UCRL-91646
PREPRINT

CONF-850310--61

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This paper was prepared for submittal to the 6th ANS Topical Conference on Technology of Fusion Energy held in San Francisco, California on March 3-7, 1985.

February 28, 1985

M85010002

UCRL--91646

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BLANKET OPTIMIZATION STUDIES FOR CASCADE*

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ABSTRACT

A nonlinear, multivariable, blanket optimization technique is applied to the Cascade inertial confinement fusion reactor concept. The thickness of a two-zone blanket, which consists of a BeO multiplier region followed by a $LiAlO_2$ breeding region, is minimized subject to constraints on the tritium breeding ratio, neutron leakage, and heat generation rate in Al/SiC tendons that support the chamber wall.

INTRODUCTION

A nonlinear, multivariable method for optimizing the design of a fusion reactor blanket has been developed and is described in Refs. 1 and 2. The optimization method is based on successive application of two-point variational interpolation[3]. With this method, the blanket neutronic performance can be estimated as a function of n blanket design variables based on the results of 2^n reference point neutron transport calculations. A direct search, nonlinear optimization algorithm is then used to minimize the figure of merit subject to constraints on the design. The figure of merit and constraints can be any function of the design variables and resulting neutronic performance.

In this paper, the optimization method is applied to Cascade, an inertial confinement fusion reactor concept. The primary feature of Cascade is a rotating chamber in which a cascading blanket of solid lithium ceramic granules breeds tritium, acts as the heat transfer medium, and protects the chamber wall from the damaging effects of neutrons, x-rays and target debris.[2,3] Granules are injected at each end of the chamber, and are held against the wall by centrifigal action. The granules cascade toward larger radii, then are removed and sent to heat exchangers. Heat and tritium are extracted, and the granules are recirculated to the chamber.

As originally reported,[4] the solid breeding material used in Cascade was Li_2O. While Li_2O is a good tritium breeding material, there are some concerns about the corrosive effects of LiOH which is formed from Li_2O. From a compatibility standpoint, a more attractive ceramic tritium breeding material is $LiAlO_2$. Unfortunately, $LiAlO_2$ will not give a tritium breeding ratio greater than one unless a neutron multiplier is placed between the fusion neutron source and the $LiAlO_2$ breeding blanket.

DESCRIPTION OF THE PROBLEM

In this optimization problem, a Cascade chamber using a $LiAlO_2$ breeding blanket and a BeO neutron multiplier is investigated. Beryllium is an excellent neutron multipiier with a threshold of only 1.85 MeV. Beryllium oxide is proposed here to allow for high temperature operation, which is one of the goals of the Cascade concept. A flowing layer of BeO granules can be maintained on the surface of the $LiAlO_2$ blanket by fabricating the BeO larger and less dense than the $LiAlO_2$ granules.

Three blanket design variables are considered in the Cascade optimization problem. They are

x_1 = ^{6}Li fraction in Li,

x_2 = $LiAlO_2$ blanket thickness, m, and

x_3 = BeO multiplier thickness, m.

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

FIGURE OF MERIT FOR CASCADE

The figure of merit chosen for this design is simply the sum of the $LiAlO_2$ blanket thickness and the BeO multiplier thickness. That is, we seek to minimize

$$F = x_2 + x_3. \qquad (1)$$

At this stage in the development of the Cascade concept, it is not possible to optimize a more general system parameter, such as the cost of electricity, since costestimates for the reactor plant have not yet been made. By minimizing the total blanket thickness (the multiplier is considered part of the blanket) the size of the rotating chamber can be minimized. The inner radius of the blanket is assumed to be fixed by the damaging effects (ablation and vaporization) of the x-rays and target debris.

CONSTRAINTS ON THE DESIGN

Three constraints are imposed on the Cascade design. The first is a requirement for a tritium breeding ratio greater than 1.05. This constraint is expressed as,

$$T \geq 1.05. \qquad (2)$$

The second constraint relates to the mechanical design of the Cascade chamber. GA Technologies has proposed a concept where the rotating chamber is constructed of individual SiC panels held together by Al tendons.[5] The Al tendons are actually a composite of Al and SiC fibers to increase tensile strength of Al. Based on a temperature limit of 400°C for the tendons, the heat generation rate in the tendons due to neutron and gamma heating must be less than 0.85 W/cm^3. The second constraint is

$$G \leq 0.85\ W/cm^3. \qquad (3)$$

A third constraint is placed on the total neutron leakage rate from the Cascade chamber. This parameter gives an indication of the effectiveness of the blanket design in performing one of its primary functions, namely, capturing the fusion neutrons. The beam ports at the ends of the Cascade chamber provide a direct leakage path from the chamber. The two ports subtend 1.25% of the total solid angle. The neutron leakage through the ports, however, will be greater than 1.25% of the fusion neutron source. There will also be some neutron leakage through the $LiAlO_2$ blanket itself. The constraint on the total neutron leakage is set at 0.1 neutrons per DT reaction. That is,

$$L \leq 0.1. \qquad (4)$$

REFERENCE POINT NEUTRONICS CALCULATIONS

The neutronics model of the Cascade chamber is shown in Fig. 1. The double cone shaped chamber is approximated by a sphere. The 14.1 MeV neutron source is uniformlydistributed throughout a region of DT compressed to a density-radius product of 3.0 g/cm^2. The target, zone 1, is located at the center of the chamber. The region between the target and the blanket is void.

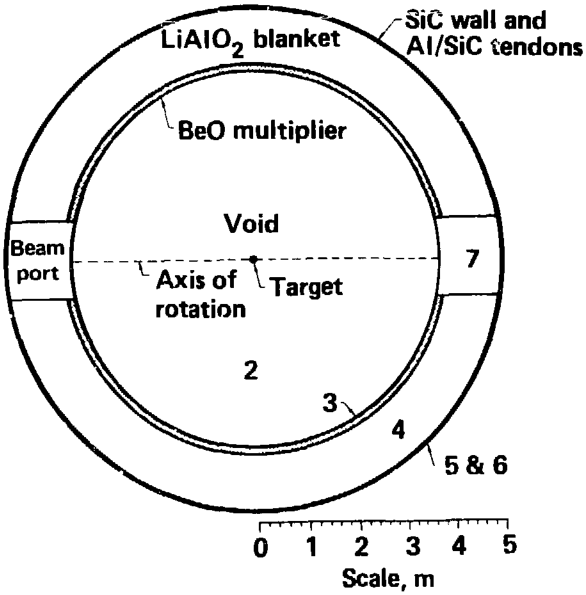

Fig. 1 Neutronics model of the Cascade chamber.

The innermost blanket region, zone 3, contains the BeO neutron multiplier. This zone is 0.1 m thick and has an inner radius of 3.4 m. The density of BeO within zone 3 is varied to represent variations in the effective multiplier thickness, x_3. The $LiAlO_2$ breeding blanket, zone 4, extends from a radius of 3.5 to 4.5 m. Again the material density is varied to represent variations in the breeding blanket thickness, x_2. The ^6Li fraction of lithium in this zone is the third design variable, x_1. The two beam ports are represented by cylindrical voids in the blanket. The radius of these holes is 0.72 m so that the solid angle fraction subtended at the outer edge of the blanket is 1.25%.

Outside the breeding blanket is a 2-cm-thick shell, zone 5, of SiC representing the chamber wall. This is followed by a

Table 1. Results of reference point neutronic calculations

Reference point	1	2	3	4	5	6	7	8
BeO thickness, m	0.05	0.05	0.05	0.05	0.15	0.15	0.15	0.15
$LiAlO_2$ thickness, m	0.30	0.30	0.50	0.50	0.30	0.30	0.50	0.50
^6Li Fraction, %	7.42	50.00	7.42	50.00	7.42	50.00	7.42	50.00
Reactions[a]								
$^6Li(n,T)\alpha$	0.797	0.948	0.999	1.100	1.158	1.217	1.263	1.276
$^7Li(n,n'T)\alpha$	0.070	0.038	0.075	0.040	0.023	0.012	0.023	0.012
Be(n,2n)	0.269	0.266	0.264	0.267	0.562	0.569	0.561	0.556
Neutron balance[a]								
Target	1.057	1.056	1.055	1.057	1.052	1.051	1.061	1.057
BeO	0.189	0.188	0.187	0.184	0.321	0.318	0.325	0.315
$LiAlO_2$	-0.893	-1.046	-1.104	-1.179	-1.179	-1.252	-1.290	-1.305
Port leakage	-0.046	-0.033	-0.043	-0.030	-0.057	-0.051	-0.056	-0.050
Blanket leakage	-0.303	-0.161	-0.094	-0.031	-0.136	-0.065	-0.039	-0.016
Remainder	0.004	0.004	0.001	0.001	0.001	0.001	0.001	0.001
Energy deposited[a], Mev								
Target	1.80	1.85	1.85	1.83	1.81	1.83	1.84	1.83
BeO	3.05	3.02	3.06	3.03	6.89	6.82	6.94	6.82
$LiAlO_2$	9.19	9.98	10.77	11.28	7.77	7.91	8.36	8.38
SiC wall	0.11	0.11	0.03	0.02	0.05	0.04	0.01	0.01
Tendons	0.059	0.059	0.013	0.014	0.026	0.024	0.007	0.006
Port leakage	0.20	0.20	0.19	0.18	0.21	0.20	0.18	0.19
Blanket leakage	0.66	0.65	0.14	0.13	0.28	0.26	0.06	0.06

[a] per DT reaction

2-cm-thick region, zone 6, that contains the Al/SiC fiber composite and represents the tendons. The heat rate in the tendons is calculated from,

$$G = E_t P_f / 17.6 V_t, \qquad (5)$$

where E_t = energy deposited in zone 6, MeV per DT reaction, P_f = the fusion power, W, and V_t = volume of zone 6, cm^3. Since the volume of zone 6 is 5.09×10^6 cm^3, the heat rate in the Al/SiC tendons for 3000 MW of fusion power is equal to 33.5 E_t.

Since there are 3 blanket design variables, eight reference point transport calculations are required for the Cascade chamber optimization problem. The eight points are defined by the combinations of two values for each of the three design variables. The reference values for the design variables are ^6Li fractions of 7.42 and 50%, $LiAlO_2$ blanket thicknesses of 0.30 and 0.50 m, and BeO multiplier thicknesses of 0.05 and 0.15 m.

The results are given in Table 1. Listed are the reaction rates, the neutron balance and the energy deposition per DT reaction. The neutron balance gives the net neutron gain or loss in the various regions of the chamber. The small remainder is the neutron capture in the SiC wall and Al/SiC tendons.

ESTIMATED NEUTRONIC PERFORMANCE

The neutronic performance is estimated as a function of the three design variables by successive, two point variation interpolation. In particular, the constraints on the tritium breeding ratio, the tendon heat generation rate, and the total neutron leakage must be determined. These three constraints are shown as a function of the ^6Li fraction and the $LiAlO_2$ blanket thickness for 0.05 m of BeO in Fig. 2. The hash marks are on the unacceptable side of the constraint lines.

The tritium breeding ratio increases with increasing ^6Li fraction and with increasing blanket thickness. To meet the constraint of $T \geq 1.05$ with a 0.05-m-thick BeO multiplier requires a $LiAlO_2$ blanket thickness greater than ~0.37 m if the Li is enriched to ~40% ^6Li. With a 0.15-m-thick BeO multiplier (not shown here), the tritium breeding ratio exceeds the minimum required value of 1.05

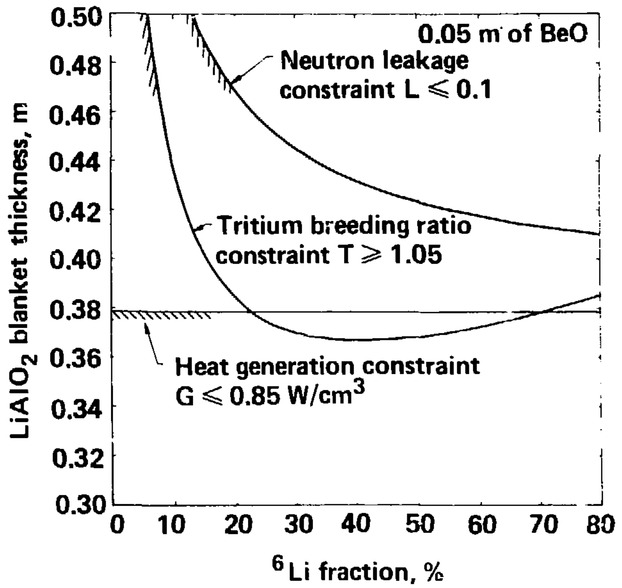

Fig. 2 Three constraints as a function of ^6Li fraction and $LiAlO_2$ thickness with 0.05 m of BeO.

over the entire range of ^6Li fractions and $LiAlO_2$ blanket thickness except for thin blankets (~0.3m) with denatured Li; i.e., less than ~3% ^6Li.

As indicated in Table 1 the energy deposition in the Al/Sic tendons is independent of the ^6Li fraction. The heat generation rate decreases as the thickness of either region increases. To keep the heat rate below 0.85 W/cm^3, the required $LiAlO_2$ thickness is ~0.38 m with 0.05 m of BeO. The required thickness decreases with increasing BeO thickness to ~0.30 m with 0.15 m of BeO.

The neutron leakage is calculated from a neutron balance with the net gain in the BeO region and the net absorption in the $LiAlO_2$ blanket being estimated by successive two point interpolation. That is

$$L = 1.056 + N_g - N_a, \qquad (6)$$

where N_g = net neutron gain in BeO, and N_a is the net neutron absorption in $LiAlO_2$. The factor of 1.056 is the number of neutrons emitted by the target per DT reaction. It exceeds one because of (n,2n) reactions with D and T in the compressed fuel zone.

The leakage decreases with increasing ^6Li fraction and with increasing blanket thickness since in both cases more neutrons are captured by ^6Li as these variables increase. With a 0.05-m-thick BeO multiplier and with the Li enriched to 80% in ^6Li, a 0.41-m-thick blanket is required to keep the neutron leakage below 0.1 per DT reaction. With a 0.15-m-thick BeO multiplier,the neutron leakage is lower. In this case, the minimum required breeding blanket thickness decreases from ~0.49 m with natural Li to ~0.33 m with Li enriched to 80% ^6Li.

It is desirable to find the minimum value of the $LiAlO_2$ thickness such that for a given BeO thickness, the figure of merit, $x_2 + x_3$, is minimized by selecting the minimum $LiAlO_2$ thickness. As seen in Fig. 2, for 5 cm of BeO, neutron leakage is the limiting constraint over the entire range of ^6Li fractions. Similar figures are shown for 0.10 and 0.15 m of BeO in Ref. 1.

OPTIMAL DESIGN POINT

The direct search algorithm gives the optimal design point as 63.6% ^6Li, 0.397 m of $LiAlO_2$ and 0.040 m of BeO.[1] This result is shown graphically in Figs. 3 and 4. Figure 3 shows the minimum blanket thickness as set by the neutron leakage constraint and the heat generation constraint as a function of the BeO thickness. Note that the neutron leakage constraint goes through a maximum at ~9 cm of BeO. This rise and fall in the required blanket thickness is related to the two modes of neutron leakage. As indicated in Table 2, increasing the BeO thickness increases the neutron leakage through the ports and decreases the blanket leakage. In some cases, the increase in port leakage can exceed the decrease in blanket leakage. As a result a thicker breeding blanket is required to maintain a constant total leakage rate of 0.1 per DT reaction.

For less than 0.04 m of BeO the heat generation rate is the limiting constraints. Between 0.04 and 0.16 m of BeO, neutron leakage is the limiting constraint. Beyond 0.16 m, the $LiAlO_2$ blanket thickness is again limited by the heat generation rate. The tritium breeding constraint, which is not shown, only comes into play as the BeO thickness approaches zero.

Also shown in Fig. 3 is the figure of merit; i.e., the total blanket thickness. Note that there are two local minima, one at 0.04 m of BeO and the other at 0.16 m. The minima at 0.04 m however, is the lower of the two.

The constraints as a function of the ^6Li fraction and the $LiAlO_2$ thickness are shown in Figure 4 for the optimal 0.04 m of BeO. Note again how the optimal design point lies at the intersection of the neutron leakage and heat generation rate constraints. Clearly higher ^6Li enrichments give the same

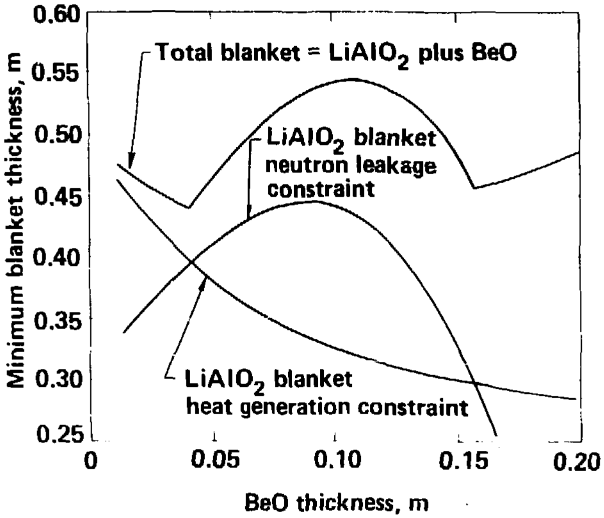

Fig. 3 Minimum blanket thickness as a function of BeO thickness. The lower curves show the minimum $LiAlO_2$ thickness as set by the neutron leakage and heat rate constraints. The top curve is the total blanket thickness including the BeO thickness.

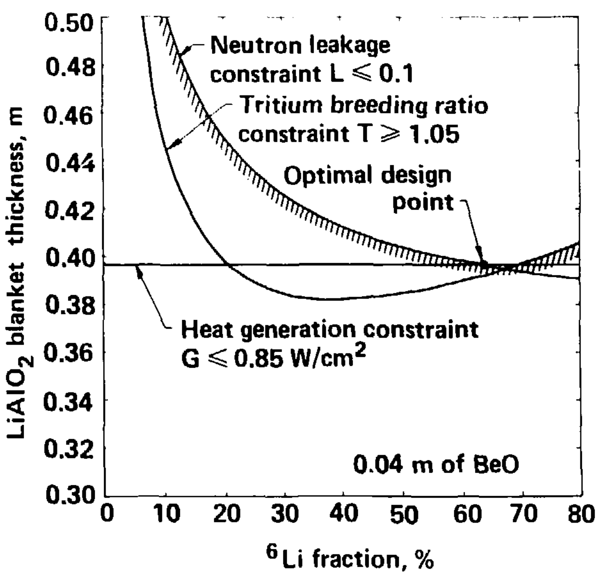

Fig. 4 First estimate of the location of the optimal design point. The point lies at the intersection of the neutron leakage and heat generation rate constraints.

minimum thickness since the heat rate is independent of this variable. The minimum acceptable ^{6}Li fraction, 63.6%, is chosen from a resource consideration.

Comparison to transport calculation at the optimal point.

An additional neutron transport calculation was carried out at 63.6% ^{6}Li, 0.40 m of $LiAlO_2$ and 0.04 m of BeO. We found that the estimated tritium breeding ratio was ~3% higher than the TART result and the estimated neutron leakage was low by ~6%. While these are acceptable differences, heat generation rate in the Al/SiC tendons given by the new TART calculation was 22% higher than the estimated result. This difference is largely due to the fact that a significant fraction of the energy deposited in the Al/SiC tendons is photon energy that originates in the $LiAlO_2$ blanket.[1] The variational interpolation formula used to predict the energy deposition in the tendons only accounts for variations in the neutron flux in that region. It does not account for variations in the photon source in adjacents region and the transport of those photons into the tendons.

An alternate approach is therefore used to estimate the heat rate in the tendons as a function of the BeO and $LiAlO_2$ blanket thicknesses. It is assumed that the heat generation rate decreases exponentially with the thickness of BeO and with the thickness of $LiAlO_2$. Using the energy deposition results given in Table 1, we get

$$E = 0.827 \exp(-7.37x_2) \exp(-8.59x_3). \quad (7)$$

Using this expression, the predicted energy deposition for the optimal design point of x_2 = 0.40 m and x_3 = 0.04 m is 0.031 MeV or 1.03 W/cm^3. This is exactly the same as the TART result at that point.

The optimization problem was rerun, using the exponential estimate for the heat generation rate in the tendons. The optimal design point in this case is 34.2% ^{6}Li, 0.424 m of $LiAlO_2$, and 0.042 m of BeO. The constraints and location of the optimal design point for this case are shown in Fig. 5.

A final transport calculation was carried out at the new optimal point. The results are compared to the estimated results in Table 2. In this case the agreement is close for all the relevant parameters.

SUMMARY

The Cascade chamber can be designed with a $LiAlO_2$ breeding blanket if a BeO neutron multiplier is used. The configuration that minimized the total blanket thickness is

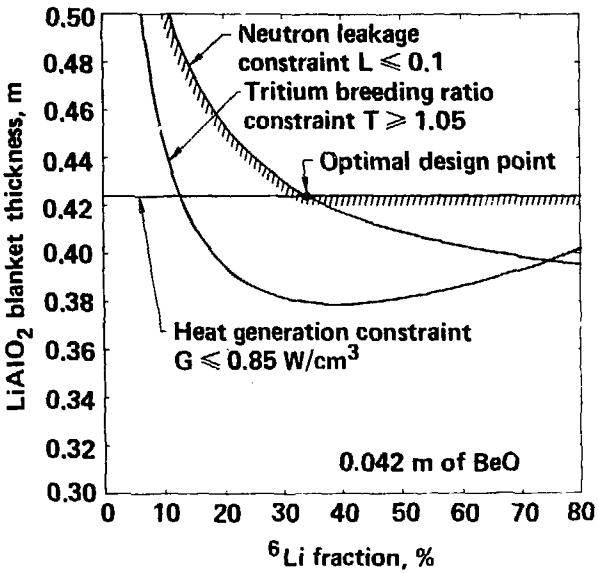

Fig. 5 Final estimate of location of optimal design point.

Table 2. Comparison of neutronic performance at $x_1 = 34.2\%$, $x_2 = 0.424$ m, and $x_3 = 0.042$ m.

Parameter[a]	TART	Estimated
$^6Li(n,T)\alpha$	1.019 (1.0)[b]	1.029
$^7Li(n,n'T)\alpha$	0.040 (1.1)	0.057
Tritium breeding ratio	1.059	1.086
Total neutron leakage	0.097 (3.7)	0.100
Energy deposited in tendons, MeV	0.024 (3.0)	0.025

[a] per DT reaction.
[b] percent standard deviation.

0.042 m of BeO followed by 0.424 m of $LiAlO_2$. The Li must be enriched to at least 34.2% in ^6Li. Since the blanket is a granule bed, the actual thickness is the effective thickness divided by the granule packing fraction. Assuming a 50% packing fraction gives an actual total blanket thickness of 0.93 m.

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