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Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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Nuclear Engineering Department
University of Wisconsin
Madison, Wisconsin 53706

* Babcock and Wilcox Company, Lynchburg, Virginia

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GRAVITY CIRCULATED SOLID BLANKET DESIGN FOR A TOKAMAK FUSION REACTOR

D. K. Sze, D. C. Schluderberg*, I. N. Sviatoslavsky

NUCLEAR ENGINEERING DEPARTMENT, UNIVERSITY OF WISCONSIN

*The Babcock and Wilcox Company, Lynchburg, Virginia

A blanket design based on a flowing Li_2O microspheres cooling breeding con-concept is presented. The flow characteristics, thermal performance and the power cycle system for this blanket are discussed. This design is based on the unique heat transfer feature of D-T reactors, namely that 80% of the heat is generated in the coolant. Therefore, a good thermal transport medium rather than a good heat transfer medium is needed as the coolant. By using gravitational flow of Li_2O as the coolant, it is possible to have a low pressure blanket with good breeding characteristics.

INTRODUCTION

The blanket of a D-T fusion reactor is the zone where the energy of the nuclear reaction is deposited. Therefore, a coolant must be used within the blanket to remove the thermal energy and transfer it to a power conversion unit. Since the primary object of any power station is to generate electric power, an efficient coolant scheme for the blanket is of major importance. In picking a coolant and the associated cooling scheme, the following constraints must be observed:

a. Compatibility with tritium breeding and recovery concepts
b. High operating temperature
c. Low system pressure
d. Simple and efficient blanket design
e. Efficient heat transport

Various cooling-breeding schemes are suggested for D-T tokamak type reactors. The breeding materials are either pure lithium or lithium compounds. The coolants most frequently used are lithium or helium. None of these combinations, unfortunately, are very satisfactory. A few of the possible choices of coolants, breeding materials and energy conversion systems, and the problems associated with each design are listed in Table 1.

The lithium compound used as the breeding material has frequently served the dual function of coolant and breeder. In such a blanket design, the cooling and tritium recovery loops are combined. The blanket design is thus simplified since only one set of feed/discharge pipes and headers is required. The effort needed to replace part of the blanket will also be reduced. However, if a lithium compound is used as the coolant, the heat transfer problem associated with the blanket is less conventional and an appropriate cooling scheme for the blanket must be developed.

If a lithium compound is used as the coolant, it will have to occupy about 95% of the volume of the blanket to maximize

Table 1. Coolants and Breeding Materials Used by Various Designs

System	Nature of Cooling	Breeding Material	Coolant	Intermediate Loop	Power Cycle	Problems
UWMAK-I(1	Direct	Li	Li	Na	Steam	T Recovery, MHD, Corrosion
UWMAK-II(2	Indirect	$LiAlO_2$	He	Na	Steam	Sintering, Be Resource, Energy Storage
UWMAK-III(3	Direct Indirect	Li -	Li He	Na -	He	T Recovery, Corrosion
ORNL(4	Indirect	Li	k-Vapor	-	k-Vapor	Advanced Technology, Energy Storage, T Recovery
PRD(5	Indirect	Flibe	He	-	Steam	Corrosion, Be Resource, High Circulation Power, Energy Storage
Brookhaven(6	Indirect	LiAl $LiAlO_2$ Li_7Pb_2	He	-	Steam	Be Resource, Sintering, High Circulation Power, Energy Storage

breeding. In such a system, around 80% of the heat is generated inside the coolant with the remaining 20% being deposited in the first wall and structure. Thus, if the first wall is separately cooled, there will not be a heat transfer problem associated with the blanket. Rather, there will be a heat transport problem, and most of the effort ordinarily devoted to obtaining good coolant heat transfer characteristics (resulting in a large h) is basically not needed. The real effort would be limited to selecting a coolant with good heat transport properties, namely, one which would have a high value of ρCp/ pumping power.

A gas carried-solid concept makes a very efficient heat transport system. A dense phase of Li_2O particles, for example, will provide excellent breeding and will not require a neutron multiplier like Be. If properly designed, such a system has the advantage of low pumping power and low pressure. The constraints for picking the coolant and breeding material listed above all appear to be satisfied.

Such concepts(7) and their neutronic and tritium considerations(8,9) have been presented previously. This paper discusses the mechanical and thermal-hydraulic design associated with such concepts.

BLANKET DESIGN AND PERFORMANCE

The reactor considered is UWMAK-III.(3) The blanket and power conversion systems have been redesigned. Plasma parameters, the basic shape of the blanket, the shield and magnet designs are unchanged. The major parameters of UWMAK-III are listed in Table 2 and a cross-sectional view of the reactor is shown in Figure 1.

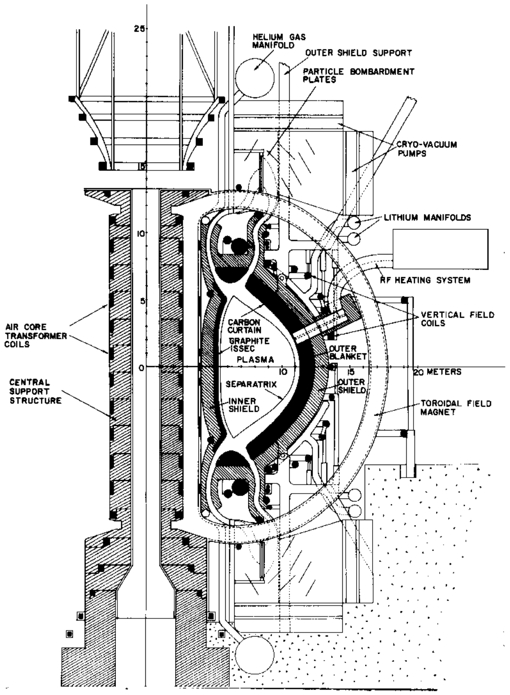
Table 2. Major Characteristics and Parameters of UWMAK-III

Fuel Cycle	(D-T), Li
Number of Toroidal Field Magnets	18
Magnet Superconductor	NbTi
Magnet Structural Material	Al Alloy, 2219T87
Maximum Magnetic Field	8.75T
On Axis Magnetic Field	4.05T
Plasma Dimensions	
Major Radius	8.1m
Half Width	2.7m
Height to Width Ratio	2
Plasma Shape	"Triangular D"
Plasma Current	15.8 MA
Impurity Control Method	Divertor + Low Z Liner
Plasma Heating Method	RF (Fast Wave - 60 MHz)
Burn Time	1800 sec
Duty Factor	0.947
Average Neutron Wall Loading	1.91 MW/m^2
Power Output During Burn	5000 MW(th)

a. Mechanical Design

A cross section of the reactor indicating the coolant flow is shown in Fig. 2. An isometric view of a blanket module with some construction details is shown in Fig.3. The blanket coolant consists of Li$_2$O microspheres moving by gravitational force at a pressure of 1 atmosphere. The blanket structural material is 316 stainless steel at a maximum design temperature of 650°C. The first wall coolant is low temperature boiling heavy water giving the wall a maximum temperature of 300°C. Graphite is used as a neutron reflector.

Since the driving force is gravitational, the flow pattern has to be once through top to bottom. The coolant to the blanket is supplied by a feed tube which fits through the opening between the TF magnets. A flow distribution plate, with openings of different sizes decreasing from the front to the back of the blanket, sets the proper velocity



CROSS SECTION VIEW OF UWMAK III

FIG. 2

CROSS SECTION VIEW OF A LIO$_2$
MOVING BED TOKAMAK

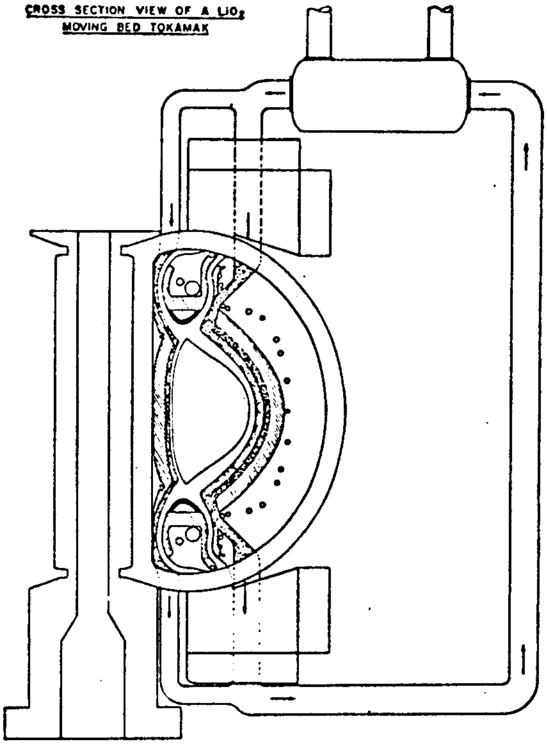
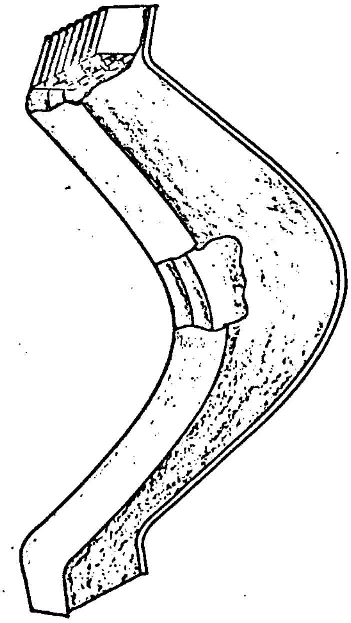


Figure 3

Li_2O MOVING BED TOKAMAK
BLANKET MODULE



distribution of the coolant, providing faster flow near the plasma than away from it. Layers of baffles are used to divide the blanket, such that the proper coolant velocity can be maintained through the coolant passages. The coolant is then discharged through a return tube which fits between the magnets on the bottom side of the reactor.

The water coolant passage for the first wall is parallel to the Li_2O flow. The first wall is made of 1 cm diameter tubes joined together. The maximum pressure of the water is 300 psi so that the stress in the first wall is relatively low. The first wall structure is protected from the plasma by a low Z liner.

The coolant discharged from the blanket then goes to a steam generator and a thermal storage tank. Circulation of the coolant is accomplished by a pneumatic transport system. The design and performance of the steam generator and the transport system will be discussed later in this paper.

b. Neutronic Performance

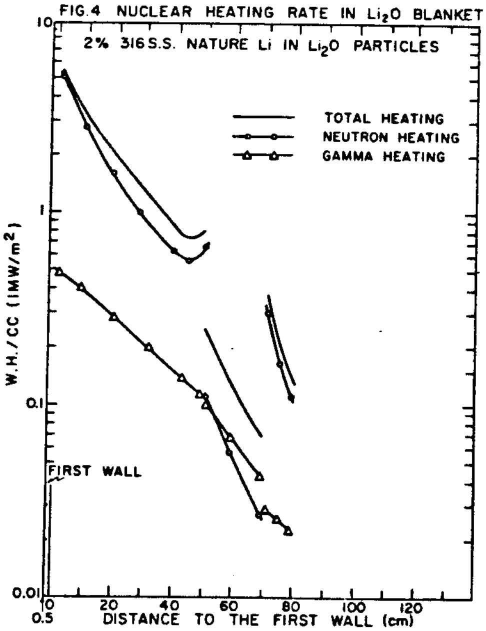
The results of neutronic calculations for a Li_2O blanket were reported by Cheng.(9) Table 3 summarizes some of the results of his calculations. The most important result is the high breeding ratio which is possible due to the unique neutronic characteristics of Li_2O. The total neutronic heating is only 14.97 MeV, compared to 18.17 MeV per fusion of UWMAK-III. This is due to the low structural fraction (2% 316 SS) made possible by the low pressure in the blanket. The energy leakage to the shield is 0.083 MeV out of 14.97 MeV, showing that the shielding effect of the blanket is adequate.

Table 3. Summary of Neutronics Results

Li_2O Density	31.3% Li_2O	60% Li_2O
T_6	0.7974	0.8289
T_7	0.3924	0.4267
Total Tritium Breeding Ratio	1.1898	1.2556
Neutron Heating	11.71	12.14
Gamma Heating	3.10	2.83
Total Heating	14.81	14.97
Neutron Energy Leakage to the Shield	0.126	0.083
Breeding Zone Thickness	54 and 6cm	32.4 and 6cm

Figure 4 shows the heat generation profile in the blanket. This is the input needed for the heat transfer calculation presented in the next section.

FIG.4 NUCLEAR HEATING RATE IN Li_2O BLANKET



c. Thermal Performance

Since the driving force for the Li_2O is gravitational, there is little lateral mixing of the coolant. Therefore, a flow distribution plate and baffles are used to control the velocity of the coolant as a function of distance from the first wall. This is necessary to offset the effect of the heat generation rate shown in Fig. 4. A high average exit coolant temperature can be obtained in this way.

The maximum coolant temperature is limited by the strength of the structural material. For 316 SS at low stresses, the maximum structural temperature can be 650°C. A maximum coolant exit temperature of 600°C is, therefore, picked. A coolant temperature rise of 200°C is used to achieve good steam conditions. A coolant velocity distribution which results in a more even coolant exit temperature is shown in Fig. 5. The coolant exit temperature, as shown in Fig. 6, is calculated by a finite difference method, with the thermal conductivity of the solid-gas mixture estimated from the results of Ref. 10.

Most power cycle designs for D-T fusion reactors need an intermediate loop.(1,2) The purpose of this loop is to prevent tritium from diffusing into the steam and/or to prevent a lithium-water reaction. In this design, the tritium diffusion through the primary heat exchanger is only 0.6 curie/day.(8) A Li_2O-water reaction caused by a leak in the steam generator is not hazardous. Therefore, an intermediate loop is not required. The elimination of the intermediate loop will have a significant impact on the economics of the system while at the same time providing better steam conditions.

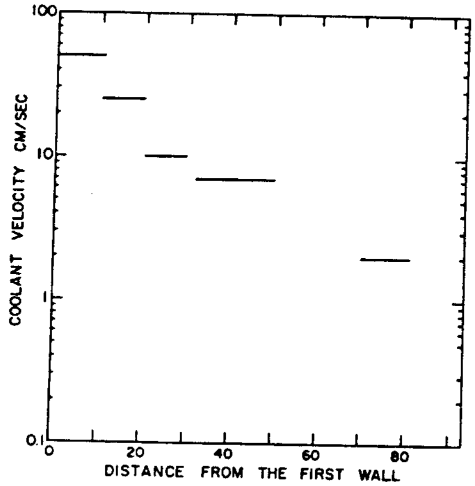


FIG. 5 COOLANT VELOCITY DISTRIBUTION IN THE BLANKET

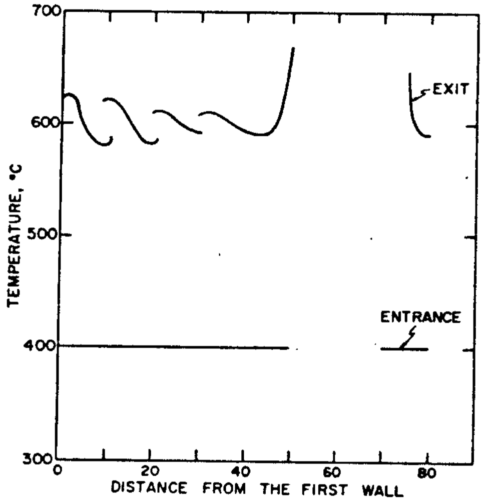


FIGURE 6 COOLANT TEMPERATURE

The first wall is separately cooled by boiling water. Its temperature is kept below 200°C to keep the water pressure low as well as to reduce the effects of radiation damage. The large temperature difference between the first wall and the blanket can be maintained because of the poor heat transfer characteristics of the Li_2O flow. This low temperature steam obtained from cooling the first wall is fed to a steam turbine.

The Li_2O particle size selected is a compromise between tritium diffusion, structural erosion, particle attrition, particle fabrication and material handling problems. The optimum particle size is between 100 to 200 μ. For a solid particle of this size at a velocity of $\leq$ 1 m/sec, structural erosion does not appear to be a serious problem.(11) Tritium recovery is possible if the solid particles are porous, such that the average diffusion length is on the order of .5 μ.(9)

The major parameters of the thermal performance of the blanket are summarized in Table 4.

Table 4. Blanket Thermal Hydraulic Parameters

First Wall	316 SS 5MM Thick
Structure	316 SS @ 2%
Coolant	Flowing Li_2O Microspheres
Coolant Pressure	1 ATM
Coolant Design	1.2 g/cm^3
Coolant Specific Heat	.431 cal/g-°C
Coolant Temperatures	400 to 600°C
Maximum Coolant Velocity	50 cm/sec
Coolant Flow Rate	4.2 x 10^7 kG/hr
Circulation Power Required	~40 MW
First Wall Coolant	Boiling D_2O
Max. First Wall Temp.	300°C
Max. Structure Temp.	650°C

d. Design Considerations for Pulsed Operation

A tokamak operates in a pulsed mode. This operation results in thermal cycling of the structure and the coolant. The cyclic temperature change in the blanket structure produces thermal fatigue, which should be minimized in a good blanket design. The time average reactor thermal output, however, has to be uniform so that input to the power conversion system is continuous. This usually necessitates a thermal storage unit.

Various designs(1,2,5) have considered thermal storage systems, usually in conjunction with an intermediate sodium loop. In the UWMAK-II design,(2) it was found that an intermediate loop was needed just for the purpose of thermal storage because the blanket was helium gas cooled. In this design, Li_2O is used for thermal storage. A mass of 8.4×10^5 kg of Li_2O is needed to supply the thermal energy during the plasma down time.

The problem of thermal fatigue has only been recognized. No system design has yet attempted to minimize the magnitude of the temperature change, nor has it determined the effect of this temperature cycling on the life of the structure.

The temperature cycling comes from two sources. The first source is the coolant temperature rise, $T_{out} - T_{in}$, which is on the order of 100°C. The second source is the temperature difference due to heat transfer through the structural wall, namely $\int(q/k)dx$, which is on the order of 10°C. It is, therefore, important to minimize the coolant temperature rise. Boiling water is used as the first wall coolant to make use of its latent heat such that the coolant temperature rise can be minimized. In the rest of the blanket, thermal cycling can be avoided by simply stopping the flow of Li_2O. Since its velocity is low, this can be easily accomplished. Thermal cycling in this blanket will be on the order of 10°C due to the cyclic behavior of the plasma, an order of magnitude less than in the UWMAK systems.

SOLIDS TRANSPORT SYSTEM

Gravity flow of Li_2O microspheres through the reactor and heat exchange equipment will, of course, require corresponding material lifts to complete the flow path in each loop of the nuclear steam supply system.

Figure 7 illustrates a nuclear steam supply system loop utilizing pneumatic conveying wherein the microspheres are carried by low pressure nitrogen in concurrent disperse phase flow. Alternate methods of conveying are dense phase mass lift as defined in Ref. 12 or by mechanical means. Choice of the best method of conveying will require further study with the objectives of minimizing cost, pumping power, particle attrition and equipment maintenance.

In the reference tokamak design the total Li_2O microsphere flow rate of 4.2×10^7 kg/HR is assumed to require two lifts of 25 meters each, giving a total work input of 5.19 MW. Preliminary estimates of pumping power requirements by each of the three conveying methods mentioned above are tabulated below:

Carrying Methods	Approximate Pumping Power (MWe)
Pneumatic-Disperse Phase Flow	36.5
Pneumatic-Mass Life	50.6
Mechanical	10.6

These values include a reasonable contingency plus allowance for fan, motor and conveyor losses and use available data considered at least roughly applicable. In each case, the total pumping power requirement seems acceptable for a plant producing 1790 gross MW_e.

STEAM GENERATORS AND REHEATER DESIGN CONSIDERATIONS

The free-flowing characteristics of Li_2O microspheres provides an opportunity to obtain better heat transfer coefficients than normally provided by fluidized bed techniques. Such geometrics are designed to thoroughly mix the microspheres as they pass over the heating surface. Table 5 summarizes the expected heat transfer characteristics.

Figure 7

SKETCH SHOWING GENERAL ARRANGEMENT OF
MOVING BED NSS LOOP
FOR TOKAMAK REACTOR

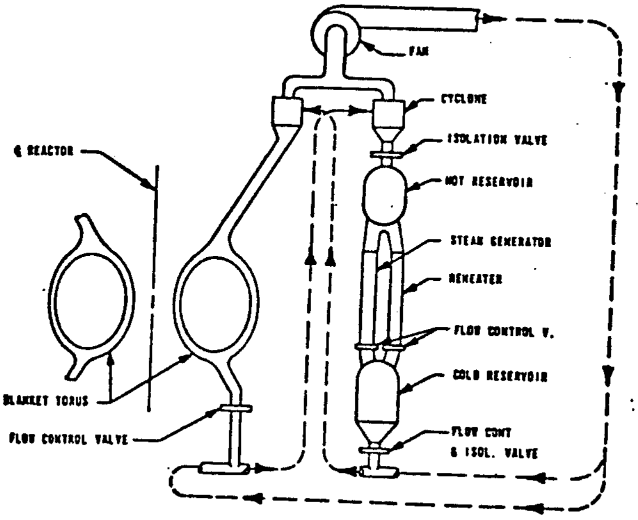


Table 5. Estimate of Flowing Bed Heat Transfer

A. Heating Surface Based on H_B = 125
B. Rough Conservative Calculation H_B = 157
C. Glass Microsphere Flow Expt. u = 1.5 Centipoises(13)
D. Static Bed Thermal Cond. K = .171 BTU/HR °F FT (11)
E. RE = 2057 P_R = 9.77 (Cp = .4607)
F. NU = 74.8(14)

A candidate steam generator design, Fig. 8, utilizes 1"OD horizontal tubes in a staggered array with flow control baffles after each 8 rows to minimize voids and maintain a uniform flow rate over the tubes. Design parameters are listed in Table 6:

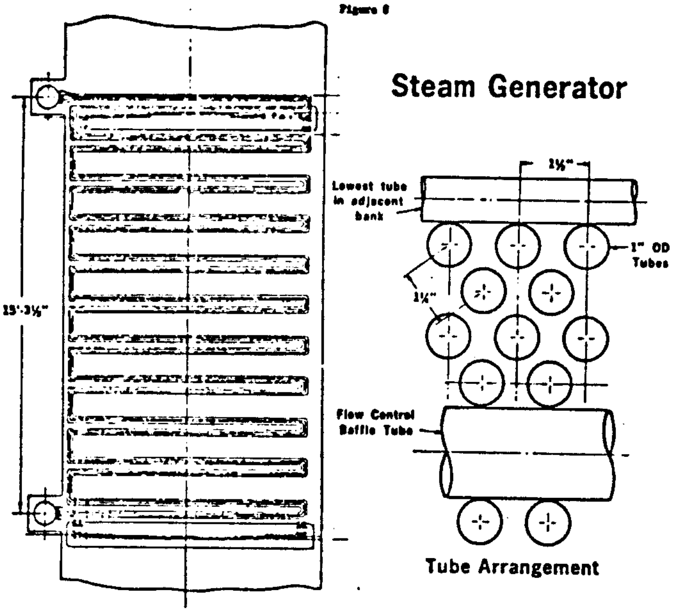
Table 6. Steam Generator Parameters

MWT	188.84
Steam Flow ∿ LB/HR	653,728
Heating Surface ∿ FT^2	38,000
Li_2O Flow ∿ LB/HR	4.143×10^6
Li_2O Velocity Past Tubes ∿ FT/SEC	.49
Tube OD/Material	1.00/Cr. Steel
S. G. Type	Once Thru
FT^2/KWE (SG + RH)	.49

The value of .49 FT^2 of heating surface per KWe is about equal to that found in large fossil fired utility steam power plants.

A candidate reheater design shown in Fig. 9 contains vertical tubes with studs attached thereto to provide the mixing action needed to extract heat from the flowing bed of Li_2O particles. Reheater design parameters are shown in Table 7:

Figure 8

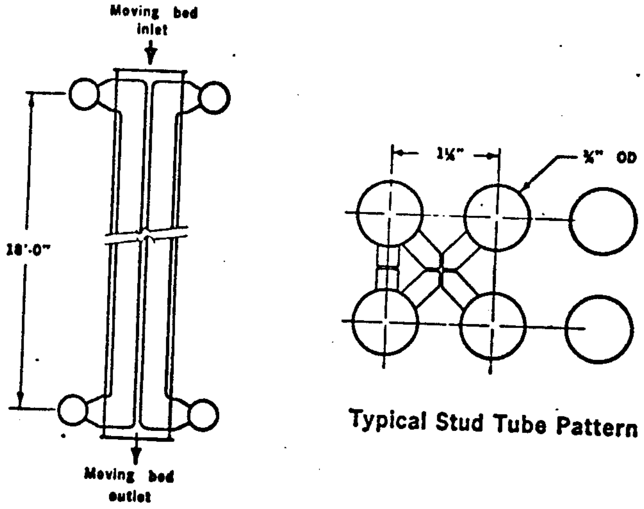


Steam Generator

Tube Arrangement

Figure 9

General Arrangement of Reheater



Typical Stud Tube Pattern

Table 7. Reheater Parameters

MWT	34.21
Steam Flow ∿ LB/HR	567,810
Heating Surface ~FT^2	8640
Li$_2$O Flow ∿ LB/HR	761,520
Li$_2$O Velocity Past Tubes ∿ FT/SEC	.5+
Inlet/Outlet Steam Temperature ∿ $^{\circ}$F	635/1000
Inlet/Outlet Steam Press ∿ PSIA	606/545
Inlet/Outlet Li$_2$O Temp. ∿ $^{\circ}$F	1112/752

+Vertical Component

The steam generator and reheater designs shown in Figs. 8 and 9 will be contained in cylindrical welded casings (not shown) to assure adequate system leak-tightness. Nitrogen gas between casings will be monitored to detect tube to header joint leaks. Low alloy steels appear suitable throughout these units for tubes, casings, supports, etc.

NUCLEAR STEAM SUPPLY SYSTEM DESIGN CONSIDERATIONS

Distinguishing features of this system (See Fig. 7) are listed below:

a. No intermediate coolant loop
b. Provision for continuous steam generation uninterrupted by reactor down time between "burns" - Li$_2$O heat storage
c. Low system loop pressure (not exceeding 60 psig)
d. Utilizes flowing bed and particle transport technology developed in other fields.

Principal NSS parameters are shown in Table 8. The Li$_2$O flow shown is the average flow thru steam generators and reheaters. Low alloy steels in piping and components in combination with a 2400 psi 1000°F steam cycle with 1000°F reheat correspond with current fossil fired central station practice - thereby providing a sound basis for attractive economics and reduced engineering development costs.

Table 8. NSS Parameters

Avg. Blanket Power ∿ MWT	4023.5
Gross MWE	1704.0
Li_2O Flow ∿ KG/HR	4.0×10^7
T_H/T_C ∿ $^{\circ}$C	600/400
Steam Cond.	2500 psi, 1000 $^{\circ}$F/ 1000 $^{\circ}$F
Steam Flow ∿ LB/HR	11.757×10^6
Feed Temp. ∿ $^{\circ}$F	484
No. Loops	18

CONCLUSIONS

A preliminary blanket design utilizing gravitational flow of Li_2O as the coolant-breeding material has been presented. This is the third paper in a study which has included neutronic calculations (9) and tritium recovery considerations (8). This cooling scheme is feasible because of the unique heat transfer characteristics associated with a fusion reactor blanket, the most important of which is that 80% of the thermal energy is deposited in the coolant. Therefore, good coolant heat transfer characteristics are not required.

This study shows that many serious problems faced by blanket designers can be alleviated. The low pressure blanket results in lower stresses and requires less structural material, which is important neutronically. The elimination of an intermediate loop reduces the cost and improves the steam conditions. The reduction of thermal fatigue improves the reliability of the structure and prolongs its life. The power conversion system can be designed using present day technology. In previous papers, we have shown that the design can breed tritium without a neutron multiplier and tritium recovery is feasible. It is, therefore, felt that this design concept can have a major impact on reliability, safety, economics and material resources.

As with any new concept, there are many problems to be solved. The diffusion of tritium through Li_2O is the most uncertain area, since no information is available. Other problems to be solved are listed in Table 9. The investment required to establish the feasibility of this approach, however, is very small compared to the potential advantages that can be gained.

Table 9. Areas to be Investigated

1. Flow Characteristics of a Moving Li_2O Bed
2. Blanket Design Problems for Abnormal Conditions
3. Li_2O Pellet Fabrication
4. Tritium Diffusion and Recovery Studies
5. Thermodynamics of $Li_2O + H_2O$ System
6. Corrosion
7. HX Design
8. Solid Circulation
9. Erosion
10. Attrition

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