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MASTER

FUSION BLANKETS FOR HIGH EFFICIENCY POWER CYCLES

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APRIL 1980

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INFORMAL REPORT

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INTRODUCTION

To achieve high efficiency in a thermal power cycle, high coolant temperatures are necessary; in general, the higher the temperature available, the higher the efficiency of the cycle. The operating temperatures of conventional structural materials such as austenitic stainless or ferritic steels are limited to approximately 500°C, which corresponds to a maximum cycle efficiency of about 40 percent. Coolant temperatures above 500°C are possible, however, using either of the following approaches:

1. A structural material with higher temperature capability can be used (e.g., a refractory metal like molybdenum (TZM) or niobium).
2. The blanket can be designed to be a "two temperature zone" blanket in which the structural material and first wall operate at a much lower temperature than the bulk of the blanket. The former approach requires either a liquid metal (or vapor) coolant or an inert gas coolant. Structural strength considerations limit the maximum temperature to ~ 800 to 1000°C, depending on choice of coolant and blanket design. In the two temperature approach, first proposed by BNL⁽¹⁾ for minimum activity blankets, the high energy (14 MeV) neutrons from the DT fusion reactions penetrate deeply and deposit their energy over the volume of the blanket, rather than on the first wall. If a thermally insulating layer is placed between the hot interior and the cooler structural shell of the blanket module, heat can be extracted at two different temperature levels by separate coolant streams for the interior and structural shell.

In general, the temperature available in the coolant from the hot interior will be limited by the corrosion/erosion behavior of the interior material in the coolant and not by structural stress considerations. With inert gas coolants (e.g., He or A) and refractory interiors (e.g., graphite, oxides, or carbides),

it appears possible to achieve coolant temperatures up to 2500°C. With more reactive coolants (e.g., steam or potassium vapor) accompanied by the use of a refractory metal structure, maximum coolant temperatures will be somewhat lower, though they can still be very high. For example, materials experiments with steam coolant have been carried out at BNL as part of a development program on high temperature blankets for synfuel applications⁽²⁾, and indicate that coolant temperatures of at least 1500°C are practical using either ZrO_2 or Al_2O_3 . In fact, higher operating temperatures may be possible with yttria stabilized ZrO_2 , judging from tests on this material in high temperature wind tunnels.

The mode of tritium breeding will also affect the temperature capability of two-zone blankets. The temperature capabilities discussed above assume that there is no tritium breeding in the hot interior of the blanket (though breeding could be carried out in the low temperature shell). If tritium breeding takes place in the hot interior, allowable coolant temperatures will be significantly reduced.

There appear to be two approaches to breeding tritium in the hot interior--solid lithium compounds and liquid lithium in refractory metal tubes. In the first approach, high melting point solid lithium compounds (e.g., Li_2O or $LiAlO_2$) can be used in the module interior; the bred tritium would be released to the high temperature coolant stream, with subsequent recovery and recycle to the plasma. However, in order to ensure adequate tritium release capability, it is necessary to maintain small particle size in the solid lithium compound and to prevent sintering. Tests at BNL⁽³⁾ have investigated the tritium release characteristics of solid lithium compounds at elevated temperatures (up to 1000°C) for extended periods of time (up to 3 months). Li_2O and $LiAlO_2$ appear suitable for use up to at least 1000°C and possibly higher. It is doubtful, however,

that substantially higher operating temperatures can be achieved, since at 1000°C the materials are entering the range (~ 0.6 of T_m) where sintering effects become important.

Thus tritium breeding in the hot interior appears to limit maximum coolant temperatures to $\sim 1000^\circ\text{C}$, assuming inert gas coolant. Tritium breeding with a reactive coolant such as steam is probably not feasible because of the chemical reaction between steam and solid lithium compounds and the difficulty of isotopically separating tritium from hydrogen in steam.

The two temperature zone blanket approach can be used with a hot interior of liquid lithium in refractory metal tubes (with a thermal insulator between the hot interior and the cooler metal shell). The interior would then be cooled either by an inert gas or potassium coolant. Tritium would be extracted either by circulating the lithium to an external processing unit or by releasing it to the coolant stream with subsequent trapping. Compatibility and structural considerations appear to limit maximum coolant temperatures to about 1200°C with liquid lithium interiors, however.

There appears to be no problem in obtaining adequate tritium breeding for designs where tritium is bred in the hot interior of the blanket. If tritium breeding is confined to the cooler shell region, however, it appears difficult to achieve tritium self-sufficiency for the reactor unless a thick low temperature zone is used. This significantly reduces the fraction of energy available for the high temperature coolant stream.

If it is desired to maximize temperature capability while keeping the overall breeding ratio for the reactor equal to one, the best approach is probably to have two different types of blankets in the reactor. The first type, which would breed tritium in the interior, would have as high a breeding ratio

as practical (on the order of 1.5), while maintaining the interior coolant at as high a temperature as possible (~ 1000 to 1200°C). The second type, which would breed tritium only in the cooler shell region, would operate with a higher temperature interior (up to $\sim 2500^\circ\text{C}$, depending on choice of coolant and the interior material). Breeding ratios up to ~ 0.9 to 1.0 appear practical for the second module type, so that only a relatively small fraction of the blanket would have to be devoted to the first module type.

Neutronic analyses of two temperature zone blankets indicate that 50 to 60 percent of the total fusion energy release (including alpha particle energy) can be deposited as high temperature heat in the interior of blanket modules. Essentially all of this energy can be extracted by the high temperature coolant stream. BNL tests⁽⁴⁾ of a variety of thermal insulation materials (ZrO_2 felt, ZrO_2 fibrous board, graphite felt, carbon felt, and alumina-silica mat) have been carried out as a function of temperature up to 1000°C in helium, argon, and air atmospheres. Thermal conductivities of ~ 0.1 to 0.2 watts/ m°K are found at 1000°C in argon, and ~ 0.4 to 0.5 watts/ m°K in helium, with insulation thicknesses of 2 to 3 cm between the hot interior and the module shell; it thus appears possible to keep heat leakage between the two zones to only a few percent of that deposited in the interior, for wall loadings on the order of $2 \text{ MW(th)}/\text{m}^2$.

It is the intent of this study to design a near-term reactor configuration, for this reason the reactor was sized to conform to typical TNS dimensions. As the reactor is to be near-term a low value of Q (≈ 3.0) was assumed in the calculations. Also presumed was a nominal neutron wall load of $1.5 \text{ MW}/\text{m}^2$. No divertor has been included in these design studies. A major radius of 5.0 m is utilized for the plasma which has a half-width of 1.2 m and is D-shaped with

an elongation ratio of 1.6 : 1.0. The low value of Q increases the importance of charged particle energy in these calculations and the fact that there is no divertor indicates that this charged-particle energy flux all impinges on the first wall. The small major radius will constrain the design somewhat in terms of inboard blanket and shield thickness.

The remainder of this report includes the definition of the 10 generic blanket types and the specific blanket chosen to be analyzed in detail from each of the 10 types. Dimensions, compositions, energy depositions and breeding ratios (where applicable) are presented for each of the 10 designs. Ultimately, based largely on neutronics and thermal hydraulics results, breeding and non-breeding blanket options are selected for further design analysis and integration with a suitable power conversion subsystem.

GENERIC BLANKET TYPES

Ten generic blanket types have been investigated for potential use with high efficiency power cycles. Overall characteristics of these blankets are summarized in Table 1. Each type has a range of possible coolant and material options, half the blankets being tritium breeders and the other half non-breeders. The blankets are broken into three distinct groups. The first of these groups contains types 1-4; types 5 and 6 constitute the second group and the third group consists of types 7-10. The odd-numbered blanket types are non-breeders and generally have higher interior temperatures than do their even-numbered breeding counterparts.

The materials, coolants, temperatures and pressures envisioned for the first group of blankets are summarized in Tables 2-5. Blankets 1 and 2 both are two zone with a hot interior cooled by helium. (Argon was also considered initially as a possible interior coolant). Interior and exterior materials and exterior

TABLE 1

Generic Fusion Blanket Types for High Efficiency Power Cycles

Blanket Type	One or Two Temperature Zones	Coolant		Tritium Breeding	Composition		Maximum Coolant Temperature	
		Shell	Interior		Interior	Shell	Interior	Shell
1	Two	Group A	Helium or Argon	No	graphite refractory carbide or oxide	Group B	up to $\sim 2500^{\circ}\text{C}$	up to $\sim 500^{\circ}\text{C}$
2	Two	Group A	Helium or Argon	Yes	carbide or oxide with LiAlO_2 or Li_2O	Group B	up to $\sim 1000^{\circ}\text{C}$	up to $\sim 500^{\circ}\text{C}$
3	Two	Group A	Steam	No	Al_2O_3 or ZrO_2	Group B	up to at 1500°C	up to $\sim 500^{\circ}\text{C}$
4	Two	HTS or Flibe	Steam	Yes (shell)	Al_2O_3 or ZrO_2	Group B	up to at least 1500°C	up to $\sim 500^{\circ}\text{C}$
5	One	Helium or Argon (both regions)		No	SiC or graphite	TZM or niobium	$\sim 1000^{\circ}\text{C}$	
6	One	Helium or Argon (both regions)		Yes	SiC and LiAlO_2	TZM or niobium	$\sim 1000^{\circ}\text{C}$	
7	Two	2-phase potassium-potassium vapor	Potassium vapor	No	refractory carbide in metal tubes	TZM or niobium	$\sim 1400^{\circ}\text{C}$	shell coolant goes into interior
8	Two	2-phase potassium-potassium vapor	Potassium vapor	Yes	liquid lithium in metal tubes	TZM or niobium	$\sim 1400^{\circ}\text{C}$	shell coolant goes into interior
9	One	2-phase potassium-potassium vapor	Potassium vapor	No	refractory carbide in metal tubes	TZM or niobium	$\sim 1000^{\circ}\text{C}$	
10	One	2-phase potassium-potassium vapor	Potassium vapor	Yes	liquid lithium in metal tubes	TZM or niobium	$\sim 1000^{\circ}\text{C}$	

Group A Coolants: H_2O , He, Fused Salt (HTS), Flibe

Group B Shell Materials: 316 SS, Ferrite Steel, Inconel, Aluminum Alloy, SAP, Titanium, TZM, Niobium, Vanadium

TABLE 2

BLANKET NO. 1 2-ZONE, He-COOLED

No BREEDING

Low Temp. Structure	Shell Coolant	T _{max} Coolant (°C)	P _{max} Coolant (psi)	Δx _{max} Shell Module (cm)	Interior Materials	T _{max} Coolant (°C)	P _{max} Coolant (psi)
* 316 Stainless Steel	He * H ₂ O Fused Salt	450 300 500	900 1500 150	1.0 1.0 1.0	C, <u>SiC</u> , Al ₂ O ₃ or ZrO ₂ Maximum Tempera- tures: C - 2500°C SiC - 2000°C Al ₂ O ₃ - 1500°C ZrO ₂ - 2500°C	2000	900
Inconel	He H ₂ O Fused Salt	600 300 500	900 1500 150	1.0 1.0 1.0			
Aluminum alloy	He H ₂ O	200 200	900 500	2.0 2.0			
SAP	He H ₂ O	350 300	900 1500	2.0 2.0			
Titanium	He H ₂ O Fused Salt	500 300 400	900 1500 150	0.5 0.5 0.5			
TZM	He	800	900	1.0			

TABLE 3

BLANKET NO. 2 2-ZONE, He-COOLED

T BREEDING

Low Temp. Structure	Shell Coolant	T _{max} Coolant (°C)	P _{max} Coolant (psi)	Δx _{max} Shell Module (cm)	Interior Materials	T _{max} Coolant (°C)	P _{max} Coolant (psi)
* 316 Stainless Steel	* He H ₂ O Fused Salt	450 300 500	900 1500 150	1.0 1.0 1.0	BeO with LiAlO ₂ with C, SiC, Al ₂ O ₃ or ZrO ₂	1000	900
Inconel	He H ₂ O Fused Salt	600 300 500	900 1500 150	1.0 1.0 1.0	Maximum Tempera- tures:		
Aluminum alloy	He H ₂ O	200 200	900 500	2.0 2.0	C - 1000°C SiC - 1000°C Al ₂ O ₃ - 1100°C ZrO ₂ - 1100°C		
SAP	He H ₂ O	350 300	900 1500	2.0 2.0			
Titanium	He H ₂ O Fused Salt	500 300 400	900 1500 150	0.5 0.5 0.5			
TZM	He	800	900	1.0			

TABLE 4

BLANKET NO. 3 2-ZONE, H₂O-COOLED

No BREEDING

Low Temp. Structure	Shell Coolant	T _{max} Coolant (°C)	P _{max} Coolant (psi)	Δx _{max} Shell Module (cm)	Interior Materials	T _{max} Coolant (°C)	P _{max} Coolant (psi)
* 316 Stainless Steel	He * H ₂ O Fused Salt	450 300 500	900 1500 150	1.0 1.0 1.0	Al ₂ O ₃ , SiC, or ZrO ₂	1500	1500
Inconel	He H ₂ O Fused Salt	600 300 500	900 1500 150	1.0 1.0 1.0	Maximum Tempera- tures: Al ₂ O ₃ - 1500°C SiC - 1100°C ZrO ₂ - 1600°C		
Aluminum alloy	He H ₂ O	200 200	900 500	2.0 2.0			
SAP	He H ₂ O	350 300	900 1500	2.0 2.0			
Titanium	He H ₂ O Fused Salt	500 300 400	900 1500 150	0.5 0.5 0.5			
TZM	He	800	900	1.0			

TABLE 5

BLANKET NO. 4 2-ZONE, H₂O-COOLED

T BREEDING

Low Temp. Structure	Shell Coolant	T _{max} Coolant (°C)	P _{max} Coolant (psi)	Δx _{max} Shell Module (cm)	Interior Materials	T _{max} Coolant (°C)	P _{max} Coolant (psi)
* 316 Stainless Steel	He * H ₂ O Fused Salt	450 300 500	900 1500 150	1.0 1.0 1.0	BeO and LiAlO ₂ with Al ₂ O ₃ , <u>SiC</u> , or ZrO ₂	1000	150
Inconel	He H ₂ O Fused Salt	600 300 500	900 1500 150	1.0 1.0 1.0	Maximum tempera- tures: Al ₂ O ₃ - 1100°C SiC - 1100°C ZrO ₂ - 1100°C		
Aluminum alloy	He H ₂ O	200 200	900 500	2.0 2.0			
SAP	He H ₂ O	350 300	900 1500	2.0 2.0			
Titanium	He H ₂ O Fused Salt	500 300 400	900 1500 150	0.5 0.5 0.5			
TZM	He	800	900	1.0			

coolant options are identified and corresponding maximum operating temperatures and pressures are delineated in Tables 2 and 3. After surveying the potential material and coolant combinations, a most favorable set of combinations was chosen for detailed neutronic and thermal hydraulic analysis for each of the blanket types. This most favorable set of options is indicated by asterisks and underlining on Tables 2 and 3. For blanket type 1 (the non-breeder) a 316 stainless steel water-cooled exterior is chosen and a helium-cooled SiC interior is selected. It is estimated that the maximum interior temperature may be 2000°C. For breeding blanket type 2 once again the water-cooled 316 stainless steel exterior is chosen with SiC being the major interior material choice. For breeding purposes LiAlO_2 is chosen and BeO is utilized as a neutron multiplier. Aiding in the selection of the material and coolant combinations were overall power cycle considerations depicted in Figures 1 and 2. In fact, blanket flow sheets were constructed for each of the ten blanket types prior to any narrowing of the material and coolant options.

Tables 4 and 5 present the materials and coolant options for blanket types 3 and 4. The options are similar to types 1 and 2 except that in these cases the hot interior is cooled by high temperature steam. Figures 3 and 4 illustrate the overall power cycle for these two blanket types. As in the case of the previous blankets, a material/coolant combination is selected for each blanket type to be analyzed in greater detail. For blanket type 3 water-cooled 316 stainless steel is chosen for the exterior structure and Al_2O_3 is chosen for the hot interior. A maximum coolant temperature of 1500°C is envisioned in the hot interior. For the breeding blanket type 4, stainless steel with steam coolant is chosen for the exterior structure with SiC selected for the hot interior. LiAlO_2 is utilized as breeding material with a BeO neutron multiplier, and breeding requirements necessitate a maximum temperature of 1000°C in the hot interior.

GENERIC BLANKET FLOW SHEET #1 [He COOLANT]

Figure 1

GENERIC BLANKET FLOW SHEET #2 [He COOLANT]

* He MAY BE ANY INERT GAS
 ** MAY REQUIRE TRITIUM BARRIER BETWEEN SHELL AND INTERIOR

Figure 2

GENERIC BLANKET FLOW SHEET #3 [STEAM COOLANT]

Figure 3

GENERIC BLANKET FLOW SHEET #4 [STEAM COOLANT]

* TRITIUM BARRIER REQUIRED TO PREVENT TRITIUM ENTERING HIGH TEMPERATURE STEAM CIRCUIT

Figure 4

The second group of blankets is composed of types 5 and 6. These are one zone helium cooled blankets with material options summarized in Tables 6 and 7. The fact that these blankets are one zone simplifies the power cycle processes illustrated in Figures 5 and 6. For blanket type 5 TZM (an alloy primarily composed of molybdenum) is chosen as the exterior structural material and SiC is selected for the hot interior. Maximum coolant temperatures of 1000°C are desirable. Breeding blanket type 6 again has a TZM exterior and a SiC interior. LiAlO_2 is used as breeding material Be included as a neutron multiplier. Maximum coolant temperature is again expected to be 1000°C.

The final group of blanket types are depicted in Tables 8-11. These blankets utilize a two-phase mixture of potassium as exterior coolant and potassium vapor to cool the hot interior. Blanket types 7 and 8 are two-zone blankets. Material options are summarized in Tables 8 and 9. The power cycle elements are depicted in Figures 7 and 8 for these two blanket types. Particular material options which have been selected for further analysis are indicated in Tables 8 and 9. For blanket type 7 TZM is selected as the exterior material and the two-phase coolant is anticipated to have a maximum temperature of 1200°C. The interior will consist of ZrC canned in TZM and will be cooled by potassium vapor with a maximum temperature of 1400°C. Breeding blanket type 8 has an exterior composed of TZM and the interior consists of FLIBE canned in TZM. Both interior and exterior maximum coolant temperatures are expected to be 1200°C.

Blanket types 9 and 10 are one-zone, two-phase potassium cooled blankets. The material options are presented in Tables 10 and 11. Since the blankets are one zone, simplified power cycle elements are necessitated; these are shown in Figures 9 and 10. For blanket type 9 TZM is chosen as structural materials; ZrC is canned in TZM in the blanket interior. For the breeding blanket type 10, TZM is again utilized with FLIBE canned in TZM used as breeding material. Blankets 9 and 10 both have desired maximum coolant temperatures of 1200°C.

TABLE 6

BLANKET NO. 5 1-ZONE, He-COOLED

No BREEDING

Low Temp. Structure	Shell Coolant	T _{max} Coolant (°C)	P _{max} Coolant (psi)	Δx _{max} Shell Module (cm)	Interior Materials	T _{max} Coolant (°C)	P _{max} Coolant (psi)
SiC	He	1400	900	---	SiC tubes	1400	900
* TZM	He	1000	900	0.5	SiC, C, Al ₂ O ₃ , or ZrO ₂	1000	900

TABLE 7

BLANKET NO. 6 1-ZONE, He-COOLED

T BREEDING

Low Temp. Structure	Shell Coolant	T _{max} Coolant (°C)	P _{max} Coolant (psi)	Δx _{max} Shell Module (cm)	Interior Materials	T _{max} Coolant (°C)	P _{max} Coolant (psi)
SiC	He	1000	900	---	Be, BeO, and LiAlO ₂ in SiC tubes	1000	900
* TZM	He	1000	900	0.5	Be and LiAlO ₂ with <u>SiC</u> , C, Al ₂ O ₃ , or ZrO ₂	1000	900

GENERIC BLANKET FLOW SHEET #5 [He COOLANT]

* He COOLANT MAY BE ANY INERT GAS

Figure 5

GENERIC BLANKET FLOW SHEET #6 [He COOLANT]

* He COOLANT MAY BE ANY INERT GAS

Figure 6

TABLE 8
BLANKET NO. 7 2-ZONE, K-COOLED
No BREEDING

Low Temp. Structure	Shell Coolant	T _{max} Coolant (°C)	P _{max} Coolant (psi)	Δx _{max} Shell Module (cm)	Interior Materials	T _{max} Coolant (°C)	P _{max} Coolant (psi)
Niobium	K(1)	1200	150	1.0	ZrC canned in shell material	1400	150
Tungsten/ Rhenium	K(1)	1200	150	1.0	ZrC canned in shell material	1400	150
* TZM	K(1)	1200	150	1.0	ZrC canned in shell material	1400	150

TABLE 9

BLANKET NO. 8 2-ZONE, K-COOLED

T BREEDING

Low Temp. Structure	Shell Coolant	T _{max} Coolant (°C)	P _{max} Coolant (psi)	Δx _{max} Shell Module (cm)	Interior Materials	T _{max} Coolant (°C)	P _{max} Coolant (psi)
Niobium	K(1)	1200	150	1.0	Li or FLIBE canned in shell material	1200	150
Tungsten/ Rhenium	K(1)	1200	150	1.0		1200	150
*TZM	K(1)	1200	150	1.0		1200	150

GENERIC BLANKET FLOW SHEET #7

Figure 7

GENERIC BLANKET FLOW SHEET #8

Figure 8

TABLE 10

BLANKET NO. 9 1-ZONE, K-COOLED

No BREEDING

Low Temp. Structure	Shell Coolant	T _{max} Coolant (°C)	P _{max} Coolant (psi)	Δx_{max} Shell Module (cm)	Interior Materials	T _{max} Coolant (°C)	P _{max} Coolant (psi)
Niobium	K(l)	1200	150	1.0	ZrC canned in shell material	1200	150
Tungsten/ Rhenium	K(l)	1200	150	1.0		1200	150
* TZM	K(l)	1200	150	1.0		1200	150

TABLE 11

BLANKET NO. 10 1-ZONE, K-COOLED

T BREEDING

Low Temp. Structure	Shell Coolant	T _{max} Coolant (°C)	P _{max} Coolant (psi)	Δx _{max} Shell Module (cm)	Interior Materials	T _{max} Coolant (°C)	P _{max} Coolant (psi)
Niobium	K(ℓ)	1200	150	1.0	Li or FLIBE in shell material	1200	150
Tungsten/ Rhenium	K(ℓ)	1200	150	1.0		1200	150
* TZM	K(ℓ)	1200	150	1.0		1200	150

GENERIC BLANKET FLOW SHEET #9

Figure 9

GENERIC BLANKET FLOW SHEET #10

Figure 10

This concludes the preliminary description of the ten generic blanket types which were identified and the particular options which were selected for further analysis. There is an additional blanket approach which was also considered though not analyzed in any significant detail. In reality the blankets were developed to the point that flow sheets (Figures 11 and 12) could be prepared. This blanket approach allows the recovery of injected energy at the high temperatures desired for a high efficiency thermal power cycle. This concept involves depositing all of the fusion energy, including the radiolytic x-ray and plasma energy, in a high temperature ($\sim 2000^{\circ}\text{C}$) graphite block structure which surrounds the plasma. During the plasma burn period, the temperature of the block increases steadily; when the burn ceases, the deposited energy is removed by direct cooling with an inert gas stream that passes through channels in the graphite blocks into the plasma chamber. The chamber is rapidly pumped down by a two stage process (turbomolecular pumps followed by cryopumps) and the next burn initiated. Thermal hydraulic studies of this direct cooled blanket approach indicate that plasma burn times of ~ 1000 seconds can be accommodated with temperature increases of $\sim 500^{\circ}\text{C}$ during the burn. Gas pumpdown studies indicate that adequately low pressures can be achieved in ~ 200 seconds, with $\sim 1\%$ of the plant output recirculated to the pumpdown equipment. The energy extracted from the hot graphite structure during the dwell part of the plasma cycle is transferred to intermediate thermal storage from which it acts as a steady thermal source for the power cycle. All of the fusion and injected energy is available at high temperatures for the high efficiency efficiency power cycle.

GENERIC BLANKET FLOW SHEET # 11 [INTERMITTENT DIRECT COOLED]

----- GAS CIRCULATION OPERATES ONLY WHEN PLASMA IS OFF

Figure 11

GENERIC BLANKET FLOW SHEET #12 [INTERMITTENT DIRECT COOLED]

----- GAS CIRCULATION OPERATES ONLY WHEN PLASMA IS OFF

Figure 12

DESIGN RESULTS

Each of the ten material and coolant options selected in the previous section have undergone neutronic and thermal hydraulic analyses. These results are summarized for each of the ten blankets in this section.

A nucleonic (neutronic and photonic) analysis was performed on each of the ten generic blankets. This analysis consisted of the following steps:

(1) determination of the equivalent geometry and atomic concentrations of the blanket module, (2) neutron and photon fluxes are found by performing a transport calculation using the computer program ANISN⁽⁵⁾ together with the 121 energy group (100 neutron groups and 21 photon groups) coupled neutron-photon cross section set, EPR⁽⁶⁾. Cylindrical geometry, with a P_3 - S_8 expansion-quadrature was used, (3) nucleonic fluxes were folded with appropriate kerma factors and reaction cross-sections to calculate heating rates and, where applicable, breeding ratios.

A representative blanket module for the first group of blankets (types 1-4) is shown in Figure 13. A number of module sub-sections are mounted on a rigid backing plate and are inserted or removed from the reactor as a unit. The long straight sides of each sub-section have a 2/1 elliptical head facing the plasma, with the sub-sections placed next to each other on the backing plate. The structural shells that form each sub-section are cooled by an attached array of small tubes, carrying a coolant such as water. The hot interior is insulated from the shell by a fibrous mat layer of graphite (blanket types 1 and 2) or refractory oxide (blanket types 3 and 4). The coolant for the hot interior passes through the packed refractory bed, either along the long axis of the module or radially from integral header tubes.

A cross-section of blanket type 1 is shown in Figure 13. The materials used

BLANKET TYPE 1

Figure 13

in this blanket are listed in Table 12. The stainless steel coolant tubes contain water, and the thermal insulator region separates the hot interior (SiC) from the cooler structural material and first-wall regions. The backing plate and shield are of similar design in all ten of the blankets presented here. The total and 14 MeV neutron fluxes for blanket type 1 are shown in Figure 14. The distance parameter is measured from plasma center and this coordinate has been adjusted in performing step (1) in nucleonic analysis. One can see that the 14 MeV neutron flux is reduced by a factor of ~ 350 over the blanket and by a factor of ~ 150 over the hot interior. These factors indicate large fractions of energy deposition in the blanket and particularly in the hot interior. This fact is verified by Figure 15, an illustration of the total energy deposition across the blanket region. For blanket type 1 only $\sim 8\%$ of incident energy penetrates beyond the blanket region, and 58% of the total energy is deposited in the hot interior.

Using blanket type 1 as a base case as delineated in Table 13, a number of design variations were performed (see Table 13, 1B-1J) to increase the fraction of energy deposited in the high temperature interior. The effect of these design variations is summarized in Table 14. The fraction of neutron and gamma energy deposited in the various blanket/shield regions is given, along with the fraction of total fusion energy (including alpha particle energy) that appears as high temperature heat in the hot interior of the module (thermal leakage through the insulation is not included).

The base case design yields a fractional fusion energy deposition in the hot interior of 58% (including alpha particle energy). The thickness of the module shell has a large effect on high temperature efficiency, with a change of $\pm 4\%$ from the original value of 58% per ± 0.25 cm change in shell thickness (cases 1B and 1C). Changing shell material to aluminum from stainless steel has

Table 12
Blanket Type # 1

<u>Region</u>	<u>Material</u>	<u>Dimensions</u>
Coolant Tubes	316 SS (H ₂ O)	0.5 cm ID 0.2 cm wall
Shell	316 SS	0.75 cm thick
Insulator	SiC (10%)	3.1 cm thick
Hot Interior	SiC (80%) (He)	52.9 cm high 22.3 cm wide
Backing Plate	316 SS (H ₂ O)	15 cm thick
Shield	316 SS (20%) B ₄ C (80%) (H ₂ O)	100 cm thick
Hot Interior Energy Fraction	58%	
Breeding Ratio	None

Figure 14

Figure 15

Table 13

Sensitivity Studies for Two Temperature Zone Blanket
(Blanket Type #1)

Base Case (Blanket 1A)

Configuration = Log with 2/1 Elliptical Head

Module Width = 30 cm

Shell Thickness = 0.75 cm (316 Stainless)

Tube Construction on Shell = 316 SS Tubes with H₂O Coolant
(0.9 cm OD, 0.5 cm ID)

Insulation Thickness = 3 cm (SiC, 10% effective density)

Interior Material = SiC with He Coolant (80% effective density for SiC)

Straight Side Length = 53 cm

Backing Plate Thickness = 15 cm

Square Plasma Chamber

Design Variations

1B Shell Thickness → 0.50 cm

1C Shell Thickness → 1.00 cm

1D Straight Side Length → 10 cm longer

1E Interior Material → MgO

1F Shell Material → 6061 Aluminum Alloy

1G Plasma Chamber → Round

1H Insulation Thickness → 1.00 cm

1I Effective Density of Interior → 91%

1J Module Width → 45 cm

Table 14

Results of Sensitivity Studies for Two Temperature Blankets
(Blanket Type # 1)

Blanket Region	% of Neutron and Gamma Deposition in Blanket Region									
	<u>Case #</u>									
<u>Blanket Region</u>	1A	1B	1C	1D	1E	1F	1G	1H	1I	1J
Tubes	9	10	9	9	10	6	9	10	9	9
Shell	10	7	13	10	11	5	9	10	10	10
Insulation Fiber in Head	2	2	2	2	2	2	2	1	2	2
Ceramic in Head	9	10	8	9	11	11	8	16	10	18
Straight Section	61	62	60	65	61	64	61	57	62	51
Back Fiber	0	0	0	0	0	0	1	0	0	0
Backing Plate	8	9	8	3	5	6	9	6	6	9
Shield	0	1	0	2	0	5	1	0	0	1
% of Fusion Energy in Hot Interior (including particle energy)	58	63	54	61	61	69	58	63	61	62

a large effect on high temperature efficiency, increasing it from the original 58% to 69% (case 1F). Decreasing insulation thickness (case 1H) to 1.0 cm from the original 3.1 cm also significantly increases the high temperature efficiency (from 58% to 63%). Smaller increases (e.g., to 62, 61, and 61 respectively) are obtained by increasing the module width, making it radially thicker, substituting MgO for SiC, and increasing the density of the interior material (cases 1J, 1D, 1E, and 1I). Changing the shape of the plasma chamber from square to round had no significant effect on the high temperature efficiency.

Not studied were the effects of using D₂O coolant instead of H₂O in the coolant tubes attached to the lower temperature module shell, and the effects of using an interior material with a substantially higher kerma factor, e.g., molybdenum carbide. The former will probably have relatively small effect, since the effective thickness of the H₂O coolant is small; the latter should have a substantial effect, however.

Two dimensional neutronic transport analyses (Twotran) have been carried out on two temperature blankets of the types considered here⁽⁷⁾. Results for the fraction of energy deposited in the hot interior computed by two-dimensional analyses agree fairly closely with those for one-dimensional analyses, except that the former are generally a few percent lower. The analysis consisted of the following steps: (1) Determination of the equivalent geometry and atomic concentrations of the blanket module for the computer simulation. (2) The one-dimensional nucleonic (neutron and photon) flux was found by performing a transport calculation using the computer program ANISN⁽⁵⁾ together with the 121 energy group (100 neutron and 21 photon groups) coupled neutron-photon cross-section set, EPR⁽⁶⁾. Spherical geometry, with a P₃-S₈ expansion-quadrature, was used. The system was modeled as a spherical shell with a point source of 14 MeV neutrons at its center. (3) An appropriate collapsed energy group structure was

chosen for use in the two-dimensional calculation. (4) The two-dimensional nucleonic flux was determined with a P_3 - S_8 expansion-quadrature run of the computer program TWOTRAN-II⁽⁸⁾. R-Z cylindrical geometry was used, with the Z-axis as the axis of symmetry of the module, and the R-axis perpendicular to the Z-axis. The source was modeled as a 14 MeV neutron beam directed along the +Z-axis, with a small angular spread. (5) The two-dimensional heating analysis was performed by using the nucleonic flux, the collapsed 20 group kerma factors, and the atomic concentrations. In the case examined in reference (7), the hot interior absorbed 82% of the total nucleonic heat absorbed by the module, indicating a very promising high efficiency blanket concept.

Blanket type 2 is illustrated in Figure 16 and Table 15. The stainless steel tubes again contain water, the breeding material chosen is LiAlO_2 , and BeO is utilized as a neutron multiplier. Initially, a breeding ratio of .82 was obtained for this blanket. An increase in thickness of the breeding zone by 50% raised the breeding ratio to .91. Further improvements such as those envisioned for blanket type 1 could be utilized to increase the breeding ratio and thus blanket type 2 would be a viable breeder.

Blanket type 3 is a two-zone concept which is entirely water and steam cooled. This blanket type is shown in Figure 17 and Table 16. This design is similar to blanket type 1, and the improvements in the amount of energy absorbed proposed for blanket type 1 could be reiterated here. Blanket type 4 (Table 17) is the breeding version of blanket type 3 and has been examined in more detail. BeO and LiAlO_2 are included in the hot interior and a breeding ratio of 1.06 results. It should be emphasized again that this ratio has not been optimized. In fact, with Al_2O_3 used as insulator and steam coolant only ~ 17% of the energy is deposited in the hot interior. A study of the type performed for blanket type 1 then appears necessary to increase this percentage.

BLANKET TYPE 2

Figure 16

Table 15
Blanket Type # 2

<u>Region</u>	<u>Material</u>	<u>Dimensions</u>
Coolant Tubes	316 SS (H ₂ O)	0.5 cm ID 0.2 cm wall
Shell	316 SS	0.75 cm thick
Insulator	SiC (10%)	3.0 cm thick
Breeding Zone	BeO (60%) LiAlO ₂ (5%) (He)	10 cm thick +2 cm at edge of hot interior
Hot Interior	SiC (80%) (He)	43 cm thick
Blanking Plate	(See Table 12)	
Shield		
Hot Interior Energy Fraction	26%	
Breeding Ratio	.91	

BLANKET TYPE 3

Figure 17

Table 16
Blanket Type # 3

<u>Region</u>	<u>Material</u>	<u>Dimensions</u>
Coolant Tubes	316 SS (H ₂ O)	0.5 cm ID 0.2 cm wall
Shell	316 SS	0.75 cm thick
Insulator	SiC (10%)	3.1 cm thick
Hot Interior	SiC (80%) (H ₂ O)	52.9 cm high 22.3 cm wide
Backing Plate	316 SS (H ₂ O)	15 cm thick
Shield	316 SS (20%) B ₄ C (80%) (H ₂ O)	100 cm thick
Hot Interior Energy Fraction	58%	
Breeding Ratio	None	

Table 17
Blanket Type # 4

<u>Region</u>	<u>Material</u>	<u>Dimensions</u>
Coolant Tubes	316 SS (H ₂ O)	0.5 cm ID 0.2 cm wall
Shell	316 SS	0.75 cm thick
Insulator	Al ₂ O ₃ (10%)	3.1 cm thick
Breeding Zone	DeO (77%) LiAlO ₂ (14%) (H ₂ O)	18 cm thick +2 cm sides of hot interior
Hot Interior	SiC (80%) (H ₂ O)	38 cm thick
Backing Plate	(See Table 12)	
Shield		
Hot Interior Energy Fraction	17%	
Breeding Ratio	1.06%	

Neutron fluxes and heat deposition profiles are shown in Figures 18 and 19.

The separator region of the hot interior (separating breeding and non-breeding zones) composed largely of stainless steel seems to contribute a great deal to the reduction in heat deposition. Further analysis of this effect is indicated in line with optimization studies mentioned previously.

The second group of blanket types utilizes one-zone temperature blankets. A refractory metal shell (TZM or niobium) is used with a refractory interior (SiC or other refractory carbide) and helium cooling. The module geometry is cylindrical, with the axis of the cylinder normal to the plasma surface, and a hemispherical head on the end facing the plasma (Figure 20). The inert gas coolant is distributed from an internal header system, first cooling the module shell and then returning through the interior. In practice, the interior will operate at somewhat higher temperature than the shell due to the sensible heat pickup by the inert gas coolant as it passes through the module. Maximum coolant exit temperatures will be on the order of 1000°C. Blanket types 5 and 6 are shown in Figures 21 and 22 and Tables 18 and 19, respectively. These blankets are one-zone helium-cooled with TZM exteriors and largely SiC interiors. Due to a lack of TZM kerma factors, the only nucleonics analysis that was performed was the neutron flux profile shown for blanket type 6 in Figure 23. Some optimization was performed on this design when it was discovered that molybdenum had a large neutron capture cross-section which was detrimental to breeding. The breeding ratio was increased from .28 to .68 in the course of this analysis. The original breeding ratio of .28 was raised to 0.40 by increasing the thickness of the breeding zone (Figure 22) from 10 cm to ~ 25 cm. The breeding ratio was next increased to 0.53 by increasing the lithium enrichment from 50% to 90%. The final increase of the breeding ratio to 0.68 was obtained by doubling the lithium concentration to 10% and decreasing the Be and SiC volume fractions

Figure 18

Figure 19

CASE #5,1-ZONE
He-COOLED NO BREEDING

WALL FACE AS VIEWED
FROM PLASMA

HELIUM OUTLET FLOW IS DOWN THROUGH CENTER
OF EACH CYLINDER TO LOWER PLENUM

Figure 20

CASE #5,1-ZONE
He-COOLED NO BREEDING

Figure 21

CASE #6.1 - ZONE
He-COOLED WITH BREEDING

SEE CASE #5 FOR
CONSTRUCTION DETAIL

Figure 22

Table 18
Blanket Type # 5

<u>Region</u>	<u>Material</u>	<u>Dimensions</u>
Shell	TZM (He)	0.5 cm thick + 0.2 cm thick interior shell
Interior	Sic (65%) (He)	4 cm diam. balls 80 cm high x 17 cm wide
Insulator	Al ₂ O ₃ (10%)	1 cm thick 2 separate regions
Backing Plate	TZM	15 cm thick
Shield	B ₄ C (80%) TZM (20%) (He)	100 cm thick
Hot Interior Energy Fraction	N/A	
Breeding Ratio	None	

Table 19
Blanket Type # 6

<u>Region</u>	<u>Material</u>	<u>Dimensions</u>
Shell	TZM (He)	0.5 cm thick + 0.2 cm thick interior shell
Breeding Zone	Be (60%) LiAlO ₂ (5%) (He)	4 cm diam. balls 25 cm thick x 17 cm wide
Hot Interior	SiC (60%) LiAlO ₂ (5%) (He)	4 cm diam. balls 55 cm thick x 17 cm wide
Insulator	Al ₂ O ₃ (10%)	1 cm thick 2 separator regions
Backing Plate	(See Table 18)	
Shield		
Hot Interior Energy Fraction	N/A	
Breeding Ratio	0.68

Figure 23

accordingly. It is unlikely that further increases in breeding ratio are readily obtainable.

The final group of blankets (types 7-10) utilizes both one and two-zone potassium cooled blankets as illustrated in Figures 24 and 25. The thermally insulated hot interior contains stagnant liquid lithium or FLIBE in thin refractory metal tubes, held by an inner metal shell. Alumina insulator is used between the hot interior and the cooler shell, which is cooled by a set of attached coolant tubes carrying a two-phase mixture of potassium liquid and vapor. [The quality of the two-phase mixture is held relatively high (e.g., ~ 0.7) so that the electrical resistivity of the mixture is much higher than that of the liquid metal. MHD pressure drops due to flow through the background magnetic field should be very small.] The interior is separately cooled by potassium vapor, which can be superheated to relatively high temperatures ($\sim 1400^{\circ}\text{C}$) depending on the materials compatibility. A vapor-liquid separation operation on the two-phase coolant (outside the blanket) appears necessary with the separated vapor returned for superheat in the module interior.

Blanket types 7 and 8 are two-zone designs. These blankets resemble the one depicted in Figure 13 in that they are cylindrical rather than circular in design as are types 5 and 6. In type 7 (Table 20) TZM is the main structural material and is utilized to can ZrC in the hot interior. In the breeding blanket type 8 (Table 21), TZM is used to can liquid Li or FLIBE in the hot interior. Figure 26 illustrates the neutron fluxes found for blanket type 8. Again due to the lack of kerma factors for TZM, no heating profile is plotted. Due to the high neutron capture cross-section of molybdenum, it was necessary to optimize the design (decrease the amount of molybdenum) to raise the breeding ratio from .10 to .30. In order to obtain heating profiles, a substitution of niobium for TZM in blanket type 8 was made (Table 21). Figures 27 and 28 depict neutron

BLANKET #7 AND #8
2-ZONE
K-COOLED (2 PHASE)

Figure 24

BLANKETS #9 AND #10
1 - ZONE
K - COOLED (2 PHASE)

Figure 25

Table 20
Blanket Type # 7

<u>Region</u>	<u>Material</u>	<u>Dimensions</u>
Coolant Tubes	TZM (K-20)	3 cm OD .2 cm wall
Shell	TZM	.3 cm thick inside and outside shells
Insulator	Al ₂ O ₃ (11%)	2 cm thick
Hot Interior	ZrC (81%) TZM (9%) (K vapor)	4 cm OD rods TZM cans ZrC 67 cm high x 16 cm wide
Backing Plate	(See Table 18)	
Shield		
Hot Interior Energy Fraction	N/A	
Breeding Ratio	None	

Table 21
Blanket Type # 8

<u>Region</u>	<u>Material</u>	<u>Dimensions</u>
Coolant Tubes	TZM (K-20)	3 cm OD .2 cm wall
Shell	TZM	.3 cm thick inside and outside shells
Insulator	Al ₂ O ₃ (11%)	2 cm thick
Hot Interior	FLIBE (81%) TZM (9%) (K vapor)	4 cm OD rods TZM cans FLIBE 67 cm high x 16 cm wide
Backing Plate	(See Table 18)	
Shield		
Hot Interior Energy Fraction	N/A	
Breeding Ratio	0.30	
---Niobium instead of TZM---		
Hot Interior Energy Fraction	48%	
Breeding Ratio	0.31

Figure 26

Figure 27

Figure 28

fluxes and heating profiles for this material substitution. Although the breeding ratio was increased only to .31, it was found that 48% of the energy was deposited in the high temperature interior.

Blanket types 9 and 10 (Figure 25) as depicted in Tables 22 and 23 are one-zone designs cooled by two-phase potassium coolant. Figure 29 depicts the neutron fluxes for blanket type 10. A breeding ratio of .17 was found for this blanket without any type of optimization of design. Decreasing TZM thicknesses could be expected to raise the breeding ratio as in the case of blanket #8.

CONCLUSIONS

Basically, the blanket types examined all appear technically viable, though the performance in some cases is not acceptable. The first group of blankets (types 1-4) do appear most promising. The analysis which was carried out and summarized in Tables 13 and 14 lead us to reach the following conclusion regarding blankets 1-4:

Combinations of design changes that significantly increase high temperature efficiency should result in a module design with high temperature efficiency approaching 70%, even retaining the present material compositions (stainless steel, SiC, H₂O, and He). These would probably comprise a somewhat thinner insulation layer and a thicker/wider module. Higher values appear difficult to achieve, since alpha particle energy inherently limits efficiency to a value not much greater than 80% (Q values for these blankets are on the order of 20 MeV).

Neutronic analyses have also been carried out for the other blanket types. The general conclusions drawn from these studies indicate:

Table 22
Blanket Type # 9

<u>Region</u>	<u>Material</u>	<u>Dimensions</u>
Shell	TZM	0.5 cm thick
Interior	ZrC (81%) TZM (9%) (K-20)	4 cm OD rods TZM cans ZrC 70 cm high x 20 cm wide
Backing Plate		
(See Table 18)		
Shield		
Hot Interior Energy Fraction	N/A	
Breeding Ratio	None	

Table 23
Blanket Type # 10

<u>Region</u>	<u>Material</u>	<u>Dimensions</u>
Shell	TZM	0.5 cm thick
Interior	FLIBE (81%) TZM (9%) (K-20)	4 cm OD rods TZM cans FLIBE 70 cm high x 20 cm wide
Backing Plate		
(See Table 18)		
Shield		
Hot Interior Energy Fraction	N/A	
Breeding Ratio	.17

Figure 29

1. Two temperature zone blankets can be designed with a high (60-70%) efficiency for deposition of fusion energy in the hot interior.
2. Blankets with solid lithium compounds in the hot interior (e.g., type #2 blankets) can achieve tritium breeding ratios of ~ 1.5 if suitable neutron multipliers (e.g., Be) are used.
3. The tritium breeding ratios of the high temperature liquid lithium blankets (types # 8 and 10) are well below one, because of the relatively large volume fraction of small diameter (4 cm OD) refractory metal tubes containing the liquid lithium in the interior. This type of blanket cannot achieve a breeding ratio of one unless the metal volume fraction is made much smaller, which would require impractically thin tubes or very large tubes.
4. The tritium breeding ratios of blankets with breeding in the shell (by lithium containing fused salts) and steam cooled non-breeding interiors (type #4) are relatively low (~ 0.5 to 0.7) with most oxide refractories (MgO , Al_2O_3 , etc.). If BeO is used in the interior, however, breeding ratio approaches one.

Thermal hydraulic analyses of the various blankets indicate that cooling should not be a problem in the interior of the blankets, since internal surface area is relatively high and volumetric power densities relatively low at the wall loads considered, $1\text{-}2 \text{ MW(th)}/\text{m}^2$. Substantial thermal gradients are anticipated at the first wall, however, due to the high surface thermal flux resulting from low Q operation. [The injected power to maintain the plasma is assumed to reach the first wall as x-rays (Bremsstrahlung) and kinetic energy of plasma ions and electrons]. Using 316 stainless steel tube walls for blankets 1 to 4, for example, the limiting temperature differences of 50°C in the tube wall are reached at wall loads of $1 \text{ MW(th)}/\text{m}^2$ and $Q = 3$. Somewhat

higher wall loads would be possible with the more thermally conductive ferritic steels. With aluminum structure, temperature differences are quite small, and high wall loads (e.g., 3-4 MW(th)/m²), low Q operation (e.g., $Q \sim 2$) appears practical.

Even if blankets can handle low Q operation, however, the effect on power cycle efficiency will be very important, since the injected energy will be recovered from the lower temperature coolant circuit cooling the first wall (except in mirror type reactors, where it can be recovered in a direct converter). [It appears likely that the injected energy will have to go through a thermal cycle in tokamak reactors, because of the much lower plasma temperature and the difficulty of coupling a direct converter to a tokamak divertor.]

The above leads us to the overall conclusion that blanket type 1 represents the best alternative among the non-breeding blankets. The question of a breeding blanket remains somewhat open. A combination of blanket type 2 with a non-breeder appears to represent the most promising possibility at this time. Therefore, it is the blankets of the first group which comprise the basis of the detailed design study which initiates the second major phase of the analysis of fusion blankets for high efficiency power cycles.

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