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Abstract

The Cascade reactor is double-cone shaped with a maximum radius of 5 m. It rotates at 50 rpm. The average temperature of a three-material flowing granular blanket leaving the reactor is 1440 K. Heat from the blanket is transferred to helium gas in a shell- and ceramic-tube-type heat exchanger that has a separate region for each blanket material. Diffusion of tritium from the blanket granules through the heat exchanger is only 25 Ci/d, so no intermediate loop is needed for isolation. We selected a simple once-through, regenerative, 5-MPa helium gas-turbine (Brayton) cycle for power conversion because of its simplicity and high efficiency. Fusion power is 1500 MW; this is multiplied to 1670 MW_t in the blanket. Power conversion efficiency is 55%. Net electric power is 815 MW_e, produced with a net plant efficiency of 49%.

Introduction

We recently completed a two-year study[1,2] of the Cascade concept for an inertial-confinement-fusion power plant. Advantages include high efficiency and simplicity. The reactor (see Fig. 1) is double-cone shaped with a maximum radius of 5 m. It rotates at 50 rpm so that a flowing granular blanket is held against the wall by centrifugal force.

Fusion energy is deposited as heat in a 1-m-thick, three-material granular blanket that flows through the reactor and exits at an average temperature of 1440 K. Heat energy is transferred from the blanket granules to 5-MPa helium gas in a shell- and ceramic-tube-type heat exchanger. We selected a simple once-through high-pressure helium gas-turbine (Brayton) power conversion cycle with a regenerator but no reheats. Helium at 1300 K flows from the heat exchanger into a turbine-generator where energy is extracted to produce 815 MW net electric power. We obtained a power conversion efficiency of 55%, which results in a net plant efficiency of 49%. In comparison, a coal-fired power plant capable of delivering the same net electrical power achieves a net plant efficiency of about 35%.

In this paper we describe the final design of the reactor, heat exchanger, and power conversion system.

The Cascade Reactor

The Cascade reactor[3-5] (see Fig. 1) has the form of a double cone with a maximum radius of 5 m. It is evacuated to permit efficient illumination of the fusion-fuel pellets by laser or ion beams. Its walls are silicon carbide (SiC) panels held in compression by SiC-fiber/aluminum-composite tendons that gird the chamber circumferentially and axially. The blanket is composed of three zones: an inner 10-mm-thick surface layer of pyrolytic carbon granules, a 90-mm-thick front zone of beryllium oxide (BeO) granules, and an outer 900-mm-thick tritium breeder zone of lithium aluminate ($LiAlO_2$) granules. Besides breeding tritium, the blanket protects the reactor wall from damaging radiation, mitigates shocks generated by the fusion reactions, and acts as a heat transfer medium. The reactor rotates at 50 rpm, so that the blanket is held against the inside of the reactor wall by centrifugal force. All granules are 1 mm in diameter. The granule density if lowest in the surface layer, intermediate in the front zone, and greatest in the tritium breeder zone. Hence each blanket layer or zone floats on the next one radially outward, and mixing between the three zones is minimized. The granules enter the reactor through ports at the smaller radius ends, and flow along the reactor wall to exit shelves that rotate with the reactor at the larger-radius center. As the granules flow through the reactor, they absorb energy from 300-MJ fusion fuel pellets that are injected into the center of the reactor at 5 Hz.

One-third of the fusion energy produced in the pellets leaves in the form of x rays and pellet debris. This energy is deposited in the first few micrometers of the surface layer. The rate of energy deposition in this thin region is high enough to vaporize about 1 kg of material, which fills the center of the reactor, then cools by radiative and convective heat transfer and recondenses on the remaining granules at the inner surface on the blanket. In the final design, we chose elemental pyrolytic carbon for the surface-layer material because it can withstand temperatures of 1600 K without adversely interacting with the adjacent material, and because an elemental material will recondense in a similar form. If a multi-element material such as beryllium oxide were used for the inner surface layer, the vaporized material could dissociate; some of the beryllium could recondense separately, leaving oxygen gas in the chamber. A significant increase in the capacity of the vacuum pumps would be required to remove the oxygen before the next fusion energy pulse. The elemental beryllium would remain in a liquid state, and could interact adversely with the solid granules.

The remaining two-thirds of the fusion energy takes the form of energetic 14-MeV neutrons and is deposited throughout the blanket with a profile that decreases exponentially with radius. The BeO front zone acts as a neutron multiplier for the outer $LiAlO_2$ tritium breeder zone. Calculations[6] show that the pyrolytic carbon vaporized from the inner blanket surface recondenses in less than 10^{-5} s after it reenters the surface layer. No vaporized carbon reaches the front zone. If it did so, incondensible CO would be formed,[7] which again would require an increase in the capacity of the vacuum

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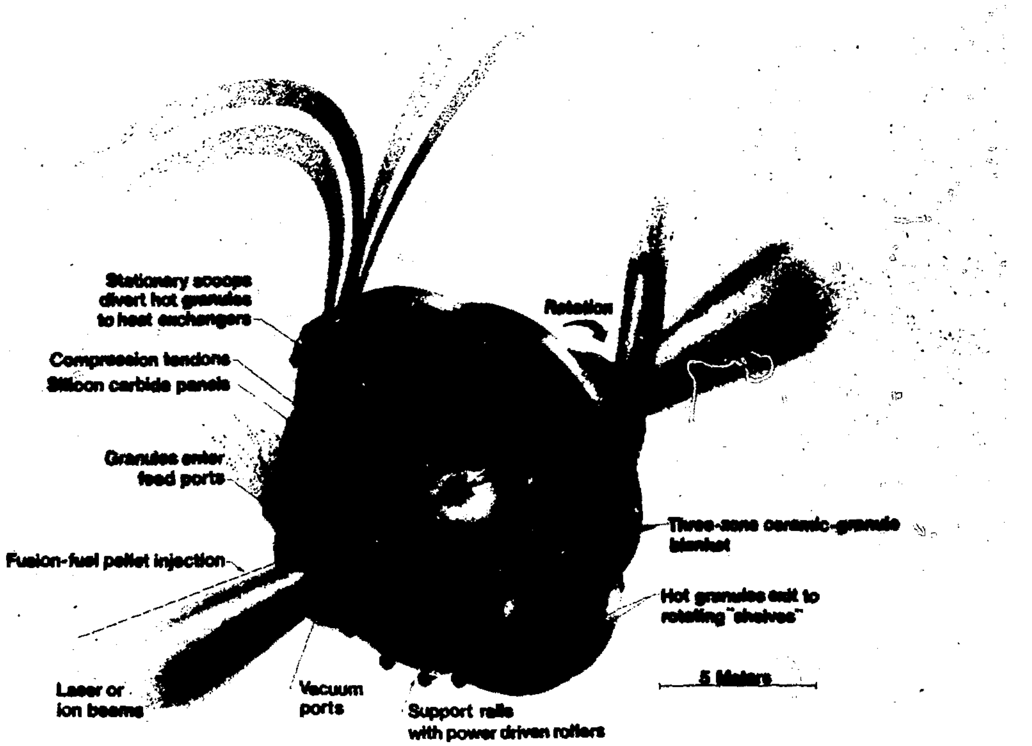

Fig. 1. Cascade: a rotating, ceramic-granule-blanket reactor.

system. Details of the recondensation are discussed by Hogan and Peterson.[8] A tritium-breeding ratio of 1.05 is attained, so that tritium burned in the fusion-fuel pellets can be replaced. Blanket energy multiplication is 1.11.

A maximum blanket outlet temperature is obtained if the radial velocity profile across the granular blanket is similar to the heating-rate (energy deposition) profile. The exit temperature of each zone would then be constant across its radius and could be made equal to the maximum material compatibility temperature. Granular-flow tests on rotating cones[9] and on a chute[10] showed that two-layered granular flow with a radial velocity profile somewhat similar to the heating-rate profile is feasible in the Cascade reactor. In the chute tests, the surface layer (corresponding to the surface layer in the Cascade reactor) flowed freely and rapidly and exhibited good mixing. The bottom layer (corresponding to the front and tritium breeder zones in the Cascade reactor) moved more slowly. The granule speed increased roughly as the square of the distance from the chute surface; the speed was controlled by openings at the exit. Given these data on granular flow, and heating rates from neutronics calculations, we determined that the velocity ratio between the surface layer and the front zone, and between the inner and outer surfaces of the tritium breeder zone are 8 and 9, respectively, in Cascade. The corresponding heating rate ratios are both 30. Although the heating-rate and velocity ratios are not equal, performance is much better than could be achieved without two-layered flow.

Meier[11] found that neutron activation of the Cascade blanket is dominated by ^{24}Na produced by (n,α) reactions with the aluminum in the $LiAlO_2$ tritium breeder zone. He found that the 1-GCi total activity in Cascade at shutdown is lower by a factor of 4 than that in recent conceptual magnetic fusion power plants operating at the same net electric power.

Heat Exchanger

The heat exchanger transfers energy from the blanket granules to 5-MPa helium gas used in the power-conversion system. Each blanket zone has a separate heat exchanger region; the helium gas flows through each region in series in a countercurrent direction. Figure 2 shows the temperature of the blanket granules and the helium gas as a function of normalized distance through the heat exchanger. Fifty-nine percent of the total energy is transferred to the helium gas in the tritium breeder zone region, which has the lowest temperature; 13% is transferred in the front zone region, and 27% is transferred in the surface layer region, which has the highest temperature. The temperature discontinuities between

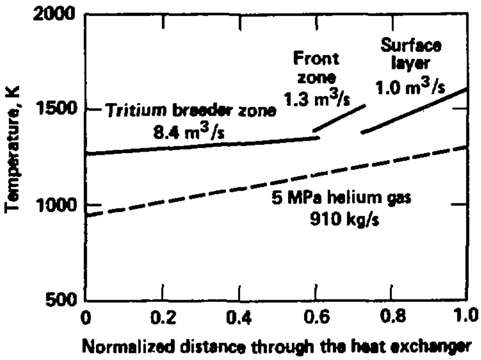

Fig. 2. Temperature profiles in the Cascade heat exchanger. The solid curves represent the granule side of each heat exchanger region. The dashed line represents the helium side of the heat exchanger.

regions on the granule side of the heat exchanger are caused by the difference in average temperature of the granules in each blanket zone as they leave the reactor. The helium behaves as a perfect gas, and its temperature rise through the heat exchanger is linear. Note that the average temperature difference between the granules and the helium gas in each region is nearly constant. This improves heat transfer efficiency where the maximum allowable granule temperatures are restricted. Inside the heat exchanger, the granules flow around an array of 1.5-m-long horizontal ceramic tubes through which helium gas flows. The tubes have an outside diameter of 25 mm and a wall thickness of 2 mm. Total heat transfer area is about 13 000 m^2. The outside of the heat exchanger and the piping connecting the heat exchanger to gas turbines are metallic and have internal insulation. Total pressure in the granule side of the heat exchanger is 1.3 Pa, considerably lower than inside the reactor, where the pressure before each fusion energy pulse is 13 Pa if a laser driver is used. The lower pressure in the heat exchanger eases the removal of tritium bred inside the $LiAlO_2$ granules and reduces the total tritium inventory to 260 g. About 140 g of this inventory has a characteristic release time of 10 hr; the remainder has a release time of about 100 yr. The vacuum system recovers tritium at a rate of 8.2×10^6 Ci/d; this constitutes essentially all of the tritium introduced into the system in fuel pellets and that generated in the tritium breeder zone, less that consumed in fusion reactions. About 25 Ci/d permeates through the heat exchanger into the helium gas, but this tritium is also recovered. Because tritium leakage other than into the vacuum system and heat exchanger is so low (0.03 Ci/d), actual losses to the environment were not calculated but are expected to be negligible.

Power Conversion System

We studied several closed-cycle power conversion systems to determine which was best suited for Cascade. Results of our study are shown in Fig. 3, in which power conversion efficiency is plotted against peak working fluid temperature. Below 900 K, the standard steam Rankine cycle used in essentially all fossil-fired and nuclear power plants gives the highest efficiency. At intermediate temperatures the steam Field cycle,[12] which is a combination of the Rankine and Brayton cycles, appears promising. Above

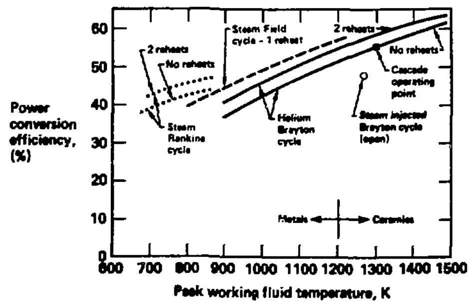

Fig. 3. Power conversion efficiency for various thermodynamic cycles as a function of peak working fluid temperature. Ceramic heat exchanger tubes must be used above 1200 K because of material limitations for metallic tubes.

about 1200 K, the helium gas turbine (Brayton) cycle has the highest efficiency. The steam-injected gas turbine (open Brayton cycle) is shown in Fig. 3 for comparison.

We chose the once-through regenerative, no-reheat Brayton cycle (see Fig. 4) for Cascade because of its simplicity, cost effectiveness, and high efficiency. The cycle includes three compressors with intercoolers, a regenerator, heat addition in the heat exchanger, and a turbine-generator to extract energy and produce electrical power. The regenerator transfers heat from the helium gas exiting the turbines to the compressed gas before it enters the heat exchanger as shown by the dashed arrows. The maximum pressure ratio is 2.3. No intermediate loop is needed to isolate the tritium present in the granules from helium gas, because diffusion of tritium through the heat exchanger is only 25 Ci/d. This improves thermal efficiency and eliminates costly equipment.

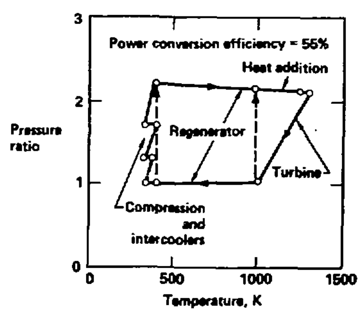

Fig. 4. Pressure-temperature plot of the Cascade 5-MPa helium gas turbine (Brayton) power conversion system.

Fusion power is 1500 MW; this is multiplied to 1670 MW by neutron capture in the blanket. 25 MW are lost in the heat exchanger, but 1645 MW of thermal power are converted to 905 MW gross electrical power in the turbine generator. Ten percent of the gross electric power is recycled for the laser (75 MW) and auxiliary systems (15 MW), resulting in a net electrical power of 815 MW. The heat exchanger tubes must be ceramic because of the high granule and helium temperatures; however, enough expansion occurs in the nozzles of the turbine to lower the temperature of the helium impinging on the turbine blades. This allows the use of metallic turbine blades, which reduces cost and improves reliability.

Conclusions

1. A simple once-through regenerative high pressure (5 MPa) helium-gas turbine (Brayton) cycle without reheats was chosen for power conversion. Advantages include simplicity and a 55% power conversion efficiency (49% net power plant efficiency). No intermediate heat-exchange loop is required, because tritium permeation through the heat exchanger is only 25 Ci/d.

2. The reactor contains a flowing three-material granular blanket that protects the reactor wall from damaging radiation, mitigates shocks produced by the fusion reactions, and acts as both a heat exchanger and tritium breeder. The radial heating rate profile approximately matches the radial velocity profile, so that a high average blanket outlet temperature (1440 K) is obtained.

3. A shell- and ceramic-tube-type heat exchanger transfers energy from the blanket granules to high pressure (5 MPa) helium gas at temperatures exceeding 1300 K.

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