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Development of the Cascade Inertial-Confinement-Fusion Reactor

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ABSTRACT

Cascade, originally conceived as a football-shaped, steel-walled reactor containing a Li_2O granule blanket, is now envisaged as a double-cone-shaped reactor containing a two-layered (three-zone) flowing blanket of BeO and $LiAlO_2$ granules. Average blanket exit temperature is 1670 K and gross plant efficiency (net thermal conversion efficiency) using a Brayton cycle is 55%.

The reactor has a low-activation SiC-tiled wall. It rotates at 50 rpm, and the granules are transported to the top of the heat exchanger using their peripheral speed; no conveyors or lifts are required. The granules return to the reactor by gravity. After considerable analysis and experimentation, we continue to regard Cascade as a promising reactor concept with the advantages of safety, efficiency, and low activation.

INTRODUCTION AND GENERAL DESCRIPTION

Cascade[1] is a concept for an ultra-safe, highly efficient, easily built reactor to convert inertial-confinement-fusion (ICF) energy into electrical power. The reactor (see Fig. 1) rotates at 50 rpm about its horizontal axis; fusion fuel pellets are injected into the center of the reactor 5 times per 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. This fusion energy, in the form of x rays, pellet debris, and neutrons, is deposited in a 1-m-thick moving ceramic-granule blanket held against the reactor wall by centrifugal force. Heated granules flow out of the large-radius section at the midplane of the reactor with temperatures from 1390 to 2300 K. The granules remain on rotating "shelves" outside the reactor chamber until they are diverted by stationary scoops. The peripheral speed of the granules is high enough to carry them to the top of the heat exchanger. The granules flow through the heat exchanger, where their heat energy is transferred to high-pressure helium gas,[2] and then back into the reactor. The reactor and the primary (granule) side of the heat exchanger are kept at vacuum for greater simplicity. No vacuum locks or granule conveyors are required. A vacuum of only 0.1 Torr is needed if laser beams are used to illuminate the fuel pellets. Maintaining a vacuum on the primary side of the heat exchanger reduces heat transfer, however, the effect is small because the dominate heat transfer mechanism at our high granule temperatures is thermal radiation. The heat exchanger[2] consists of tubes, submerged in a bed of granules, carrying high-pressure helium (secondary) gas. The helium is used in a standard Brayton cycle, in which gas-turbine generators produce electricity; the gross plant efficiency (net thermal conversion efficiency) is 55%.

The blanket and heat exchanger are each divided into three regions. The outer 900 mm of the blanket (see Fig. 2), called the breeder zone, is composed of flowing lithium aluminate ($LiAlO_2$) granules 1 mm in diameter (about the size of sand grains). The $LiAlO_2$ granules absorb neutrons, capturing their energy in the form of heat and producing tritium to replace that burned in the fusion reactions. We require that the tritium breeding ratio (tritium bred to tritium burned) be greater than unity, so that no additional tritium need be supplied to the reactor. Granules from the breeder zone leave the reactor at 1390 K and are used in the first section of the heat exchanger for initial heating of cold helium gas returning from the turbine-generators.

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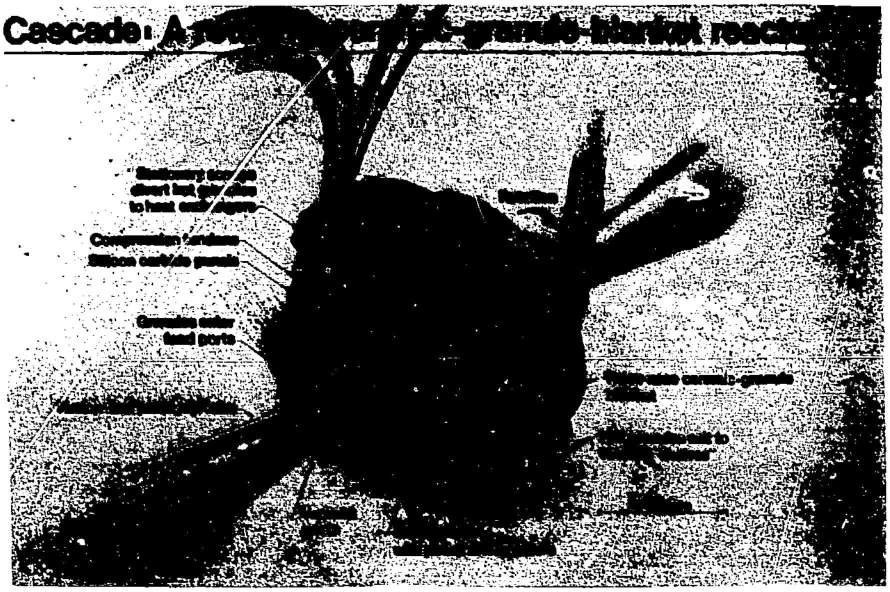


Fig. 1. Rendering of the Cascade reactor.

The Cascade blanket is composed of three regions

	Surface layer	Front zone	Breeder zone
Material	BeO	BeO	$LiAlO_2$
Thickness, cm	1	9	90
Inlet temperature °K	2100	1440	1330
Outlet temperature, °K	2300	1510	1390
Total flowrate, m^3/s	1.0	1.3	8.4
Power fraction	0.29	0.13	0.58
Peak exit velocity, m/s	1.9	0.25	0.25

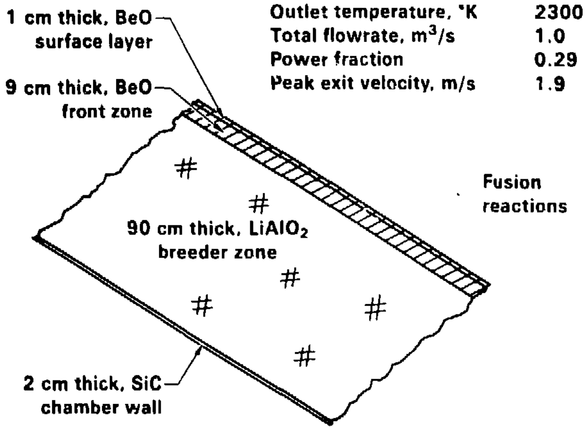


Fig. 2. Characteristics of the Cascade blanket.

A 90-mm-thick middle region of the blanket, called the front zone, is composed of 1-mm-diam beryllium oxide (BeO) granules. BeO acts as a neutron multiplier, so that tritium breeding ratios greater than unity can be obtained in the breeder zone. The BeO granules have a density slightly less than that of the $LiAlO_2$ granules, so that they "float" on the surface of, and do not mix with, the $LiAlO_2$ granules. The front-zone granules, which leave the reactor at 1510 K, are used for intermediate heating of the helium gas in the heat exchanger. The velocity distribution of the front- and breeder-zone granules in the reactor is continuous and decreases with radius. There is about an order of magnitude change from the highest to lowest velocity.

A thin, 10 mm-thick innermost blanket region, called the surface layer, is also composed of 1-mm-diam BeO granules. The granules in this layer absorb the x ray and fuel-pellet debris; they move with about an order of magnitude greater velocity than granules in the front zone, and leave the reactor at 2300 K. These granules are used for final heating of the helium gas in the heat exchanger. The high velocity of the surface layer--discontinuous from the velocity in the front zone--has been verified by experiments[3] of sand flow on inclined chutes, and is necessary to keep the exit temperature of the surface-layer granules within reasonable bounds.

As originally conceived,[1] the Cascade reactor was football-shaped and had walls of ferritic steel. It was to operate with a single-region blanket of lithium oxide (Li_2O) granules. Incompatibility of Li_2O with the fusion-chamber environment (in particular, its tendency to oxidize metals and to decompose above 1200 K) restricted the reactor exit temperature to 1200 K. Neutron activation of the steel wall was relatively high, and the wall required active cooling.

GA Technologies[4] suggested switching to a wall of trapezoidal silicon carbide (SiC) tiles held in compression by longitudinal and circumferential composite SiC/aluminum tendons. Such a wall has several advantages. It can operate at temperatures higher than that of the blanket granules, so that no active external cooling is required. By adding insulation (not shown in Fig. 1) outside the tiles, we can keep the tendons below 700 K by thermal radiation to the surroundings. With this design, the blanket can be kept at a higher temperature, thus increasing the thermal efficiency of the energy conversion.

SiC is also a low-activation material, which mitigates maintenance and disposal problems. Ninety percent of the neutrons and all of the x rays and fuel-pellet debris are absorbed in the blanket and never reach the wall. Activation of the reactor[5] is low enough to allow hands-on maintenance once it is moved to a disassembly area. Disposal of the activated reactor components by shallow land burial is permitted.

We considered several blanket designs[4,6] to improve the performance of the reactor. Each design had advantages, but we chose the three-region, BeO-$LiAlO_2$ design (Fig. 2) because it gave a high power-averaged blanket outlet temperature (1670 K) and because the materials were more compatible with the reactor environment. Lithium aluminate is less reactive than Li_2O and can be heated to temperatures up to 1500 K. Beryllium oxide protects the $LiAlO_2$ from the high x-ray and pellet-debris energy deposition, can be heated to 2300 K, and is less susceptible to thermal cracking than Li_2O or $LiAlO_2$.

The Cascade concept has inherent safety because it uses only low-activation materials that have no exothermic reactions. None of the materials--SiC, $LiAlO_2$, or BeO--will burn. The worst consequence of a failure of the reactor structural components would be that the blanket material would slump to the bottom of the chamber. Thermal radiation to the surroundings is adequate to remove the low afterheat energy without raising the blanket materials to their melting point. If the support system failed, the rotational energy of the rotating chamber and blanket would be only enough to carry the reactor uphill to a height of twice the reactor diameter.

Use of BeO requires safeguards, but no more than those required for many other industrial materials. Industrial use of BeO caused berylliosis before 1950, but a study of this problem led to regulations on allowable beryllium concentrations in air. A maximum in-plant concentration of 25 $\mu g/m^3$ and a maximum average in-plant concentration of 2 $\mu g/m^3$ (over an 8-hr day) were suggested. A maximum concentration of 0.01 $\mu g/m^3$ for the air in the immediate area surrounding the plant was also suggested to protect the general population. Berylliosis has not occurred[6] as long as these regulations were followed, and the problem is essentially nonexistent today.

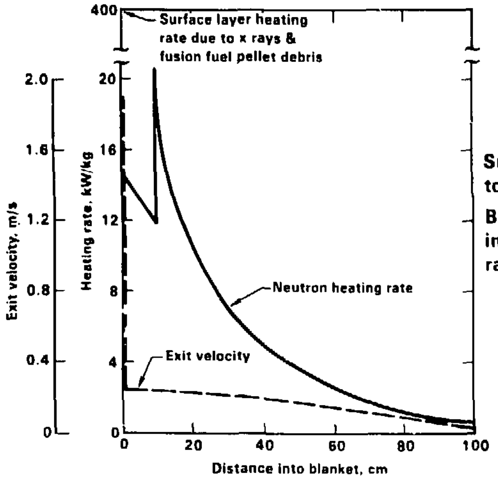
THE GRANULAR BLANKET

The granular blanket is the key component in the reactor. It absorbs the fusion energy, breeds tritium by neutron interactions with lithium, reduces neutron activation in the reactor wall, and ameliorates wall stresses. The blanket is held against the wall by centrifugal force, leaving a central cavity into which fusion fuel pellets can be injected for illumination with laser or ion beams. The radial velocity profile of the granules should match the energy deposition profile as closely as possible, so that a high granule exit temperature, and correspondingly high thermal efficiency, can be obtained. Low-activation blanket materials that have high maximum allowable temperatures are desirable. The Cascade blanket attempts to satisfy these needs.

We carried out analyses and experiments that showed that flow of granular ceramic material through the reactor is feasible.[3] A central cavity can be maintained if the rotational speed is 50 rpm or greater. If the angle between the wall and the axis is greater than the granule angle of repose, two-layered flow occurs naturally. The surface layer is thin and moves rapidly (in so-called supercritical flow); there is considerable mixing of the granules, so that the temperature is nearly uniform across the layer even though most of the x-ray and pellet-debris energy is deposited near the inner (free) surface. The outer-radius layer moves more slowly (in subcritical flow), and the flow rate of material in this layer is controlled at the outlet. Experiments show that the velocity profile across the outer-radius layer decreases with radius, and that there is about an order of magnitude difference in velocity from surface to surface. The velocity profile through the complete blanket[3] is somewhat similar to the heating-rate profile[6] caused by x-ray, pellet-debris, and neutron energy deposition (see Fig. 3). An exact match was not feasible, but we did obtain a velocity ratio of 8 between the surface layer and the front zone: the heating-rate ratio is 30. Similarly, between the inner and outer radii of the $LiAlO_2$ breeder zone, velocity and heating-rate ratios were 9 and 30, respectively. This is far better than would have been achieved in the original, football-shaped Cascade reactor.

A difficulty with this blanket is the step in the heating rate at the interface between the BeO front zone and the $LiAlO_2$ breeder zone. The flow rate must be high enough to keep the exit temperature in the $LiAlO_2$ at the interface below 1500 K. Because the velocity profile is continuous in the front and breeder zones, this flow rate, along with the heating-rate profile, results in average outlet temperatures below the

The blanket velocity profile is shaped as much as possible to match the heating rate profile



	Heating rate ratio	Velocity ratio
Surface layer to front zone	30	8
Breeder zone inner to outer radius	30	9

Fig. 3. Velocity and heating rate profiles in the Cascade blanket.

maximum values permitted. The average outlet temperature for the BeO front zone is only 1510 K, but the BeO can withstand temperatures up to 2300 K. Similarly, the $LiAlO_2$ breeder zone average exit temperature is 1390 K, which is 110 K below the allowable 1500 K. Only the BeO surface layer, whose velocity can be set independently from the rest of the blanket, has an outlet temperature equal to its allowable maximum value.

This non-optimum average exit temperature for the front and breeder zones, along with the fact that 58% of the fusion energy is deposited in the lowest-temperature breeder zone, reduces the temperature of the helium in the heat exchanger. Helium behaves like a perfect gas with constant specific heat, so that the temperature rise in each region of the heat exchanger is proportional to the energy transferred. Because 58% of the energy is associated with the low-temperature breeder zone, 58% of the helium temperature rise is associated with the corresponding region of the heat exchanger. Further, the temperature of the helium leaving the breeder-zone region of the heat exchanger is only 1090 K (the 1390 K average exit temperature of the breeder zone less 300 K, which we used as a minimum temperature drop across the heat exchanger). Final helium exit temperature from the heat exchanger is 1130 K, well below the 2000 K (2300 K less 300 K) possible in the region of the heat exchanger associated with the surface layer. Efficiency of the conversion system increases with temperature. A gross plant efficiency of 55% is feasible with a 1130 K helium temperature. Should a more acceptable breeder material be found that has a higher allowable temperature than $LiAlO_2$, or should blanket tritium breeding ratios less than unity be allowed, then a higher helium exit temperature, and a correspondingly increased conversion system efficiency, could be attained.

A zoned blanket has the further advantage that it reduces cracking of the surface-layer granules as they absorb x-ray and pellet-debris energy. If the surface layer is made of Li_2O, as in the original Cascade design, thermal stresses exceed those allowed and some granule cracking would be anticipated. If the surface layer is composed of BeO or SiC, however, little or no cracking is expected.

CONCLUSIONS

The Cascade concept now includes a zoned BeO-$LiAlO_2$ blanket and a SiC-tiled reactor wall held in compression by tendons. The concept has the advantages of safety, efficiency, and low activation.

Two-layered (three-zone) granule flow in the blanket permits a radial velocity profile somewhat similar to the blanket heating-rate profile. Problems still exist because the heating rate is discontinuous at the interface between the BeO front zone and the $LiAlO_2$ breeder zone. Because the velocity profile is continuous at this interface, blanket outlet temperatures are lower than optimum. Even so, the average blanket exit temperature is high (1670 K), and a gross plant efficiency (net thermal conversion efficiency) of 55% is reached using a Brayton cycle with helium gas turbine-generators.

Analysis and experiments have shown that two-layered flow is feasible if the reactor is a double cone with the large-radius sections joined. The flow consists of a thin, fast-moving surface layer on top of a slower-moving layer if the chamber half angle is 35^o, slightly greater than the angle of repose of the blanket granules. The granules are transported from the reactor to the top of the heat exchanger using their exit peripheral speed (without conveyors or lifts) and return to the reactor by gravity.

Our analyses and experiments have not revealed any major limitations, so that we continue to regard Cascade as a promising reactor concept for the conversion of ICF energy into electricity.

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