DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

**PRIMARY HEAT TRANSFER LOOP DESIGN
FOR THE
CASCADE INERTIAL CONFINEMENT FUSION REACTOR**

K. A. Murray

M. W. McDowell

**Energy Technology Engineering Center
Rockwell International
Golden, Colorado 80401**

I. SUMMARY

A conceptual heat transfer loop for Cascade, a centrifugal-action solid-breeder reaction chamber,¹ has been investigated and results are presented. In the Cascade concept, a double-cone-shaped reaction chamber rotates along its horizontal axis. Solid Li_2O or other lithium-ceramic granules are injected tangentially through each end of the chamber. The granules cascade axially from the smaller radii at the ends to the larger radius at the center, where they are ejected into a stationary granule catcher. Heat and tritium are then removed from the granules, and the granules are reinjected into the chamber.

A 50% dense Li_2O granule throughput of $2.8 \text{ m}^3/\text{s}$ is transferred from the reaction chamber to the steam generators via continuous bucket elevators. The granules then fall by gravity through four vertical steam generators. The entire transport system is maintained at the vacuum conditions present inside the reaction chamber.

A granule size of 2 mm in diameter was determined by choosing the largest (for mixing reasons) of those sizes that have reasonable residence time constraints. Each resulting steam generator is 20 m high, 3.8 m in diameter, and has 18,000 tubes. The heat exchange area can be reduced if mixing within the steam generator can be increased.

Power balance calculations revealed a net electrical output of 1280 MWe to the busbar and a resulting net efficiency of 39%. Higher efficiencies can be obtained with fluidized-bed heat exchangers. This concept is being investigated in a companion study by GA Technologies.

II. INTRODUCTION

This study investigates a heat exchanger and balance of plant design to accompany the Cascade inertial confinement fusion reaction chamber concept.¹ The concept uses solid Li_2O or other lithium-ceramic granules, held to the wall of a rotating reaction chamber by centrifugal action, as a tritium breeding blanket and first wall protection. The Li_2O granules enter the chamber at 800 K and exit at 1200 K after absorbing the thermal energy produced by the fusion process.

A fixed power output of 3300 MWt and primary loop ΔT of 400 K results in a Li_2O throughput of 10^7 kg/h. At an assumed packing fraction of 0.5, the volumetric throughput is $2.8 \text{ m}^3/\text{s}$. Li_2O heat transfer properties used in this study are a heat capacity of $2890 \text{ J/kg}\cdot\text{K}$, thermal conductivity of 3.7 W/mK , and density of 1810 kg/m^3 . The latter two are for granules containing 10.3% internal voids.

The reaction chamber must be kept at the low vacuum conditions of 0.1 Torr pressure to allow laser beam propagation. In this analysis, the entire primary heat transport system is also maintained at that pressure. This avoids the problem of keeping vacuum conditions in one portion of the heat transport loop and pressurized conditions in another portion. It does, however, reduce the heat transfer effectiveness of the Li_2O granules. As an alternative, fluidized-bed heat exchangers can be used that increase the overall heat transfer coefficient. However, the design of a plant involving fluidized-bed heat exchangers is more complex: the granules must pass through a batch valve that separates the vacuum pressure reaction chamber from a holding tank where the pressure is near atmospheric.

The objective of this study is to provide results for a vacuum heat transport loop that can be compared with a fluidized-bed design. The more practical design will then be used with the Cascade reactor.

III. STEAM GENERATOR DESIGN

A vertical shell-and-tube steam generator incorporating double-wall tubes like those in the Westinghouse breeder reactor is used in this study. The Li_2O granules flow vertically downward past the tubes on the shell side. The double-wall design limits the migration of tritium from the granules into the water. The tubes have an outer diameter of 20.6 mm and an inner diameter of 11.1 mm. The heat-transfer coefficients through the tube wall and on the tube side have been measured by Westinghouse² as $5.7 \times 10^3 \text{ W/m}^2\cdot\text{K}$ and $1.4 \times 10^4 \text{ W/m}^2\cdot\text{K}$, respectively. Because of the high temperatures on the outside of the tube wall, 2-1/4 Cr - 1 Mo steel cannot be used for the tubes. However, Hastelloy C can withstand the temperatures and stresses for the plant lifetime.

A heat transfer coefficient between the granules and the tube walls was calculated from a correlation by Schlunder.³ The heat transfer is predominantly by thermal radiation, and the shell-side coefficient was found to be approximately $120 \text{ W/m}^2\cdot\text{K}$. However, the Schlunder correlation is for surface heat transfer only; if it is used for the entire bed, perfect mixing is implied. Because no real case involves perfect mixing, a mixing factor (or view factor) F is introduced:

$$h = Fh_s, \quad (1)$$

where h is the shell-side heat transfer coefficient. h_s is the surface heat transfer coefficient (approximately $120 \text{ W/m}^2\cdot\text{K}$), and F has a value between 0 and 1. In this analysis, two limiting cases can be defined: one of perfect mixing ($F = 1.0$) and one where no mixing is present and the granules travel by plug flow. In the plug flow case, F can be defined as

$$F = \frac{\text{cross sectional flow area of granules adjacent to tube wall}}{\text{cross sectional flow area of steam generator}} \quad (2)$$

Eq. 2 simplifies the plug flow case by assuming that only granules adjacent to the tube walls transfer heat. This highly conservative assumption will result in the maximum heat transfer surface area required.

Minimizing the steam generator cross sectional flow area maximizes the value of F in Eq. 2. However, the flow area must be large enough to accommodate the required volumetric flow rate. Rausch⁴ has proposed a correlation for gravity flow rate of solids through pipes and orifices, based on experimental results, that can be solved for the shell-side flow area needed to obtain a desired flow rate. The resulting steam generator shell-side flow area per tube for each granule size is shown in Figure 1.

To prevent granules from becoming wedged between other granules and forming a static bridge across a flow area, a common rule of thumb is that the diameter of the flow area should be approximately five to seven times the granule diameter.⁴ This ensures uninhibited granule flow. The rule applies to the shell side of the steam generator if the flow-area diameter is replaced by the hydraulic diameter. The minimum flow area to prevent bridging is also shown in Figure 1. For each granule size, the minimum shell-side flow area is the larger of the values yielded by the two correlations (shown by the dotted line).

Narrow horizontal crossbars are placed inside the steam generator on the shell side so that granules traveling around the bars will experience turbulence and mixing. In a steam generator, it is expected that mixing can be achieved halfway between perfect mixing and plug flow. The perfect mixing heat transfer coefficient has already been calculated as $120 \text{ W/m}^2\cdot\text{K}$. The plug flow coefficient can be found by determining the value of F from Eq. 2 for each granule size and inserting it in Eq. 1. The resulting heat transfer coefficients and steam generator parameters for each granule diameter are listed in Table 1.

Figure 1

Minimum Shell Side Cross-Sectional Flow Area
vs. Granule Diameter

Table 1. Summary of Steam Generator Parameters for Each Granule Size
(Assuming Four 20-m-high Steam Generators)

Parameter	Granule Diameter (mm)				
	0.1	0.2	1	2	10
Shell-side heat transfer Coefficient ($\text{W/m}^2\cdot\text{K}$)					
Perfect mixing	120	120	120	120	120
Plug flow	3.1	6.0	27.8	55.3	118
Average	61.6	63.0	73.9	87.7	119
Tube outer surface area (m^2)	33,000	32,300	27,800	23,300	17,300
No. of tubes	25,800	25,000	21,500	18,000	13,400
Steam generator diameter (m)	4.4	4.4	4.1	3.8	4.7
Residence time (s)	1.71	3.3	14.2	23.9	88.2
Interval between crossbars (m)	27.9	7.4	0.40	0.14	0.01

The steam tube outer surface area and number of tubes decreases with granule size because the heat transfer coefficient increases. The steam generator diameter decreases with granule size with the exception of the 10-mm size. At that diameter, the minimum shell-side flow area is determined by the bridging equation rather than the Rausch equation, which results in a larger shell-side flow area.

How long the Li_2O granules must stay in the steam generator to release enough heat increases with their size, as shown in Table 1. The granule flow rate can be selected to achieve the desired residence time by installing the appropriate number of crossbar rows. The crossbar interval for each granule size was calculated assuming that the granules fall freely between the crossbars and have zero velocity when they encounter a crossbar. A residence time of zero was assumed at each crossbar; i.e., when a particle hits a crossbar, it immediately begins the next free-fall. Crossbar intervals are also given in Table 1.

The 0.1-mm-diameter granule is not feasible, because the needed crossbar spacing is greater than the steam generator's height. This is because the velocity needed to obtain the desired residence time is greater than the average velocity attained in freefall from 20 m.

The 10-mm-diameter granule is also not feasible, because it requires crossbar intervals of 0.01 m, and the bars cannot be packed that closely. As a result, the desired granule size is between 0.2 mm and 2.0 mm. Because mixing can be obtained more easily with larger granules, the 2-mm size was chosen. It results in the smallest heat-transfer surface area of those granules with acceptable residence times.

IV. VACUUM PUMPING REQUIREMENTS

For a Cascade design having a burn fraction of 0.33, DT fuel is injected at a rate of 28 mg/s.⁵ A tritium-breeding ratio of 1.35 then results in a tritium pumping requirement of 3.1×10^{-3} g-mole/s. The pumping requirement for unburned deuterium is 1.9×10^{-3} g-mole/s. Helium is formed at 4.4×10^{-3} g-mole/s. A total of 9.4×10^{-3} g-mole/s needs to be pumped to retain a steady vacuum.

The reaction chamber pressure is to be kept at 0.1 Torr. Assuming that the maximum temperature of the gas is 1200 K (the temperature of the granules) and using the ideal gas law, a total volumetric flow rate of 6800 l/s is calculated. Because the gas needs to be discharged at atmospheric pressure, a primary pump system followed by a secondary and possibly a tertiary system is required.⁶

Turbopumps were chosen as primary pumps. They are used at the Tokamak Fusion Test Reactor (TFTR) and eventually will be used to pump tritium. Turbopumps are frictionless: the only energy losses are due to adiabatic compression. In comparison, Roots blowers have a high friction loss and use more power. Turbopumps with magnetic bearings are available that require no lubrication. They have maximum efficiency at 0.01 Torr and discharge at 1 Torr.

A good secondary-pump candidate is the scroll pump, a moving-spiral positive-displacement pump. Scroll pumps are being used at the Tritium System Test Assembly; they discharge at 100 Torr. For tertiary pumps to compress the air from 100 Torr to atmospheric pressure, metal bellows pumps can be used.

The total power to operate the vacuum system is about 0.1 MW.

V. SOLID GRANULE TRANSPORT SYSTEM

After the Li_2O granules are ejected from the reaction chamber, they are transported under vacuum conditions to the steam generator inlets, located 20 m above the chamber outlet. Several transport methods were investigated to determine the process with the minimum total power consumption and space requirement.

A. SUMMARY OF METHODS INVESTIGATED

Both carrying and noncarrying transport methods were analyzed. Noncarrying conveyors push material along by means of blades or scrapers; this usually leads to low efficiency and high power consumption. Carrying conveyors utilize belts or buckets to transport the material, and efficiencies tend to be higher.

Table 2 gives the number and size of conveyors needed to transport 10^7 kg/h of 50% dense Li_2O between the reaction chamber and the steam generators. For each case, the maximum possible inclination without slipping was used to minimize building size.

To avoid elevating either the reactor or the steam generators, it is necessary to have two sets of lifts: one to carry the granules up 20 m from the reaction chamber outlet to the steam generator inlets, and a second to carry the granules up 10 m from the steam generator outlets to the reaction chamber inlets. The power consumptions in Table 2 are based on the total 30-m elevation change for the two sets of lifts. With the exception of the Archimedes pump, the power consumptions were calculated from information given in the Standard Handbook for Mechanical Engineers.⁷

Table 2. Power Consumption and Size of Particle Transport Methods Investigated

Name	Type	Maximum Incline (deg)	Number of Conveyors/ Size	Power Consumption (MWe)
Flight conveyor	Noncarrying	40	100/1 m wide by 0.3 m high	3.4
Continuous flow elevator	Noncarrying	90	50/1 m wide by 0.3 m high	8.7
Screw conveyor	Noncarrying	35	330/1 m diam	5.0
Archimedes lift pump	Noncarrying	60	100/1 m diam	2.0
Continuous bucket elevator	Carrying	90	50/1 x 0.4 x 0.6 m buckets	1.7
Belt conveyor	Carrying	20	10/1 m wide	1.1

B. ARCHIMEDES LIFT PUMP

Of the noncarrying conveyors, the Archimedes lift pump has the lowest power consumption. This pump is a screw conveyor in which the outer case rotates with the screw. The granules advance along the screw by means of displacement by the granules below. The material is held in the screw by gravity, so there is a limit on the incline to keep the particles from sliding backward. In the Solase design,⁸ this inclination is 60°.

The power consumption of the Archimedes pump was scaled from the Solase design.⁸ The power is less than a conventional screw conveyor because there is less friction involved. An Archimedes pump also has less granule attrition than a conventional screw conveyor, which leads to a higher efficiency.

C. CONTINUOUS-BUCKET ELEVATOR

A continuous-bucket elevator is a carrying conveyor with the advantage of vertical path capability but a lower capacity than a belt conveyor. Its maximum speed is 0.5 m/s. A total of 25 1-m-wide elevators are needed in each set to lift 10^7 kg/h. The number can be reduced to four if the bucket size is increased. In this way, only one elevator feeds each steam generator.

D. BELT CONVEYOR

The belt conveyor has the lowest power requirement of the methods investigated and is the most widely used in the industry. It is limited to a maximum slope of 20° with loose free-flowing particulate material. This is a disadvantage in that the space requirement for the transport system is greater than for systems having a vertical carrying capability. However, a belt conveyor has a high volume capacity; its maximum speed for light, free-flowing material is 4.3 m/s. It also has low granule attrition.

E. COMPARISON OF TRANSPORT METHODS

The flight conveyor, continuous flow elevator, and screw conveyor were eliminated from consideration because of their high power consumptions. The continuous bucket elevator, Archimedes lift pump, and belt conveyor all have power consumptions below 2.0 MW. Of these three, the bucket elevator requires the least floor area (about 60% of the area required by belt conveyors) because it has vertical carrying capability. This results in the most compact transport system. A schematic of the transport system using bucket elevators is shown in Figure 2. Belt conveyors are required for the short distances between the reaction chamber and the elevators.

FIGURE 2
CASCADE SOLID GRANULE TRANSPORT SYSTEM

Rockwell International
Energy Systems Group

84-MA11-33-5

The elevators between the reaction chamber and the steam generator must operate at the Li_2O hot leg temperature of 1200 K, which is out of the range of conventional materials used in transporting solids. As an alternative, the reaction chamber can be elevated to a 20 m height so that the Li_2O travels directly from the chamber to the steam generators without a lift mechanism. In this case, the maximum operating temperatures of the elevators is only 800 K. The elevators must have a vacuum interior and be thermally insulated on the outside.

VI. BALANCE OF PLANT

The thermal energy extracted from the Li_2O granules is used to generate steam in a conventional LMFBR once-through steam cycle with reheat. The parameters for the cycle are a steam generator feedwater temperature of 530 K and a steam exit temperature of 750 K and pressure of $\frac{15.9}{14.9}$ MPa. The electrical conversion efficiency is approximately 43%. It is recognized that this cycle does not take advantage of the high Li_2O temperature to produce electricity at the maximum efficiency possible (i.e., with a gas-turbine cycle), but the shell-side heat transfer coefficient is so low under vacuum conditions that a low steam exit temperature is necessary to produce a reasonable heat transfer surface area. The use of fluidized-bed heat exchangers would raise the heat transfer coefficient, lower the required heat transfer surface area, and make high efficiency gas turbine cycles more feasible.

The power requirements for the primary heat transfer system in Cascade are lower than in most previous ICF reactor designs because of the low primary flow rate. The in-plant recirculated power requirement is 52 MWe. This value is based on an 1100-MW LMFBR design and the ratios to the plant gross thermal output used in the HYLIFE design, except for the vacuum system, Li_2O circulation, lead coolant system, and reactor rotation. This results in a 39% net efficiency. Inclusion of a gas-turbine cycle with steam bottoming and fluidized-bed heat exchangers could increase this net efficiency to 51%.

VII. CONCLUSIONS

The use of granular Li_2O in a vacuum as a primary heat transfer medium was found to be feasible. The design of reasonably sized steam generators for the plant is feasible, although uncertainties in granular heat transfer need resolution.

The bucket elevator was chosen as the granule transport method because of its vertical carrying capability and low power consumption. The construction material and operating method of an elevator at 1200 K needs to be determined.

The balance of plant produced a net efficiency of 39%, a value 1.2 times higher than HYLIFE. If fluidized-bed heat exchangers were used to boost the secondary fluid temperature, a Brayton cycle with steam bottoming could produce a thermal efficiency as high as 55%, leading to a net efficiency of 51% (1.5 times higher than HYLIFE). A companion study at GA Technologies is investigating the impact of this improvement on both plant cost and plant reliability.

Work supported by SANL 322-006 from Lawrence Livermore National Laboratory under their Prime Contract No. W-7405-ENG-48 with the Department of Energy.

VIII. REFERENCES

1. Pitts, John H., "Cascade: A Centrifugal-Action Solid-Breeder Reaction Chamber," Nuclear Technology Fusion, Vol. 4, No. 2, Part 2, p. 967-972, September 1983.
2. Waszink, R., Westinghouse BRCP, Pittsburg, PA, Private Communication, February 1983.
3. Schlunder, E.U., "Particle Heat Transfer," Proceedings of Seventh International Heat Transfer Conference, Munich, 1982.
4. Gardner, et. al, "Gravity Flow Rate of Solids Through Orifices and Pipes," Proceedings of the Conference on Coal Feeding Systems, Pasadena, California, 1977.
5. Duderstadt, J.J., and Moses, G.A., Inertial Confinement Fusion, John Wiley and Sons, New York, N.Y., 1982, p. 8.
6. Coffin, D., Los Alamos National Laboratory, Private Communication, June 1983.
7. Baumeister, T. and Marks, L. S., Editors, Standard Handbook for Mechanical Engineers, Seventh Edition, McGraw-Hill Book Company, New York, N.Y., 1967, p. 10-52 to 10-82.
8. Conn, R. W., et al, "Solase: A Laser Fusion Reactor Study," University of Wisconsin, Madison, WI, Report UWFD-220, 1977, p. XVII-B-4.