UCRL- 93554
PREPRINT

UCRL--93554

DE86 002605

CASCADE: A HIGH-EFFICIENCY ICF POWER REACTOR

John H. Pitts

This paper was prepared for submittal to the
7th International Workshop on Laser Interaction
and Related Plasma Phenomena

Monterey, California

October 31, 1985

Lawrence Livermore National Laboratory

CASCADE: A HIGH-EFFICIENCY ICF POWER REACTOR*

John H. Pitts

Lawrence Livermore National Laboratory
P. O. Box 5508, L-480
Livermore, CA 94550

ABSTRACT

Cascade attains a net power-plant efficiency of 49% and its cost is competitive with high-temperature gas-cooled reactor, pressurized-water reactor, and coal-fired power plants. The Cascade reactor and blanket are made of ceramic materials and activation is 6 times less than that of the MARS Tandem Mirror Reactor operating at comparable power. Hands-on maintenance of the heat exchangers is possible one day after shutdown. Essentially all tritium is recovered in the vacuum system, with the remainder recovered from the helium power conversion loop. Tritium leakage external to the vacuum system and power conversion loop is only 0.03 Ci/d.

INTRODUCTION AND GENERAL DESCRIPTION

Cascade,[1,2] one of the most recent and promising concepts for converting inertially confined fusion energy into electric power, has three key advantages. First, the reactor is inherently safe: the design uses only ceramic materials, which do not burn (previous designs used liquid lithium, which does burn when exposed to water or concrete). Second, high efficiency can be obtained: its ceramic blanket can withstand high temperature, which improves the conversion of heat energy into electricity, giving a net plant efficiency of 49%. Third, the ceramic materials in Cascade have minimal activation; this reduces residual radioactivity.

The reactor (see Fig. 1) is double-cone shaped with a maximum radius of 5 m and is evacuated to permit efficient illumination of the fusion-fuel pellets by the laser or ion beams. Its walls are made from silicon-carbide (SiC) panels held in compression by SiC-fiber/aluminum-composite tendons that gird the chamber both circumferentially and axially. The blanket is composed of three zones: an inner 10-mm-thick pyrolytic-carbon-granule surface layer, a 90-mm-thick beryllium-oxide-granule front zone, and a 900-mm-thick lithium-aluminate-granule tritium breeder zone. The reactor rotates at 50 rpm so that its 1-m-thick blanket is held against the inside of the

*Work performed under the auspices of the U.S. DOE by the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-38.

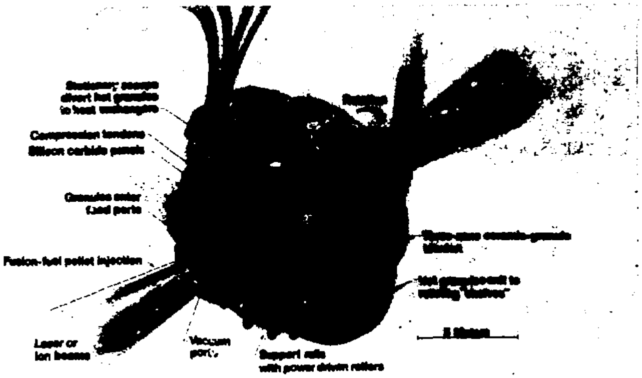


Figure 1. Cascade: A rotating, ceramic-granule blanket reactor

reactor wall by centrifugal force. The cone half-angle is 35° - slightly above the angle of repose of the blanket granules. The granules are fed into the reactor through ports 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. Peripheral speed of the hot granules leaving the reactor is high enough that stationary scoops can divert the granules from the exit shelves to heat exchangers without the use of pumps or conveyors (see Fig. 2). The granules pass through the heat exchangers and back to the reactor feed ports by gravity. Energy is extracted from the granules in the heat exchangers and used with a helium gas turbine (Brayton) cycle to produce electricity.

Two-thirds of the fusion energy produced in the pellets leaves as energetic 14-MeV neutrons, most of which are captured and absorbed by the ceramic granule blanket. The remaining one-third of the fusion energy produced in the pellets leaves in the form of x rays and fusion-fuel-pellet debris. This energy is deposited in a very thin (a few micrometers) region at the inside of the pyrolytic-carbon surface layer. The energy deposition in this thin region is high enough to vaporize ~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 of the blanket. In the final design, we chose elemental pyrolytic carbon granules 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 chosen for the inner surface layer material, then dissociation could occur when the x rays and fusion-fuel-pellet debris vaporized the inside blanket surface; some of the beryllium could recondense separately leaving some oxygen gas in the chamber. If this occurred, a significant increase in the size of the vacuum pumps would be required to remove the gaseous oxygen before

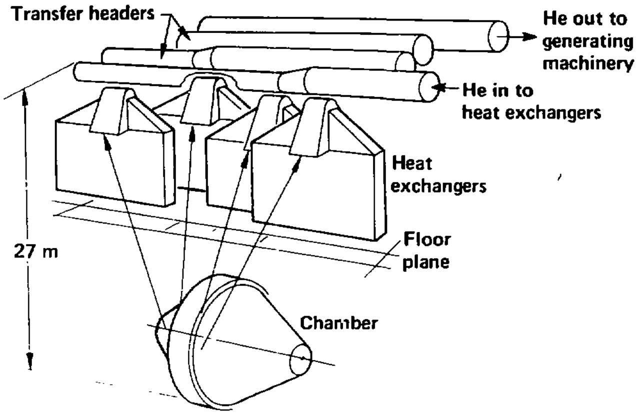
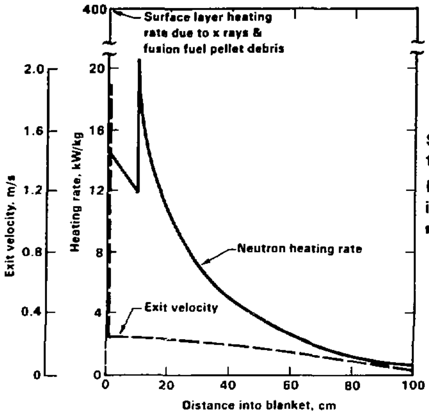


Figure 2. Cascade chamber and heat exchanger layout. Granules are transported from the chamber to the heat exchangers using their own peripheral speed.

the next fusion energy pulse, and the elemental beryllium would vaporize at a lower temperature on all subsequent pulses.

The beryllium-oxide front zone adjacent to the surface layer, acts as a neutron multiplier for the outer lithium-aluminate tritium breeder zone. Calculations[3] show that the pyrolytic carbon vaporized from the inner blanket surface recondenses in less than 10^{-5} s after reentering the surface layer. No vaporized carbon reaches the BeO front zone. If vaporized carbon did reach the BeO front zone, incondensible CO would be formed, which again would require an increase in the size of the vacuum system. 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. In this fashion, the exit temperature of each zone is constant across its radius and can be set equal to the maximum material compatibility temperature. We conducted granular flow tests on rotating cones[5] and on a chute,[6] which showed that two-layered granular flow, having a radial-velocity profile somewhat similar to the heating-rate profile, was feasible in the Cascade reactor. In the tests, the surface layer (corresponding to the pyrolytic-carbon surface layer in the Cascade reactor) is free flowing and moves rapidly with good mixing. The bottom layer (corresponding to the BeO front and $LiAlO_2$ breeder zones in the Cascade reactor) moves more slowly with a parabolic-velocity profile that is controlled by openings at the exit. Figure 3 compares the velocity profile with the heating-rate profile in Cascade. The profiles are somewhat similar and permit an average blanket exit temperature of 1440 K to be attained.



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

Figure 3. Comparison of the velocity and neutron heating rate profiles in Cascade.

The heat exchangers transfer energy from the blanket granules to 5-MPa-pressure helium gas used in the power-conversion system. Inside the heat exchangers, the granules flow around an array of horizontally oriented ceramic tubes through which helium gas flows. The tubes are 25 mm outside diameter and 1.5 m long with a wall thickness of 2 mm. Total heat transfer area is about 9000 m^2. The outside of the heat exchanger and the piping connecting the heat exchanger to gas turbines are metallic with internal insulation.

The Cascade power-conversion system is a simple once-through regenerative helium-gas Brayton cycle without reheat. The cycle includes three-stage compression with intercoolers, and achieves a thermal power conversion efficiency of 55%. Net plant efficiency is 49% based on a thermal power of 1670 MW. A power-flow diagram is shown in Figure 4. The net plant efficiency of the Cascade concept is substantially higher than for most other fusion reactor concepts, which are in the 30 to 40% range.

In addition to the advantages of safety, high efficiency, and low activation, Cascade can also accommodate a variety of operating conditions, blanket materials, and power conversion systems. For example, the fusion power level was set at 1500 MW so that the net electric power produced would be below 1000 MW. An increased power level can be accommodated with little change in the reactor design because the reactor wall is made of silicon carbide tiles held in compression by tendons. Any additional mechanical stresses caused by increasing the power level can be offset by increasing the tension in the tendons. Table 1 lists some of the key parameters chosen for the final Cascade design.

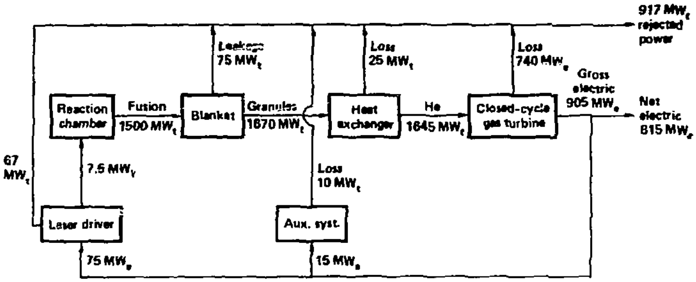


Figure 4. Cascade power flow diagram.

As with any fusion reactor concept, a few issues with Cascade remain to be resolved. We need to better understand the vaporization and recondensation of the blanket inner surface granules that are exposed to x rays and fusion-fuel-pellet debris. A first-surface illumination experiment coupled with additional analysis would assure that the 5-Hz repetition rate is feasible. We also need to develop an inexpensive granule manufacturing process so that those granules that comminute can be replaced without appreciably impacting the total cost. We believe, however, that the remaining issues can be solved and that Cascade is truly one of the most promising concepts for converting inertially confined fusion into electrical power.

ACTIVATION AND SHIELDING

Ceramic materials in the Cascade reactor generally have low activation. Calculations performed by Meier[7] show that the activity per unit of net electric power is six times less than in the MARS Tandem Mirror Reactor. The activity is dominated by ^{24}Na produced by (n, α) reactions with the aluminum present in the lithium-aluminate-granule blanket breeder zone. A summary of Meier's activation results is shown in Table 2. The activity reaches steady state shortly after start-up and remains nearly constant. Hence, the values shown in Table 2 are approximately correct for shutdowns that occur any time during the 30-year lifetime of the plant. Cascade shielding[8] has two components. Both components are actively cooled to keep temperatures during reactor operation within allowable limits. A 2 m-thick borated-water-radiation shield is placed outside the reactor and just inside the vacuum barrier. However, its position is such that it also shields the heat exchangers. Therefore, hands-on maintenance of the heat exchangers is possible one day after the reactor is shut down. A 2.5-m-thick concrete biological shield is positioned outside the heat exchangers and vacuum barrier. Dose rates exterior to the biological shield are less than 1 mrem/hr so that even during reactor operation, continuous occupational exposure is allowed.

TRITIUM CONTROL AND RECOVERY

GA Technologies[8] calculated the tritium inventory and permeation as a function of temperature and tritium overpressure in the vacuum

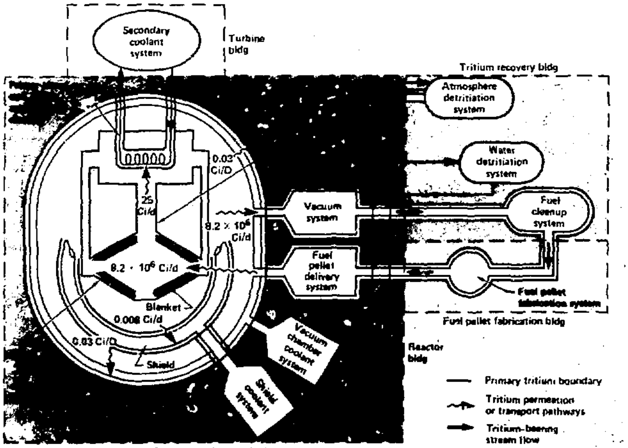
Table 1. Operating Characteristics of the Cascade Reactor

o Power Levels, MW	
Fusion	1500
Thermal	1670
Gross electric	905
Net electric	815
o Efficiency, %	
Power conversion	55
Net plant	49
o Reactor Dimensions	
Maximum radius, m	5
Half length, m	4.3
Cone half angle, degrees	35
Rotational speed, rpm	50
o Blanket	
Thickness, mm	
Pyrolytic carbon	10
Beryllium oxide	90
Lithium aluminate	900
Total	1000
Granule diameter, mm	1
Total flowrate, m^3/s	10.7
Average outlet temperature, K	1440
Tritium breeding ratio	1.05
Energy multiplication	1.11
o Laser	
Power, MW_e	75
Repetition rate, Hz	5
Efficiency, %	10
o Pellet Yield, MJ	300

system. We sized the vacuum system to maintain 13 Pa (10^{-1} Torr) total pressure in the reactor and 1.3 Pa (10^{-2} Torr) total pressure in the granule side of the heat exchangers. Tritium accounts for roughly 40% of the total pressure. Total tritium inventory is 260 g, not including the fusion-fuel-pellet manufacturing plant. About 140 g of this inventory has a characteristic release time of 10 hours; the remainder has release time in the order of 100 years. Essentially all of the tritium (8.2 X 10^6 Ci/d) is recovered through the vacuum system, which is also the primary tritium-recovery system (see Fig. 5). About 25 Ci/d leaks through the heat-exchanger manifolds and ducting to the helium gas used for power conversion. A separate auxiliary tritium

Table 2. Activity in the Cascade Reactor

	Time After Shutdown		
	Shutdown	1 Day	1 Month
Cascade Activity (MCi)			
Carbon surface layer	0.5	---	---
BeO front zone	308	0.4	0.2
$LiAlO_2$ breeder zone	731	86.4	4.1
SiC wall	3.1	---	---
Total	1042	86.8	4.3
Normalized Activity			
Cascade, Ci/W_e	1.28	0.11	
MARS, Ci/W_e	7.8	1.01	
Ratio	6.2	9.5	



Cascade tritium recovery system

Figure 5. Cascade tritium recovery system.

recovery system is included as part of the helium power conversion loop. Because the leakage external to vacuum system and heat exchangers was so low (0.03 Ci/d), actual losses to the environment were not calculated.

The wall thickness (2 mm) of the heat exchanger tubes does not allow tritium breakthrough within the 30-year lifetime of the power plant. Hence, no tritium leakage is expected through the walls of the heat exchanger tubes. If a heat exchanger tube cracked, high pressure helium gas would flow from inside the tube to the granule side of the heat exchanger until the tube was replaced, hence no additional tritium leakage would occur. The method for removing tritium from the vacuum system is similar to the design[9] for tritium recovery from plasma exhaust of the MARS Tandem Mirror Reactor.

ECONOMICS

Because Cascade has many passive safety features, the economics of Cascade were determined for two cases: one where all components were built with conventional fossil-fuel power plant construction and one where a combination of nuclear and conventional construction similar to a modern fission power plant was used. Total direct costs in constant January 1985 dollars were $900 and $1030 million for the conventional and the nuclear-plus-conventional constructions, respectively. These figures include charges for land, structures, equipment, laser, and fusion-fuel-pellet manufacturing. If indirect costs are added, the total capital requirement becomes $1486 and $1940 million, respectively. Details of the cost breakdown, and the methods of arriving at the results, can be found in Ref. 8.

Table 3 shows levelized busbar costs of electricity in constant January 1985 dollars for a plant with a starting date in the year 2005. In Table 3, the Cascade power plant is compared with a high-temperature gas-cooled-reactor (HTGR) power plant, a pressurized-water-reactor (PWR) power plant and a coal-fired power plant. The electrical busbar power output is approximately the same for each type of power plant. Because Cascade breeds enough tritium to replace that which is burned, fuel costs for Cascade are insignificant. However, the capital and operating costs of manufacturing the fusion-fuel pellets is included. Note that the cost of Cascade is competitive with the other types of power plants.

CONCLUSIONS

The Cascade reactor and blanket are made of ceramic materials so that activation is 6 times less than in the Mars Tandem Mirror Reactor of comparable power. Shielding is included so that hands-on maintenance of the heat exchangers is possible one day after the reactor is shut down.

Total tritium inventory is only 260 g and leakage into the helium power conversion loop is only 25 Ci/d. Leakage external to the vacuum system and power conversion loop is so low (0.03 Ci/d) that actual losses to the environment were not calculated.

Costs of Cascade are competitive with high-temperature gas-cooled reactors, pressurized-water reactors, and coal-fired power plants.

ACKNOWLEDGMENTS

I am indebted to GA Technologies for supplying information on activation, shielding, tritium control, and costs; to Wayne Meier of

Table 3. Cost Comparison of Cascade with High-Temperature Gas-Cooled Reactor (HTGR), Pressurized Water Reactor (PWR), and Coal-Fired Power Plants. Costs are Levelized Busbar Values for a Plant Starting Operation in 2005 and are Shown in Constant January 1985 Dollars.

	Cascade Conventional	Plant Nuclear/ Conventional	HTGR	PWR	Coal
<u>Plant characteristics</u>					
Thermal power, MW	1670	1670	2240	2400	2285
Electrical busbar power, MW	815	815	855	800	800
Net efficiency, %	49	49	38	33	35
Capacity factor	0.75	0.75	0.75	0.70	0.75
<u>Charges</u> ($ x 10^6)					
Total capital cost	1486	1940	1546	1237	889
Annual fixed charges	129	169	135	108	80
Annual O & M	52	52	37	40	28
Annual fuel	----	----	54	36	148
<u>Busbar cost summary</u> (Mills/KW-hr)					
Fixed charges	24.2	31.5	23.9	21.9	15.2
O & M	9.6	9.6	6.6	8.1	5.2
Fuel	----	----	9.6	7.3	28.2
Total	33.8	41.1	40.1	37.3	48.6
Relative cost	0.69	0.84	0.82	0.77	1.0

Lawrence Livermore National Laboratory for his help on activation and costs; to Tony Ladd and Lew Glenn of Lawrence Livermore National Laboratory and Nate Hoffman at Rockwell International's ETEC for their help on vaporization and condensation; and to Bill Hogan of Lawrence Livermore National Laboratory for his support and critique of this work.

REFERENCES

1. J. H. Pitts, "Cascade: A Centrifugal-Action Solid-Breeder Reaction Chamber", <u>Nucl. Tech./Fusion</u> 4:967 (1983)
2. J. H. Pitts, "Development of the Cascade Inertial-Confinement-Fusion Reactor", <u>Fusion Tech</u>. 8:1198 (1985).
3. A. J. Ladd and L. A. Glenn, Private Communication, Lawrence Livermore National Laboratory, September 1985.
4. N. J. Hoffman, Private Communication, Rockwell Internationl Energy Technology Engineer'ng Center, July 1985.
5. J. H. Pitts and D. R. Walton, "Granular Flow Along the Interior Surface of Rotating Cones", Lawrence Livermore National Laboratory Report UCRL-90742 (1984).

6. J. H. Pitts and O. R. Walton, "Layered Granule Chute Flow Near the Angle of Repose", Lawrence Livermore National Laboratory Report UCRL-91116 (1985).
7. W. R. Meier, "Neutron Activation in Cascade: The $BeO/LiAlO_2$ Blanket Case", Proceedings, 11th Symposium on Fusion Engineering, Austin, Texas, 1985 (to be published).
8. I. Maya, et al, Final Report under Lawrence Livermore National Laboratory Contract 2632605 with GA Technologies (to be published).
9. B. G. Logan, et al, "Mirror Advanced Reactor Study", Final Report, Lawrence Livermore National Laboratory Report UCRL-53480 (1984).

DISCLAIMER