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A CONCEPTUAL DESIGN OF A 1000-Mw(e) HTGR^{*}

by

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A CONCEPTUAL DESIGN OF A 1000-Mw(e) HTGR

As part of General Atomic's TARGET (Thermal Advanced Reactor Gas-cooled Exploiting Thorium) program (under contract to the U.S. Atomic Energy Commission), a preliminary design study has been completed on an advanced High-temperature Gas-cooled Reactor (HTGR) with a nominal electrical output of 1000 Mw. This study was undertaken to investigate the feasibility and economic desirability of applying the HTGR concept to power reactors in this size range.

Although reactor design varies as the rating and application change, HTGR designs have certain fundamental characteristics. Basically, the HTGR is a thermal-spectrum, vertical-flow, helium-cooled, graphite-moderated, pressure-vessel-type reactor operating on the uranium-thorium cycle and producing superheated steam for electrical power production. The HTGR fuel system is distinctive in that graphite serves as both fuel cladding and neutron moderator. Such an arrangement reduces nuclear losses, increases power density, and permits the core to operate at very high temperatures.

The use of helium as coolant takes advantage of the high-temperature capabilities of the core. The absence of temperature and corrosion limitations of the core and coolant allows the production of high-temperature superheated or supercritical pressure steam with the attendant advantages of modern turbines operating on high-efficiency single or multiple reheat cycles. This benefit is reflected in HTGR designs, which typically have net plant thermal efficiencies in the range of 40% to 46% with corresponding heat rates in the range of 8600 to 7500 Btu/kw-hr.

In the TARGET study, the basic HTGR characteristics were applied to a high-conversion-ratio thermal reactor of advanced design.

The reactor and turbine-generator plant are housed in an integral complex of three structures: the turbine building, the reactor building, and a service building. Figure 1 shows an aerial perspective of the plant. The turbine generator, housed in the lower structure behind the office wing, is a 3600/1800-rpm cross-compound, four-flow (CCQF), 52-in. condensing unit operating in a regenerative reheat cycle. The taller structure of Fig. 1, which houses the reactor, is constructed of conventional materials to a high leak standard but is not intended to resist pressure. A separate leak collector fits fairly closely around the reactor pressure vessel and is designed to collect leakage gases, even under emergency conditions, for transfer by a compressor to the helium storage tanks. The reactor service building, not visible in Fig. 1, is located behind the reactor building.

The basic plant process is shown schematically as a simplified flow diagram in Fig. 2. The reactor core is cooled with helium undergoing a temperature change of 720° to 1470° F, which in turn is used to generate 3500-psia, 1050° F steam with a single 1050° F reheat. The steam is used in the CCQF turbine-generator unit to produce a net output of 1040 Mw of electrical energy. The net plant efficiency is 45.8%.

The reactor utilizes uranium-thorium-graphite fuel elements arrayed vertically on a closely packed triangular pitch. The 31-ft-diameter core, the surrounding 3-ft graphite reflector, and the steam generators and helium circulators are located within the reactor structure as shown schematically in Fig. 3.

The core consists of 5489 fuel elements and 242 control rods. The reference design of the fuel element is a graphite cylinder 4-1/2 in. in diameter and 20 ft long. The fuel element is pictured schematically in Fig. 4. The central portion of the cylinders may be removed for the addition of a beryllium oxide spine, which is desirable because of the N_2N reaction and the resulting increase in conversion ratio. The fuel is contained in a series of "channels" located around the periphery of the element. The active length is 15.5 ft.

Fig. 1--Aerial perspective of TARGET plant

Fig. 2--Flow diagram of 1000-Mw(e) HTGR

Fig. 3--Cutaway view of reactor core and prestressed-concrete structure

Fig. 4--Reference-design TARGET fuel element

Table 1 lists some of the significant parameters of TARGET. As shown, the core contains approximately 2374 kg of U^{235} and 86,330 kg of thorium, and operates at a power density of 7 kw/liter. The total heat output of the core is 2270 Mw, and the equilibrium core operates at a peak-to-average power ratio of 1.3 with a fifa (fissions per initial fissile atom) of 1.85, which corresponds to a burnup of about 45,000 MwD/T of uranium and thorium.

Table 1

SIGNIFICANT PARAMETERS OF TARGET

Rating

Net electrical output	1040 Mw(e)
Net thermal efficiency	45.8%

Core

Size	31.1 ft diam. x 15.5 ft
Number of fuel elements	5489
Power density	7 kw/liter
Loading	
U^{235}	2374 kg
Thorium	86,330 kg
Peak-to-avg power	
ratio	1.3
Fifa	1.85

Helium conditions

Pressure	450 psia
Temperature	720°F/1470°F
Flow	8.32×10^6 lb/hr

Steam conditions

Pressure	3500 psia
Temperature	1050°F/1050°F
Flow	6.89×10^6 lb/hr

The reference fuel-element design utilizes coated particles supplemented by a purge-gas system to remove any gaseous fission products which escape through the coatings. The purge gas flows down the fuel

element, out through the stand-off pins which are part of the core support plate, and into the fission-product trapping system, where the fission-product gases are removed from the helium stream by means of charcoal beds. The combination of coated particles and a clean-up system is designed to give a clean primary system suitable for contact maintenance.

Analyses show that the TARGET core is capable of achieving conversion ratios of greater than 0.9, under economically attractive conditions. With fuel elements that contain BeO spines, and with fuel particles that are capable of releasing a large fraction of the volatile fission products to the external trapping system, conversion ratios of about 1.07 appear to be feasible. With operation either under breeding or near-breeding conditions, it is expected that the residence time of the fuel elements in the reactor core would be approximately six years. Fuel management of the reactor would consist of refueling by core zone or patch, whereby in an average year about 900 fuel elements could be replaced during a two-week shutdown. Figure 5 is an artist's conception of a cross section through the reactor-turbine building, showing basic elements of the fuel-handling system. Handling, removal, and insertion of new fuel elements would be performed through 127 nozzles on the top face of the reactor structure. The spent fuel elements are stored in the fuel vault for a nominal decay period of three months before shipment for reprocessing.

Reactivity control is achieved by means of the control rods located at 121 positions throughout the core. Probably the most significant aspect of HTGR control is that emergency control requirements are modest. Means of rapidly inserting large amounts of reactivity simply do not exist. This fact, along with the low heat content of the coolant and the very large heat-storage capacities of the core, negates the need for very fast control rods. The absence of stringent control requirements not only is advantageous to the simplicity and economy of design, but also contributes significantly to reactor safety. The fuel-handling equipment can be used, when needed, to replace any of the control rods.

Fig. 5 -- Cross section of reactor-turbine building

The reactor core and the primary system are contained within a prestressed-concrete reactor structure. Since pressure vessels normally use metals to resist pressure forces with membrane stresses, the term "prestressed-concrete reactor structure," or simply PCRS, has been coined to denote the difference between design approaches. The PCRS of the reference internal design is a right, circular cylinder approximately 56 ft in diameter and 40 ft high. Gas-space insulation is used to reduce the interior heat load on the structure, and a mild-steel liner is provided as a gas-tight membrane. The exterior of the reference PCRS is a right, hexagonal prism approximately 86 ft across the flats and 76 ft high, as shown schematically in Fig. 6. Embedded in the concrete, which serves as biological shielding, is conventional reinforcing steel and high-strength tendons arranged both vertically and horizontally. The tendons are located so as to avoid the penetrations necessary for servicing-equipment access, for steam and feedwater piping, and for reactor refueling and control. The strands of the tendons are enclosed in steel encasements to reduce friction and allow inspection. The projections shown on the exterior surface in Fig. 6 are the end-anchoring mechanisms used to hold the tendons and induce the desired stress by pre-tension. Our studies indicate that the use of the PCRS and the corollary equipment, including the elimination of boiler steam-generator shells and other features of the close-coupled design, will reduce the capital cost of the reactor by approximately 17%, and should increase reactor safety as well.

Although a complete evaluation of safety and hazards has not yet been made, examination of potential problems to ascertain their nature and characteristics was undertaken to establish the safeguards acceptability of the design. These studies indicate there are no postulated credible accidents that could lead to or cause an unacceptable potential hazard. In fact, on the basis of the preliminary design study, it appears that the PCRS and close-coupled design should contribute significantly to increasing reactor safeguards.

Fig. 6--Prestressed-concrete reactor structure

Cost studies indicate that the capital cost of the plant calculated under AEC ground rules should be between \$110/kw and \$120/kw. The estimate includes the reactor and turbine-generator systems, including the electrical and miscellaneous power-plant equipment, but excludes research and development, fuel, and transmission plant costs after the main transformer. Estimates based on AEC ground rules, and assuming probable future development to reduce fabrication costs, show that fuel costs will be as low as 0.6 mill/kw-hr, including fabrication capital charges. The 0.6-mill fuel cost would be increased to approximately 1.1 mill under private ownership of the nuclear fuel, including working capital on the fuel produced in the reactor during the plant's operation. Under AEC ground rules, power costs from an HTGR in this size range would be in the neighborhood of 3.6 mills/kw-hr based on an 80% load factor and 14% annual capital charges.

We believe the 1000-Mw(e) TARGET design is a logical extrapolation of the Peach Bottom HTGR, now under construction, and other HTGR design studies under development at General Atomic. The design is, however, of an advanced nature and would require additional research and development, principally in the areas of fuel development, fuel-cycle analyses, prestressed-concrete reactor structures, and the development of certain components.

In conclusion, it may be said that our studies have indicated that the HTGR system shows excellent promise of adaptability to reactors in the 1000-Mw(e) size range, and of achieving breeding or near-breeding at economically attractive power costs.