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A TECHNICAL DESCRIPTION OF

THE HETEROGENEOUS GAS CORE REACTOR*

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INTRODUCTION

Solid-fueled and liquid-fueled heterogeneous nuclear reactors have already undergone extensive analysis and development. Gas-fueled nuclear reactor studies, however, have been restricted to either (a) homogeneous core systems, (b) two large separate regions of fuel and moderator, and (c) concentric rings of fuel-moderator arrangements.

The arrangement of bundles of moderator/coolant channels arrayed in a fissionable gas or mixture of gases makes a truly heterogeneous nuclear reactor core. It is this core heterogeneity for a gas-fueled reactor which accounts for the novelty of this concept and leads to noted significant advantages over previous gaseous core systems with respect to neutron and fuel economy and heat transfer characteristics.

The gas-fueled heterogeneous core reactors consist of an array of coolant/moderator channels in a vessel containing a fissionable gas or a mixture of fissionable and non-fissionable gases. The moderator/coolant is, therefore, distributed in the core but physically separated from the gas. It is this moderator/coolant distribution in a variable lattice arrangement surrounded by the gas which constitutes the bases of this concept. The results of this arrangement on the neutron and fuel economy, power distribution, power density, and heat transfer characteristics have been found to be extremely advantageous.

Description

The investigated heterogeneous gas core reactor (HGCR) consists of a reactor pressure vessel, a core barrel, a gaseous core with its array of moderator/coolant channels, and a surrounding reflector region. The core barrel is nickel or niobium-plated low carbon steel which can bear the internal pressure of the

gaseous fuel. Control rods inserted in the reflector region are used for minor power-level control and also for shutdown of the system.

Shown in Figure 1 is a proposed configuration for a 3000 Mwth heterogeneous gas core reactor. Approximately 2800 cylindrical niobium alloy tubes are employed to convey the light-water moderator/coolant through the core. The gaseous fuel (a mixture of approximately 25% enriched uranium hexafluoride and helium) fills the rest of the core cavity. The average working temperature of the gas is around 1025°K and its core average pressure is about 43 atmospheres (20 atm. for UF_6 and 23 atm. for He). The addition of helium to the gas improves its thermodynamic and heat transfer properties and also leads to a flattening of the neutron flux in the core. The UF_6 -He gas flows through the core and transports a part of the heat energy generated within the core by the fissioning gaseous fuel to the outside heat exchanger. A unit fuel cell would have a configuration and dimensions which are similar to those shown in Figure 2. The outer radius shown in Figure 2 represents the radius of an equivalent cylindrical unit fuel cell. Also, shown in the figure is a typical average temperature profile within the unit cell. The H_2O moderator/coolant inside the niobium alloy tubes is pressurized to an operating pressure of around 1100 psi and its average operating temperature is about 512°F . Niobium is a fine structural material with a high melting point (4470°F), a high tensile strength (40,000 psi at room temperature), and with a comparatively low thermal neutron absorption cross section. Niobium is also inert to chemical reaction with UF_6 gas. The water coolant flows inside the niobium alloy tubes in the same direction as the UF_6 -He flow through the reactor cavity, and removes a portion of the heat energy generated in the core by the fissioning gaseous fuel.

One of the differentiating characteristics of this heterogeneous gas core is its peculiar unit cell, in which the moderator is inside and the fuel is

HETEROGENEOUS GAS CORE REACTOR

FIGURE 1. CONFIGURATION OF A PROPOSED 3000 Mwth REFERENCE HETEROGENEOUS GAS CORE REACTOR

FIGURE 2. SIDE VIEW OF A TYPICAL UNIT CELL AND TEMPERATURE PROFILE

outside. Use of this arrangement results in less structural material and this leads to a better neutron economy, power distribution and reactor control.

As mentioned above, the heat generated by fissioning in the core region is removed by both the UF_6 -He mixture and also by the water coolant. Around 75% of heat is removed by the circulating gas and 25% by the water. Upon leaving the core, the UF_6 -He mixture passes through steam generators where it transfers its heat to the secondary coolant and produces superheated steam. These steam generators remove not only the heat generated by fissioning within the core, but also heat produced from fissioning within the subcritical steam generator cavities. Delayed neutrons produced within the reactor core flow into the steam generators, where they work as neutron sources. As a consequence, significant power can be produced in the subcritical steam generator cavities. The heterogeneous gas core reactor, therefore, makes optimum use of available "reactor-grade" volume for power production. Figure 3 shows a proposed steam generator schematic.

The water coolant which removes about 25% of the total core heat energy is used for feedwater heating purposes. A schematic diagram of a proposed heterogeneous gas core reactor power plant is shown in Figure 4.

As in the case of the High Temperature Gas-Cooled Reactor (HTGR) systems, the heterogeneous gas core reactor primary systems are contained in a steel lined, Prestressed Concrete Reactor Vessel (PCRVR). The PCRVR associated penetrations contains all major components of the primary system, including the reactor core and steam generators. The diameter of the PCRVR for the 3000 Mwth HGCR is around 50 feet, which is half the size of that utilized by the HTGR. Shown in Figure 5 is the top view of an HGCR system.

Neutronics

Unlike steady state "homogeneous" gas core reactor, the heterogeneous gas

FIGURE 3. A PROPOSED HETEROGENEOUS GAS CORE REACTOR
STEAM GENERATOR

FIGURE 4. SCHEMATIC DIAGRAM OF A HETEROGENEOUS GAS CORE REACTOR POWER PLANT

FIGURE 5. TOP VIEW OF A PROPOSED HETEROGENEOUS GAS CORE REACTOR SYSTEM

core reactor has a relatively high power density. This is due to the internal moderation of neutrons within the core and more efficient heat removal. Figure 6 shows reactor multiplication factor versus fuel-to-moderator ratio for an HGCR utilizing light water for the moderator/coolant. The pressure of the gaseous fuel and diameter of the coolant channel are fixed while the equivalent unit cell is allowed to vary. Figure 7 illustrates the same effects as Figure 6 when heavy water is used as the moderator-coolant. Neutron multiplication factor versus equivalent unit cell radius for a fixed fuel-to-moderator ratio is shown in Figure 8. The moderator/coolant is light water. Figure 9 demonstrates the same effects as Figure 8 when heavy water is used as the moderator coolant.

In designing the unit cell, undermoderated systems should be used for reasons of control and safety. For light water systems, curves such as those presented in Figures 6 and 8 are to be used in selecting the lattice configuration. Curves similar to those shown in Figures 7 and 9 are to be used for lattice design of heavy water systems.

Typical, four-group relative neutron flux distributions for H_2O and D_2O moderated HGCR's are shown in Figures 10 and 11 respectively. For these configurations the unit cell pitch was fixed throughout the entire core. The power density distribution for the H_2O moderated system is presented in Figure 12.

Power flattening in an HGCR can be obtained through procedures which are quite different from those utilized in a conventional solid-fueled heterogeneous reactors. Since enrichment of the fuel is uniform across the core in an HGCR, different spacing for the moderator/coolant channels can be employed to flatten the neutron flux and power. The effect of this technique on power density distribution for a light water moderated HGCR is illustrated in Figure 13. This system employs four core zones, each with a different spacing for the moderator/coolant channel. The pitches, equivalent unit cell radii and corresponding fuel-

FIGURE 6. K_{eff} VERSUS FUEL-TO- H_2O MODERATOR MOLECULE RATIO

FIGURE 7. K_{eff} VERSUS D_2O FUEL-TO-MODERATOR MOLECULE RATIO

FIGURE 8. K_{eff} VERSUS RADIUS OF AN EQUIVALENT UNIT CELL FOR A FIXED FUEL-TO-MODERATOR RATIO WHEN H₂O MODERATOR IS USED.

FIGURE 9. K_{eff} VERSUS RADIUS OF AN EQUIVALENT UNIT CELL FOR A FIXED FUEL-TO-MODERATOR RATIO, WHEN D_2O MODERATOR IS USED

FIGURE 10. 4-GROUP RELATIVE NEUTRON FLUXES ALONG THE CENTER-LINE IN RADIAL DIRECTION FOR A TYPICAL HGCR WITH H₂O INTERNAL MODERATOR AND NO POWER FLATTENING

FIGURE 11. 4-GROUP RELATIVE NEUTRON FLUXES ALONG THE CENTER-LINE IN RADIAL DIRECTION FOR A TYPICAL HGCR WITH D₂O INTERNAL MODERATOR AND NO POWER FLATTENING

FIGURE 12. POWER DENSITY DISTRIBUTION ALONG THE CENTER-LINE IN THE RADIAL DIRECTION FOR A TYPICAL HGCR WITH LIGHT WATER INTERNAL MODERATOR AND NO POWER FLATTENING

FIGURE 13. POWER DENSITY DISTRIBUTION ALONG THE CENTER-LINE LINE IN THE RADIAL DIRECTION FOR A TYPICAL HGCR WITH LIGHT WATER INTERNAL MODERATOR AND POWER FLATTENING

to-moderator ratios for this reactor are tabulated in Table 1.

Table 1. Zone Pitches and Corresponding Fuel-to-Moderator Ratios for an HGCR with Power Flattening

Zone	1	2	3	4
Pitch	6.666 cm	6.095 cm	5.714 cm	4.762 cm
Equivalent Unit Cell Radius	3.5 cm	3.2 cm	3 cm	2.5 cm
F/M Molecule Ratio	3.148×10^{-2}	2.575×10^{-2}	2.229×10^{-2}	1.461×10^{-2}

Power Extraction and Thermodynamics

Heat energy due to fissioning in the core supplies energy to the H_2O -coolant primarily by heat conduction through the structural material. Since the fuel itself is flowing, the heat flux distribution in the core is expected to be quite different from the fission density distribution.

The rate of heat transfer from the UF_6 -He working fluid is governed by many factors such as fluid properties, flow velocities, and other to-be-determined design and material factors. The temperature of the water coolant is determined by the heat transfer rate from the UF_6 -He fuel to the water coolant, by the flow rate and by the heat removal loop design. The temperature of the coolant not only influences the overall cycle efficiency of the system, but also the neutronics of the core. Complete energetics, heat transfer, and fluid mechanics studies for these loops and the coupling between them are extremely complicated and have thus far undergone only a preliminary analysis. Some typical design parameters for a large power, light water moderated HGCR are presented in Table 2.

Table 2. Operational Data for a Typical
Light Water Moderated HGCR

Power	3000 Mwth
Average UF_6 Pressure	20 atm
U_{235} Enrichment (Average)	29 w/o
He Pressure	21 atm.
Core Volume	32.69 m^3
Number of H_2O Coolant Channels	2800
Initial Uranium Mass in the Core	1665 Kg
Initial U_{235} Mass	545 Kg
Average Fuel/Moderator Molecule Ratio	2.575×10^{-2}
Power Density	91.77 KW/l
Average Thermal Neutron Flux	$2.925 \times 10^{14} \text{ n/cm}^2\text{-sec}$
Initial Fuel Inventory	11,655 Kg
Initial U_{235} Inventory	3815 Kg
Velocity of H_2O	30 ft/sec.
Velocity of $\text{UF}_6\text{-He}$	50 ft/sec.
Core Throughput Energy	$2.560 \times 10^9 \text{ Btu/hr.}$
Primary H_2O Inlet Temperature	491°F
Primary H_2O Outlet Temperature	534°F
Fuel Inlet Temperature	983°F
Fuel Outlet Temperature	1767°F
Feedwater Inlet Temperature	$\sim 500^\circ\text{F}$
Steam Outlet Temperature	$\sim 1000^\circ\text{F}$
Estimated HGCR Overall Efficiency	$\sim 38\%$

Safety and Control

Safety and methods of control are of primary concern for the heterogeneous gas core reactor power plant. Inherent safety and control features are highly desirable and should be emphasized. Housing the primary system of the HGCR within a PCRV results in some desirable inherent safety features for the plant. The PCRV eliminates the need for any major external primary system piping. This significantly reduces the possibility of gaseous fuel accidentally escaping to the environment. Also, the PCRV provides the necessary biological shielding. The possibility of continuous fission product removal can keep the radioactivity of the fuel at the minimal level.

Long range power level control of the HGCR can be achieved by using movable control rods in both the core and the reflector regions. Also, boron dissolved in the primary coolant water provides additional reactivity control to reduce the movable control rod worth requirements and also additional shutdown capability. An HGCR, which is operating in an under-moderated condition, is inherently safe due to large negative temperature coefficients of reactivity for the fuel and H_2O moderator. An increase in water temperature will decrease the density of the water, which will put the system further into the under-moderated condition. This will cause the reactivity of the system to decrease. Table 3 shows typical fuel temperature, fuel pressure, water coolant temperature and coolant density coefficients of reactivity for an HGCR.

Load following for an HGCR can be accomplished by changes in flow rates, and/or pressure/temperature relationships for both the circulating fuel and the reactor coolant.

A change in the gas flow rate will provide load following capability by altering the delayed neutron precursor population in the core.

For the HGCR, a sophisticated emergency core cooling system is unnecessary. Primary emergency shutdown is easily achieved by depressurization of the water

coolant. The coolant inside the core is pressurized during normal operation. When the fuel gas pressure or temperature in the core exceeds an established set-point, the water moderator can be depressurized by means of a conventional relief valve-quenching tank system. Then the water will undergo boiling and voiding, which will decrease the neutron thermalization process in the moderator and bring out a rapid shutdown. Decay heat in the fuel can be removed by circulating the fuel through the core and coolant loops. Opening of fuel gas pressure relief valves will also lead to rapid escape of the gas from the core and the U_{235} density will drop quickly resulting in a prompt shutdown. The gas will be vented to safe-geometry emergency heat exchangers.

Table 3. Typical Coefficients of Reactivity for an HGCR

Fuel Temperature coefficient	$= -4.1 \times 10^{-5} [^{\circ}\text{K}]^{-1}$
Fuel Pressure Coefficient	$= 6.93 \times 10^{-3} [\text{atm}]^{-1}$
H ₂ O Temperature Coefficient	$= -5.0 \times 10^{-5} [^{\circ}\text{K}]^{-1}$
H ₂ O Density Coefficient	$= 0.6072 [\text{g/cm}^3]^{-1}$

Advantages of the HGCR

Some of the more important advantages of HGCR systems are as follows:

1. High Fuel Utilization (Burnup) :

Unlike solid core reactors, there are no significant problems associated with fuel rod swelling, hydriding and fuel melting in a HGCR. Therefore, this system can achieve much higher burnups than any already developed reactor concepts. Enrichment of the initial gaseous fuel can be about 30%, and can be allowed to fall to around 17% before recharging of the fuel becomes necessary. In this period of one cycle, the burnup is at least 110,000

MWD/MTU. However, in a HGCR, almost all the fissile material can be utilized by blending depleted fuel with highly enriched UF_6 . Therefore, much higher ultimate burnups can be easily realized.

2. Low Fuel Cycle Cost:

Due to the gaseous form of the fuel, its fabrication charge is eliminated. Also, reprocessing costs will be greatly reduced.

3. Simple Fuel Management:

As mentioned before, recharging of the fuel is accomplished simply by blending depleted fuel with highly enriched UF_6 . Therefore, for the HGCR complicated fuel management programs such as exist for solid fuel reactors are unnecessary.

4. Continuous Fission Products Removal:

Continuous fission products removal decreases the initial inventory of the fuel and reduced the total control rod worth requirement. Also, the primary side of the system is of reduced radioactivity.

5. Reduced Requirements for ECCS.

This aspect has previously been elaborated upon.

6. High Thermal Efficiency:

Due to the high operating temperature of the fuel, the HGCR's overall efficiency is around 38%.

7. Low Coolant Pressure:

Since the gaseous fuel is also a working fluid, the water coolant is not required to remove all the heat from the core. Therefore, the water coolant can be operated at comparatively low pressures.

8. Optimum Utilization of Reactor Primary Volume.

This important characteristic is due to the fact that significant power can be generated not only in the reactor core but also in the subcritical steam generator cavities of the PCR. The economic implications of such a scheme are far-ranged and need significant study.

9. Nuclear Proliferation

The heterogeneous gas core reactor can make a significant contribution in the nuclear proliferation area due to the fact that the gaseous fuel lends itself to an accurate and continuous control and accounting of strategic material. The control and accounting can be performed on a batch or continuously monitored basis. Additionally, by separating continuously the fissile materials from the gas mixture, it should be possible to maintain in-plant the plutonium and transuranium elements produced to enhance fuel utilization, minimize or essentially eliminate out-of-plant plutonium handling and to significantly simplify the high radioactivity waste disposal problem by burning the actinides.