broad range of process heat co-generation and/or power generation applications.
- The industry as represented by the Alliance seeks to partner with the US Government as part of the Next Generation Nuclear Plant Project to complete design, development and licensing activities and build a first-of-a-kind HTGR reactor and enable HTGR commercialization.

Definition of a High Temperature Gas-Cooled Reactor

A high temperature gas-cooled reactor, or HTGR, is an inherently safe, modular, underground helium-cooled nuclear reactor technology. The reactor and the nuclear heat supply system (NHSS) are comprised of three major components: the reactor vessel, the steam generator vessels and the cross vessels that routes the helium between the reactor and the steam generators. The NHSS supplies energy in the form of steam that can be used for the high efficiency generation of electricity and to support a wide range of industrial processes requiring large amounts of process heat in the form of steam.

Why use HTGRs?

Approximately 20% of U.S. energy consumption is associated with industrial uses (primarily in the form of process heat) and is almost completely derived from fossil fuels. It cannot be economically replaced by renewable sources such as wind and solar. The economical option within technical reach today that will provide a substantially greenhouse gas free substitute is the High Temperature Gas-cooled Reactors (HTGR).

What are the benefits of HTGR technology?

Related benefits include:

1) Reduced greenhouse gases (GHG) through large scale displacement of premium fossil fuels in a wide range of industrial and commercial applications. Each HTGR modular reactor nominally rated at 600 MW thermal can avoid ~0.8 million metric tons of CO_2 annually.
2) Reduced reliance on imported oil and gas supplies as industry fuels. For example, fifteen 100,000 barrel per day coal-to-liquids plants integrated with 480 HTGR modules can reduce US oil imports by 25% of the current oil import rate.
3) Extending life of domestic oil as a strategic asset for transportation fuels and natural gas as a chemical feedstock until alternatives become viable technically and economically
4) Sustainable expansion of American industrial manufacturing capabilities for energy intensive industries. The private sector capital investment for achieving the energy supply capability using HTGR technology is on the order of $2 trillion (2009$).
5) Job creation within the U.S. supplying materials and equipment to construct and operate HTGR-based industrial infrastructure. Each typical 4 module plant would require about 13,500 man-years effort during construction (about 4000 jobs at peak) and create about 270 permanent jobs at the site during plant operation.

Who selected AREVA’s design?

The Next Generation Nuclear Plant Industry Alliance, or Alliance, selected AREVA’s 625 MWt steam cycle high temperature gas-cooled reactor (SC-HTGR) as the reactor design concept of choice to provide high temperature process steam for industrial applications. The Alliance includes: Entergy, Dow, ConocoPhillips, Shaw, Westinghouse, PTAC, SGL Group, Technology Insights and AREVA

Why was AREVA’s design selected?

AREVA has over thirty years of internal investments in high temperature reactor design concepts, and for the past ten years has significantly invested in the HTGR concept. AREVA’s concept combines past experiences with recent developments

- Steam cycle builds directly on the experience from past operating HTGRs
- Incorporates safety characteristics of recent modular HTGR concepts
- Prismatic block reactor is based on AREVA’s ANTARES concept
- Minimizes need for advanced materials development
- Components technology is well understood
- Based on current fuel development programs

What is the government's responsibility in the NGNP Project?

- A commitment by the Administration, the Congress and the private sector to appropriately share the up-front risks to enable commercialization of HTGR technology through the NGNP Project. Sharing these risks includes the Government ensuring that existing infrastructure within the national laboratories are functional and available for NGNP Project development activities as described in the project development plans and that new infrastructure facilities essential to the demonstration of this technology are provided.
- Ongoing cooperation between the Administration, the Congress and the private sector (the NGNP Industry Alliance) with a common goal to enable this HTGR first-of-a-kind plant to be built at the earliest practical time to make important in-roads toward achieving reduced dependence on foreign energy resources and reducing carbon dioxide emissions.

What are the expected costs for the NGNP Project?

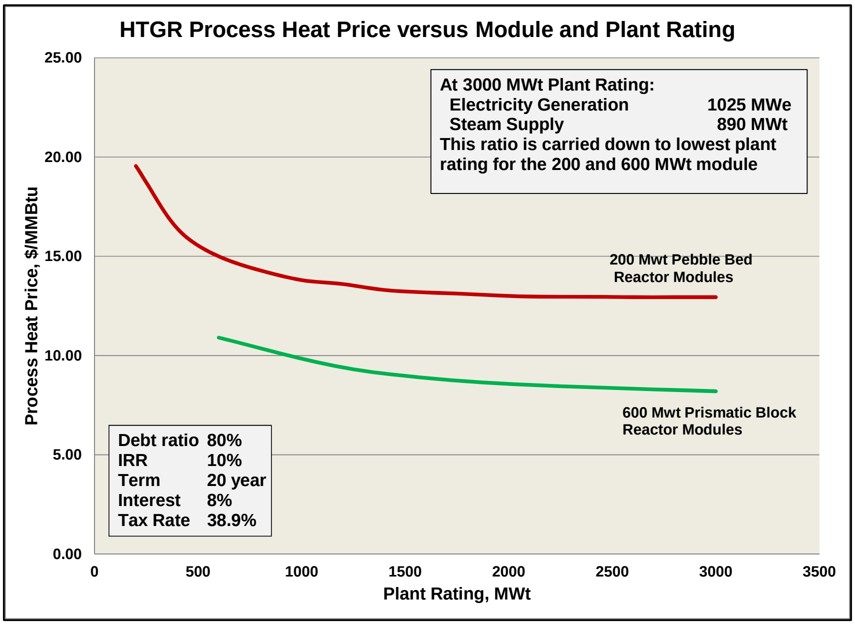
The cost for the NGNP Project has been estimated based on pre-conceptual design work performed by three subcontracted design teams, and adjusted based on results of additional studies performed to better understand selected areas of design, development and licensing risk. The total cost for the Project for initial deployment of the process steam/cogeneration option which includes non-recurring design, development and licensing activities is in the range of $4 billion in 2009. The costs for follow-on plants are estimated to be $1 billion each.

When will the HTGR pilot plant by built?

The first-of-a-kind (FOAK), lead commercial HTGR plant, is projected for startup operations by early 2020's. The long term commercialization strategy will be based on the success of the FOAK both from the regulatory and commercial view point. Plants constructed after the FOAK are estimated to take only 3 to 4 years to complete.

Why did the Alliance choose the prismatic design over the pebble bed reactor design?

Economies of scale favor the prismatic design. Currently, the pebble bed reactor design concept is limited to a rating of about 250 MWt per module compared to the prismatic design limitation of about 625 MWt per module to achieve a practical reactor design that fulfills the inherent safety features for a modular helium-cooled reactor at the desired operating conditions. For a typical total installed plant capacity in the range 2400-3000 MWt (multiple modules), the effect of the expected difference in capital cost for a 250 MWt versus 625 MWt module rating based design is shown in the adjacent figure that shows a ~30% lesser energy price would be expected for the 625 MWt module rating prismatic reactor concept compared to the pebble bed concept.

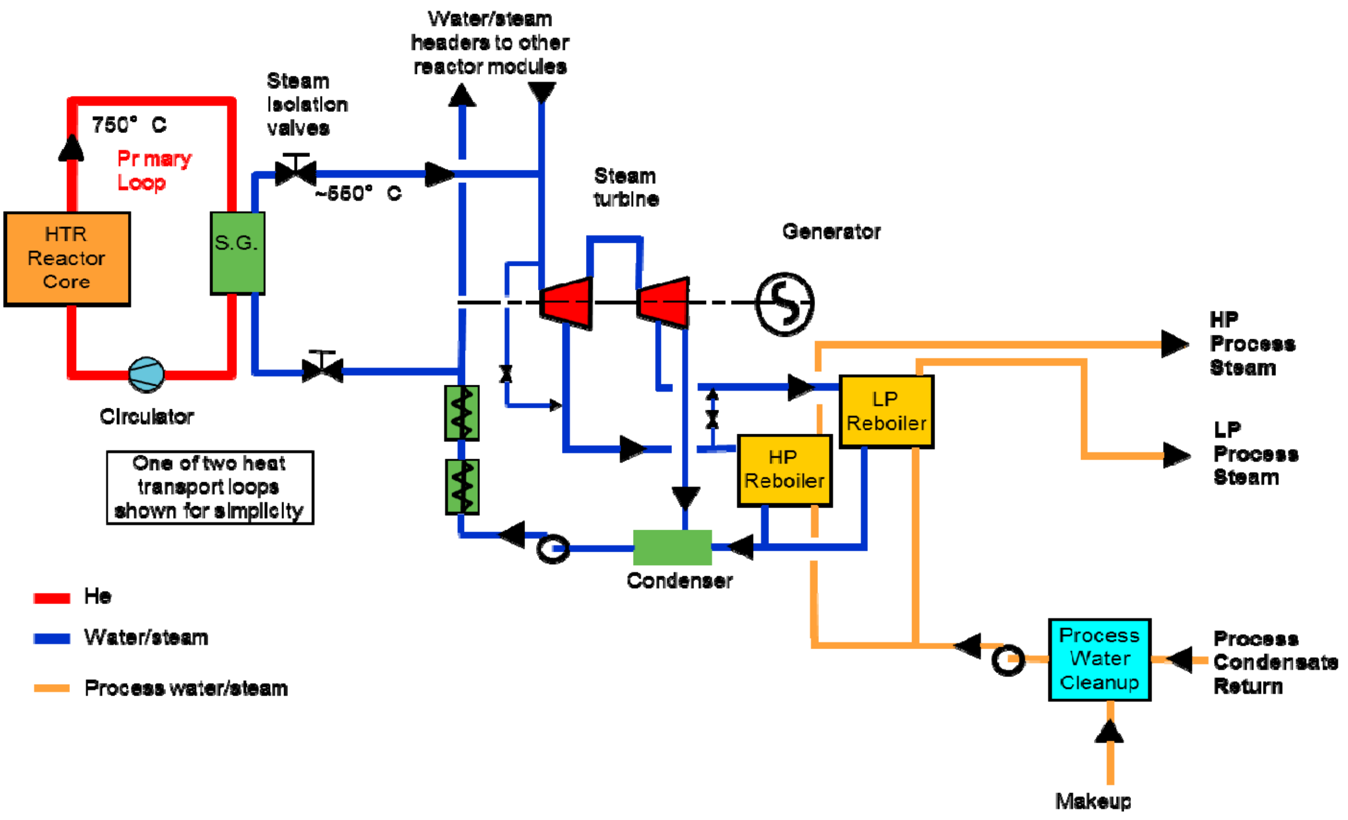


The HTGR – Gen IV Reactor

Typical Co-generation Plant Configuration

Nuclear reactors are no longer specific to electricity generation. The near term industrial applications that extend the use of nuclear energy for non-electric missions have been shown to be primarily directed toward providing co-generated process heat in the form of steam and electricity. Examples of these potential industrial applications include oil refining, chemical processing, heavy oil recovery, tar sands oil recovery, hydrogen production, etc… with similar results for other applications evaluated by the Idaho National Laboratory. Common to these potential applications is "over-the-fence" provision of steam and electricity at conditions that indicate a required reactor helium outlet temperature in the range of 750-800 ^{o}C.

The nuclear process steam supply system, typical co-generation plant configuration and design/operating parameters are shown in the following figures:



Typical Co-generation Plant Configuration

Nominal Operating Parameters – AREVA Design

Fuel type	TRISO Coated Particle
Core geometry	102 column annular 10 blocks high
Reactor power	625 MWt
Reactor outlet temperature	750°C (1382°F)
Reactor inlet temperature	325°C (617°F)
Primary coolant pressure	6 MPa (870 psia)
Vessel Material	SA 508/533
Number of loops	2
Steam generator power	315 MWt (each)
Main circulator power	4 MWe (each)
Main steam temperature	566°C (1050°F)
Main steam pressure	16.7 MPa (2422 psia)

Figure 1: Design Certificate boundaries will be consistent with AREVA's design.

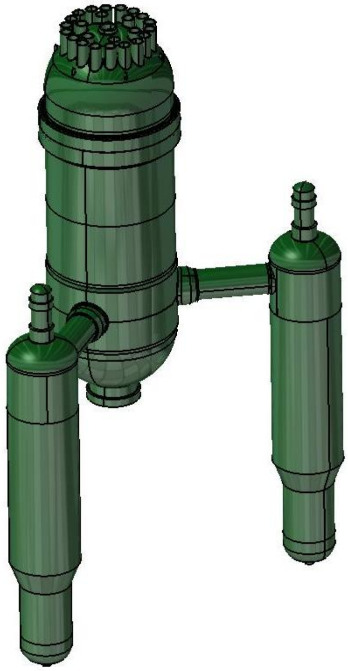
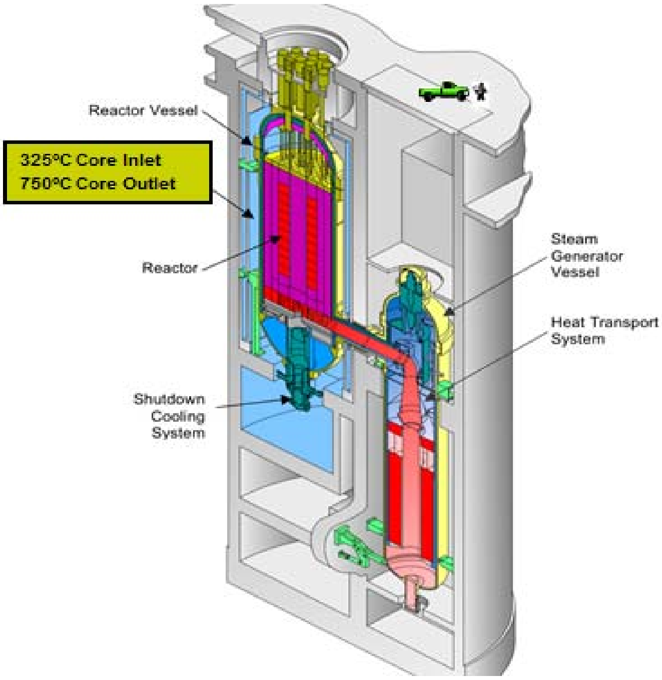
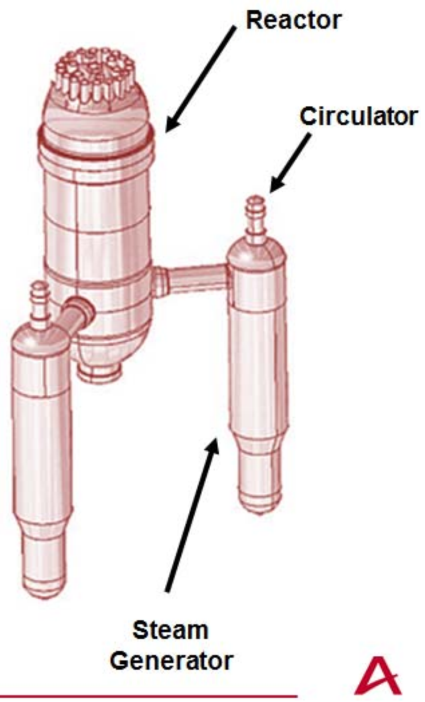


Figure 2: Reactor and Steam Generator General Arrangement



HTGR Features and LWR Comparison

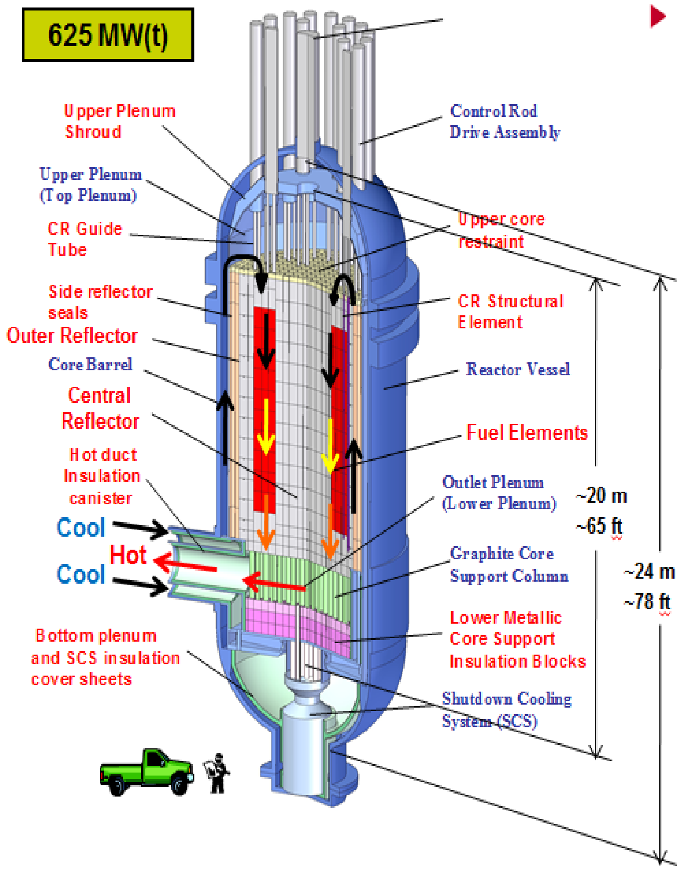
- Prismatic block annular core
- Conventional steam cycle
- Modular reactors
- Inherent safety characteristics
  - Passive decay heat removal
  - Large thermal inertia
  - Negative reactivity feedback
- Minimal reliance on active safety systems
- Sized to minimize steam production cost
- Fully embedded reactor building
  - Partially embedded alternative possible



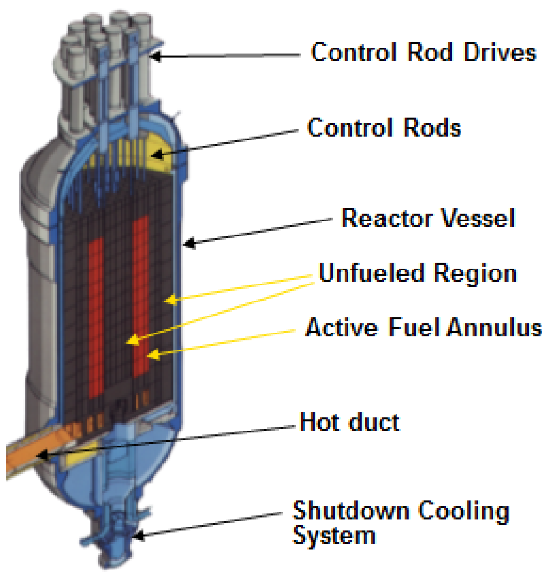
High Temp Gas-Cooled verses Light Water Reactor

Item	HTGR	LWR
Moderator	Graphite	Water
Coolant	Helium	Water
Avg coolant exit temp.	750°C	310°C
Structural material	Graphite	Steel
Fuel clad	SiC & PyC	Zircaloy
Fuel	UO_2,UCO	UO_2
Fuel damage temperature	>1800°C	1260°C
Power density, W/cm^3	4 to 6.5	58 - 105
Linear heat rate, kW/ft	1.6	19
Migration length, cm	57	6

Design Approach

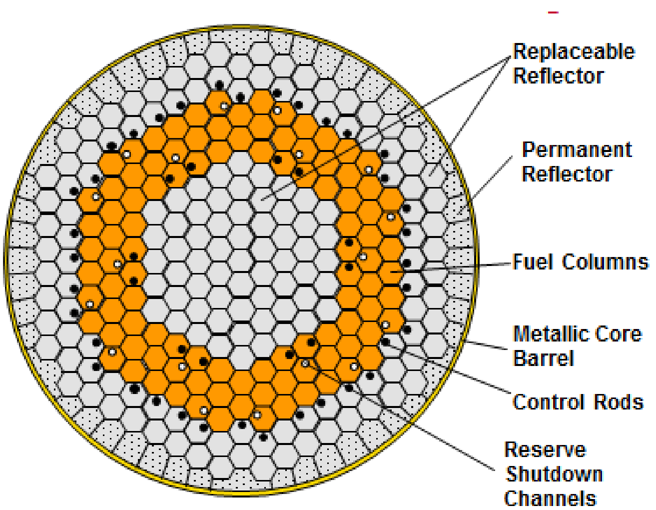


- **Passive safety features**
  - Negative temperature coefficient reduces reactivity as temperature rises
  - Helium coolant
    - Non-moderating
    - Gaseous phase during all conditions
    - Radioactively & chemically inert
      - (can be carrier gas)
  - Ceramic coated-particle fuel
    - Maintains structural integrity during LOCA
    - Contains fission products during normal operation
  - Low power density (5.8-6.6 w/cc)
    - Maintain acceptable temperatures during normal operation and accidents
  - Annular graphite core with high heat capacity
    - Limits fuel temperature during LOCA (1600°C)
    - High temperature structural stability
      - (Graphite sublimates ~3700°C)
    - High thermal inertia - long temperature rise time for LOCA
  - Cool reactor vessel & metallic internals with core inlet gas

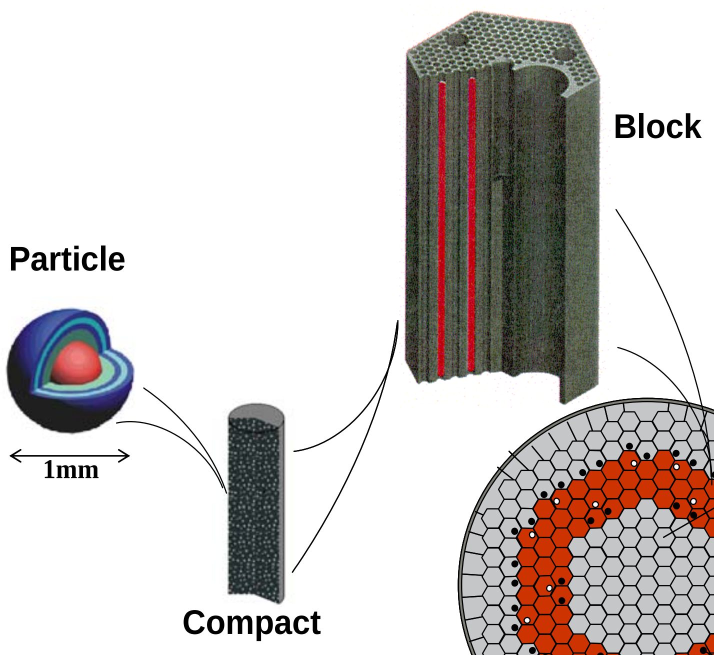


HTGR Reactor Internals

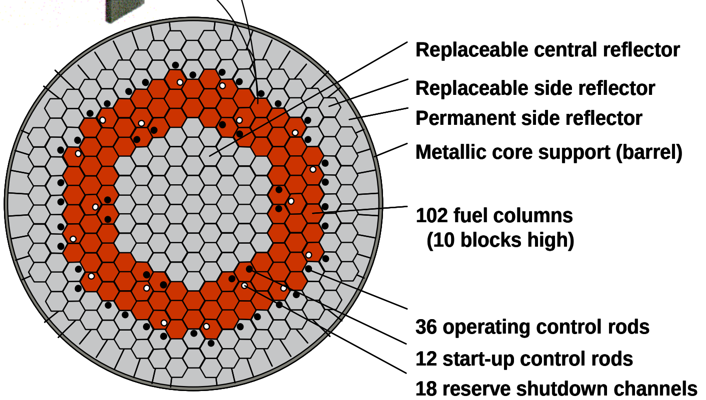
Fuel



Annular Core Arrangement



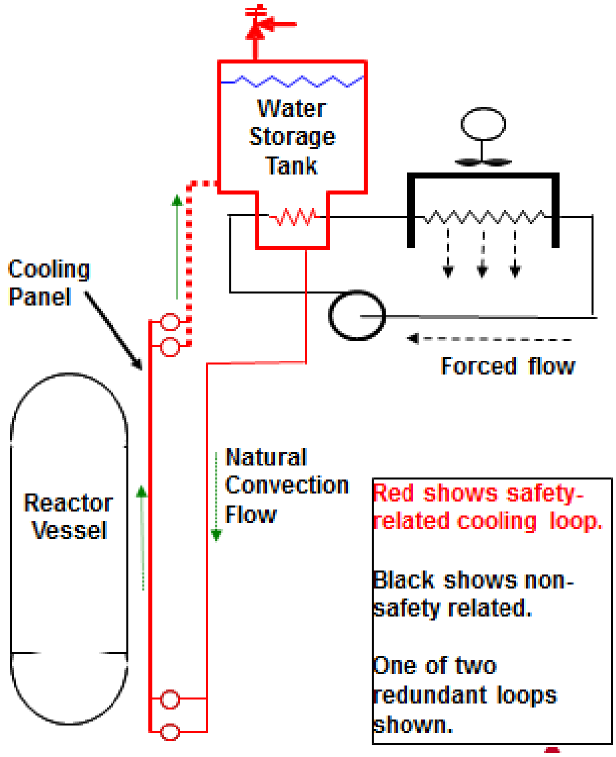
Ceramic fuel particles in Graphite prismatic block fuel elements



Cooling Systems

Optimized for reliability and safety

- **Main heat transport system**
  - **Established helical coil steam generator technology**
  - **Electric motor circulator with magnetic bearings**
- **Shutdown cooling system**
  - **Active system**
  - **Maximizes plant availability**
    - Maintenance
    - Rapid accident recovery
- **Reactor cavity cooling system**
  - **Safety related heat removal system**
  - **Passive cooling of vessel and surrounding cavity (operates continuously – safety-related)**
  - **Active cooling of water storage tank during normal operation (non-safety)**



Safety Features

The **Fukushima accident** revives the debate on nuclear energy and raises questions about the safety of nuclear power plants and their ability to withstand extraordinary events. HTGR technology provides improved safety and security through its inherent design, by ensuring no internal or external event could lead to a release of radioactive material, as proven by experimental and demonstration reactors around the world.

No need to evacuate or shelter the public and no threat to food or water supplies under any conditions.

- No harmful release of radioactive material under any conditions is assured by design.

Multiple assured barriers to the release of radioactive material are provided.

- These barriers include multiple layers of ceramic coatings on the nuclear fuel, the carbon encasement, and the graphite core structure. Additional barriers include the reactor vessel and the reactor building. The high temperature and robust structural capabilities eliminate concerns of fuel damage that could lead to significant release of radioactive materials from the nuclear fuel. The ceramic coated nuclear fuel provides the primary containment for radioactive materials rather than depending on a containment building.

Reactor power levels are limited and the nuclear reactor shuts down if reactor temperatures exceed intended operating conditions.

- Inherent to the nuclear reactor design is suppression of the nuclear reaction if the operating temperature increases. Complete shutdown is achieved through automatic insertion of control rods into the reactor core by gravity.

No actions by plant personnel or backup systems are required to either ensure shutdown of the reactor or ensure cooling.

- Conversely, actions of plant personnel cannot achieve conditions that cause the reactor fuel to lose its ability to contain radioactive material.

No power and no water or other cooling fluid is required.

- Heat removal from the reactor occurs naturally and directly to the earth if normal heat transport systems are not available. The low energy density of the reactor core combined with the large heat capacity of the graphite structure results in the reactor taking days to reach maximum temperatures (still well below temperatures that could cause fuel degradation), even if normal cooling systems are not functional.

Reactor materials including the reactor fuel are chemically compatible and in combination will not react or burn to produce heat or explosive gases.

- Helium is inert and the fuel and materials of construction of the reactor core and the nuclear heat supply system preclude such reactions.

Achievable levels of air or water intrusion do not result in substantive degradation of the capability to contain radioactive materials.

- The reactor is maintained shutdown under these conditions.

Spent or used fuel is stored in casks or tanks in underground dry vaults that can be cooled by natural circulation of air and shielded by steel plugs and concrete structure.

- No water is required for either cooling or radiation shielding and no active cooling system is required.

AREVA provides its customers with solutions for low-carbon power generation in North America and all over the world. As the leader in nuclear energy and a significant, growing player in the renewable energies sector, AREVA combines U.S. and Canadian leadership, access to worldwide expertise and a proven track record of performance.

Sustainable development is a core component of AREVA's strategy. Its nearly 5,000 U.S. and Canadian employees work every day to make AREVA a responsible industrial player helping to supply ever cleaner, safer and more economical energy to the greatest number of people.

AREVA Inc. is headquartered in Charlotte, NC.

us.areva.com

Energy is our future. Do not waste it.

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