Designing the Cascade inertial confinement fusion reactor

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1 INTRODUCTION AND GENERAL DESCRIPTION

The primary goal in designing inertial confinement fusion (ICF) reactors is to produce electrical power as inexpensively as possible, with minimum activation and without compromising safety. In this paper, we discuss our method for designing the Cascade rotating ceramic-granule-blanket reactor (Pitts 1985) and its associated power plant (Pitts and Maya 1985). Although we focus on the Cascade reactor, the design method and issues that we present are applicable to most other ICF reactors.

In developing the Cascade concept, our first objectives were to design a reactor that is inherently safe and uses low activation materials. To meet these objectives, we designed a solid, lithium-bearing, flowing ceramic-granule blanket (Figure 1) that does

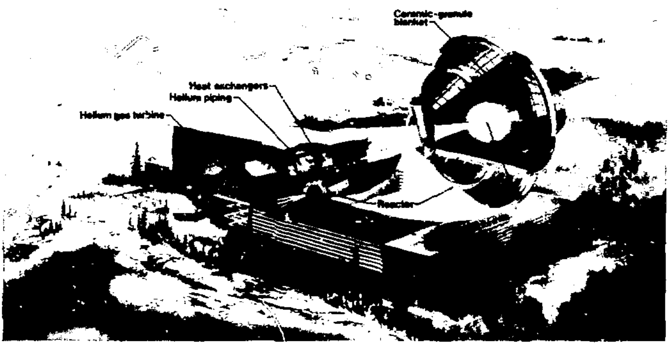

Figure 1. The Cascade power plant produces 820 MW_e at a net efficiency of 49%. The reactor is constructed of low activation materials and is inherently safe.

not burn. The ceramic granules enter the smaller radius ends of a rotating double-cone-shaped reactor in which the base of each cone is congruent. The granules form a blanket that is held against the wall by the rotation. The rotation forces the granules to flow to the larger radius central section where they exit the reactor from slots at the base of the cones. Fusion fuel pellets are injected into the center of the reactor five times a second. Laser or ion beams illuminate each pellet as it reaches the center, compressing the fuel to fusion conditions and yielding 300 MJ per pellet. The granules are heated by the fusion energy as they flow through the reactor, and are then transported to heat exchangers using their own exit peripheral speed rather than conveyors. After the heat is transferred from the granules to high-pressure (5-MPa) helium gas in the heat exchangers, the granules return to the reactor by gravity.

The blanket is composed of three radial regions: the outer breeder zone, the front neutron multiplier zone, and the inner surface layer. For the outer 900-mm-thick breeder zone, we selected $LiAlO_2$ ceramic granules because they are stable at temperatures up to 1500 K and because they, in conjunction with a neutron multiplier, allow a tritium breeding ratio greater than unity to be obtained. As a neutron multiplier in the 90-mm-thick front zone, we selected BeO ceramic granules that "float" inside the higher density $LiAlO_2$ granules.

After each fusion pulse, a micron or so of the inner surface of the blanket ablates as x-ray and fusion-fuel-pellet-debris energy is deposited on this surface. We added a thin, 10-mm-thick layer of carbon granules to this inner surface. We chose a single element material like carbon because it vaporizes and recondenses as the same material. Although carbon burns at the temperatures inside the reactor if oxygen is present, we calculated that under the worst accident scenario, no BeO or $LiAlO_2$ would vaporize. Therefore, even if the containment were breached, no toxic or activated granule material would be released, and the reactor's inherent safety would be maintained. To verify this blanket design, we conducted laboratory scale tests to determine the blanket velocity profile and to prove that the concept would produce a constant thickness blanket with a non-zero velocity at the wall.

We chose SiC ceramic for the reactor wall because it has a lower activation level than steel and because it can withstand higher temperatures (up to 2100 K). A key design issue for most reactor concepts is the ability of the reactor's first structural wall to withstand the fatigue loading caused by the fusion reactions within the reactor. Cascade is ideally suited to reduce this fatigue loading because the loosely packed, flowing ceramic-granule blanket will not propagate the shock waves that are generated after each fusion pulse as material is ablated from the inner surface of the blanket.

We calculated the stress on the reactor wall caused by the ablated material, added stresses caused by thermal gradients and rotational forces, and then we applied the American Society of Mechanical Engineer's (ASME 1980) Pressure Vessel Code design criteria. Because ceramics are strong in compression but are weak in tension, we added a network of SiC-fiber/aluminum tendons. Next, we calculated both a SiC wall-panel thickness that can withstand all stress loads and a tendon size that can keep the panels continually under compression.

We designed a simple once-through Brayton helium-gas-turbine cycle that yields a power conversion efficiency of 55% and a net plant efficiency of 49%. We found that the complete Cascade reactor and power plant has low tritium inventory and a negligible tritium release (0.03 Ci/d) to the atmosphere.

We determined the cost of the Cascade power plant and found that it is competitive with coal or fission power plants. We believe that our design method documented in this paper is consistent, addresses the key design issues, and produces an attractive reactor concept.

2 DESIGN METHOD

In the Cascade design, two transient and two steady stresses are present in the reactor wall. Transient stresses occur following each fusion pulse because carbon is ablated from the blanket's inner surface. The mass m, energy ϵ, and momentum M of the ablated carbon were calculated by Orth (1987) to be 0.34 kg, 29 MJ, and 4400 kg m/s, respectively. Following Glenn and Young's (1979) method, the peak wall stress resulting from the momentum σ_m is

(1) $$\sigma_m = M\sqrt{E/\rho} \Big/ At \cos\theta = 14 \text{ MPa} \quad ,$$

where E is Young's modulus (360 GPa), A is the area of a sphere having a radius equal to the minimum distance of the wall from the fusion reactions (210 m^2), t is the wall thickness (20 mm), θ is the angle between the wall and the cone axis (35°), and ρ is the density of the wall material (3200 kg/m^3). Peak wall stress caused by pressure buildup inside the reactor from the ablated material σ_p is

(2) $$\sigma_p = \epsilon R \Big/ 2Vt \cos\theta = 27 \text{ MPa} \quad ,$$

where R is the maximum radius of the wall (5 m) and V is the clear volume inside the blanket (160 m^3).

The two steady stresses result from the reactor's rotation and the thermal temperature gradients. Peak stress caused by the rotation σ_r is

(3) $$\sigma_r = \omega^2 \int \rho r^2 dr \Big/ t = 38 \text{ MPa} \quad ,$$

where r is the radius, which is integrated through the blanket and wall, and ω is the angular velocity (5.2 rad/s). There is no cos θ in the denominator because the rotational force is radially outward rather than normal to the wall. Peak wall thermal stress σ_t is

(4) $$\sigma_t = E\alpha\Delta T \Big/ 2(1 - \upsilon) = 3 \text{ MPa} \quad ,$$

where α is the linear coefficient of thermal expansion (4.9 x 10^{-6}/K), ΔT is the temperature difference through the wall (3 K), and υ is Poisson's ratio (0.24). The value of ΔT is small because the wall is insulated externally and cooled only by thermal radiation.

The total of these stresses (82 MPa) is resisted by the composite tendons that keep the wall continually under compression. The tendons are positioned at 0.5-m intervals on 150-mm-high SiC support posts that extend radially beyond the wall insulation. The wall is 20 mm thick so that the tendon circumferential (hoop) force is 0.82 MN. Following ASME recommendations, we used an allowable tendon stress of 80% of the tendon tensile stress (0.8 x 970 MPa), and from this we calculated the required tendon diameter of 40 mm.

We next calculated the buckling and shear stresses in the SiC panels, designed the roller supports for the reactor, and performed other miscellaneous stress calculations. We found no limiting magnitudes of stress. The reactor and heat exchangers are maintained in vacuum--0.1 Torr inside the reactor and 0.01 Torr exterior to the reactor and inside the heat exchangers. Although these pressures are different, the resulting stress added to the reactor wall is insignificant.

Vacuum pumps are positioned in the space surrounding the reactor and the volume inside the reactor is differentially pumped through the end openings. We calculated that the conductance of these openings was over 1000 m^3/s and that the total pumping load from fuel pellet and ablated material inside the reactor, which is not consumed or recondensed, was less than 100 m^3/s. If the reactor had the same pressure inside and outside, the total pumping load would need to be near the conductance of the openings, and the vacuum probably could not be effectively maintained. No difficulty exists in pumping the heat exchangers to 10^{-2} Torr because openings of any desired size can be installed in the top or sides.

Maya et al. (1985) conducted a thermal analysis of the Cascade blanket that considered the radial-energy deposition and velocity profile and accounted for conduction within the blanket. Each of the three radial-blanket regions has a uniform inlet temperature selected so that the respective peak outlet temperatures do not exceed allowable values. Good mixing is assumed in the surface layer and its outlet temperature (1600 K) is uniform. The front and breeder zones each have radial temperature variations at the exit. Their average outlet temperatures were 1505 and 1355 K, respectively.

Because of the different regions' outlet temperatures, we designed three heat exchangers connected in series--one for each region of the blanket. In the first heat exchanger, the $LiAlO_2$ in the breeder zone raises the temperature of 5-MPa helium gas from 915 to 1140 K. Next, BeO from the front zone heats the gas to 1190 K. Finally, the carbon from the surface layer heats the gas to 1300 K. The heat exchangers are shell-and-tube type with SiC used as the tube material. Gas passes through the heat exchangers in a cross-counter flow direction, with log mean temperature differences varying between 160 and 240 K.

One difficulty in the thermal design is associated with the support posts for the tendons. These tendons are located radially outward from the insulation surrounding the reactor wall. Their temperature can be kept below the allowable value (700 K) by thermal radiation alone, except possibly in the region of support posts. These posts must have high compressive strength and yet be good thermal insulators. We originally proposed using SiC for the support posts, but found the maximum temperature of the tendons where they touched the posts exceeded 700 K. Two solutions are possible: redesign the posts using a better insulator and/or post geometry, or provide local active cooling for the tendons at their attachment to the posts. Either solution is acceptable, but we have not determined which is the most economical.

Perhaps our most difficult problem in designing Cascade was determining the flow characteristics of the blanket. Because the flow of granular material is complex, we performed both analyses and experiments (Pitts and Walton 1985). The results of our analyses show that a single granule can remain on the reactor wall as long as the rotational speed is 5.2 rad/s or greater. The granules move axially down the wall with a slight (5 mm or less) sinusoidal oscillation in the circumferential direction. Our experiments with cones of different angles prove that a blanket of uniform thickness can be obtained if the angle between the wall and the cone axis is slightly above the granule angle of repose.

Figure 2. A laboratory scale experiment for measuring the velocity profile in the Cascade flowing ceramic-granule blanket.

The results of our chute experiment (Figure 2) show that a two-layered flow exists. The top surface layer is thin and fast moving (supercritical flow). A thick bottom layer moves more slowly (subcritical flow controlled at the exit) with a velocity that increases with the distance from the bottom of the chute. This is a desirable velocity profile because in Cascade about one-third of the fusion energy is deposited in the top surface (inner radius) layer in the form of x rays and fusion-fuel pellet debris. The fast speed permits a reasonable change in temperature in the surface layer even though the energy deposition is high. We measured the velocity profile with a high-speed camera and found that a non-zero velocity existed at the bottom (reactor wall). If the velocity were zero anywhere, heating would continue until that portion of the blanket melted, destroying the desirable flow characteristics of the blanket We used the velocity profile from this experiment with our thermal analysis to design an acceptable blanket.

We selected a Brayton helium-gas turbine cycle for power conversion because we could achieve higher efficiency at our operating temperatures. Besides the heat exchangers, the cycle includes a single turbine generator, a recuperator, and three compressors with intercooling. State points within the cycle were optimized to obtain maximum efficiency. Our power conversion efficiency of 55% (net plant efficiency of 49%) exceeds by a factor of up to 50% that obtained in current fission- and fossil-fired power plants.

Meier (1985) found Cascade's activation per unit of net electric power to be six times less than in the MARS Tandem Mirror Reactor (Logan et al. 1984) because of the ceramic materials used in Cascade. The Cascade activity is dominated by the ^{24}Na, which is produced by (n,α) reactions with the aluminum present in the blanket's breeder zone. Activation is so low that once the reactor is moved to the reactor maintenance building and the blanket removed, hands-on maintenance is feasible. We also designed the shielding so that hands-on maintenance of the heat exchangers is possible one day after shutdown.

Maya et al. (1985) calculated the tritium inventory and permeation as a function of temperature and pressure in the vacuum system. They found a total tritium inventory excluding fuel pellet manufacturing of only 260 g (~140 g of this inventory has a release time of about 10 h or less and the remainder has a release time of ~100 yr). Essentially all of the tritium is recovered through the vacuum system, which is also the primary tritium-recovery system. Only 25 Ci/d leaks through the heat exchanger manifolds and ducting to the helium gas used for power conversion. This tritium is also recovered and leakage external to the vacuum system and heat exchangers is so low (0.03 Ci/d) that actual losses to the environment were not calculated.

3 CONCLUSIONS

We predict that the Cascade ICF power plant concept will produce electricity at a cost of only $0.034/kW•h, which is 70% of an equivalent coal-fired power plant or 90% of a modern pressurized-water-reactor power plant. The net plant efficiency of Cascade is 49%. In addition to producing cost effective electricity, Cascade also has the advantages of low activation and low tritium inventory, and it is inherently safe.

The design method outlined here complies with the intent of the American Society of Mechanical Engineers pressure vessel code. Fatigue on the Cascade reactor wall is insignificant because the flowing ceramic-granule blanket does not propagate shock waves. Our laboratory scale experiments prove that the Cascade blanket concept is viable. We used the velocity profiles obtained from these experiments to optimize the blanket design.

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REFERENCES

ASME 1980. Boiler and Pressure Vessel Code, Code Case N-47-17.

Glenn, L.A. & D.A.Young 1979. Dynamic Loading of the Structural Wall in a Lithium Fall Fusion Reactor. Nucl. Engr. & Des. 54:1-16.

Logan, B.G. et al. 1984. MARS Mirror Advanced Reactor Study, Lawrence Livermore National Laboratory, Livermore, CA, Report UCRL-53480.

Maya, I., K.R. Schultz & Project Staff. 1985 Final Report--Inertial Confinement Fusion Reaction Chamber and Power Conversion System Study. GA Technologies Report GA-A17842.

Meier, W.R. 1985. Neutron Activation in Cascade: The BeO/$LiAlO_2$ Blanket Case Proceeding. 11th Sym. on Fusion Engineering, Austin, TX.

Orth, C.D. 1987. Profile: A Computer Code for the Deposition of Soft X Rays and the Estimation of First-Wall Mass Vaporization and Momentum Transfer. Lawrence Livermore National Laboratory, Livermore, CA. To be published (1987).

Pitts, J.H. 1985. Cascade: A High-Efficiency ICF Power Reactor. Proceedings, 7th Int. Workshop on Laser Interaction and Related Plasma Phenomena, Monterey, CA.

Pitts, J.H. & I. Maya. 1985. The Cascade Inertial-Confinement-Fusion Power Plant. 11th Sym. on Fusion Engr. Austin, TX.

Pitts, J.H. & O.R.Walton. 1985. Flow Characteristics of the Cascade Granular Blanket, Fus Tech. 8:1838-1843