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NOEL--A NO-LEAK FUSION BLANKET CONCEPT*†

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ABSTRACT

Analysis and tests of a no-leak fusion blanket concept (NOEL-NO External Leak) are described. Coolant cannot leak into the plasma chamber even if large through-cracks develop in the first wall. Blanket modules contain a two-phase material, "A," that is solid (several cm thick) on the inside of the module shell, and liquid in the interior. The solid layer is maintained by imbedded tubes carrying a coolant, "B," below the freezing point of "A." Most of the 14-MeV neutron energy is deposited as heat in the module interior. The thermal energy flow from the module interior to the shell keeps the interior liquid. Pressure on the liquid "A" interior is greater than the pressure on "B," so that "B" cannot leak out if failures occur in coolant tubes. Liquid "A" cannot leak into the plasma chamber through first wall cracks because of the intervening frozen layer. The thermal hydraulics and neutronics of NOEL blankets have been investigated for various metallic (e.g., Li, Pb_2, LiPb, Pb) and fused salt choices for material "A." With metallic "A" materials a frozen layer several cm thick is obtained for stagnant, liquid interiors. The low thermal conductivity of fused salt "A" materials, however, results in thin frozen layers unless the tube surface is finned. Liquid salt can also be circulated to an external heat exchanger to remove interior heat. This results in a frozen layer several cm thick. Acceptable (35 to 40%) power cycle efficiencies can be achieved with either metals or fused salts, with tritium breeding ratios up to 1.5. A low melting eutectic alloy (Wood's metal) was used as material "A" in a mock-up blanket module with electric heaters to simulate neutron heating. Water was used as the coolant "B." Local failures in the steel first wall were simulated by drilling holes. No leakage was observed into the surrounding vacuum, up to the maximum hole diameter (1/8 in.). The NOEL blanket would provide absolute protection against leakage if substantial through-failures occur in the first wall. Blanket operational periods could thus be much longer, perhaps up to thirty years.

1. INTRODUCTION

The NOEL blanket is a radically new blanket approach that should eliminate the possibility of leaks from the blanket and first wall coolant circuit into the plasma chamber even if large through-cracks develop in the first wall. Blankets for practical magnetic fusion power reactors will experience extremely severe radiation damage. High-neutron fluences and substantial in-situ generation of interstitial hydrogen and helium will cause extensive loss of ductility and crack growth in the first wall. In addition, if Tokamak reactors continue to be the main-line route, the many thousands of thermal cycles on the first wall and blanket will greatly exacerbate material problems. The various fusion blanket design approaches that have been proposed in reactor reference studies suffer from a serious common defect; that is, exceedingly small leaks (i.e., a total area of $\sim 10^{-3}$ cm^2, out of a total blanket area of one to two thousand m^2) in the first wall of the reactor blanket area will result in sufficient coolant leak that the plasma cannot operate. It appears to be very difficult, and indeed may not be feasible, to develop first wall materials that will be able to meet the very exacting integrity requirements, given the high-neutron fluences ($\sim 10^{23}$ n/cm^2), interstitial gas formation (several thousand appm of helium), and extensive thermal cycling ($\sim 10^5$ to 10^6 cycles for

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Tokamaks) that first walls will be subjected to.

Brookhaven National Laboratory has proposed several possible approaches to circumvent this problem, including redundant cooling [1], conduction-cooled blankets [2], and high-temperature radiation transport blankets [3]. More recently, BNL has proposed and successfully tested a new blanket concept called NOEL (NO External Leak) that appears to eliminate the leak problem. A frozen self-healing layer is maintained behind the first wall which prevents any possibility of leakage through the first wall. In tests of the NOEL concept, large failed regions were deliberately induced in the first wall of the simulated blanket module without resulting in coolant leakage into the surrounding vacuum enclosure.

Structural analyses indicate that under the conditions of neutron damage and thermal cycling in Tokamak reactors, small initial flaws can grow and penetrate the first wall in a few months [4]. If this occurs, the resultant leaks will shut down the plasma. A very small leak area in the first wall, e.g., $10^{-3} cm^2$ out of a total area of $\sim 10^7 cm^2$, will cause sufficent impurity poisoning of the plasma to shut down the reactor. Finding such leaks (or multiple smaller leaks) and repairing or replacing failed blanket sections will be extremely difficult, and may result in unacceptably low reactor availability.

The potential benefits of developing practical leak-proof blankets are very large. Development of an approach that cannot leak is of very great importance to the fusion program. Not only is reactor reliability greatly enhanced, but lifetime blankets should be feasible, which would eliminate the very difficult maintenance problems associated with removing old and installing new blankets. Besides eliminating reactor shutdowns due to leaks, such approach could lead to lifetime blankets, which would make reactors much simpler and cheaper. In addition, a wider range of structural materials would be available, and R&D costs and time necessary to develop satisfactory materials should be much less with the NOEL blanket concept. NOEL blankets use the unique property of high-energy fusion neutrons to deposit their energy deeply in matter, instead of on the surface. With appropriate design, this permits the establishment of a frozen, self-healing layer behind the first wall that will prevent coolant leaks even if numerous cracks or failed regions appear in the first wall. Analyses, described later, have been used to examine the most promising leak-proof blanket approaches. An experimental simulation of one type of NOEL blanket has been carried out; it demonstrated no leak performance when failed regions were generated in the first wall.

2. NOEL BLANKET DESIGN

The typical NOEL blanket is illustrated in fig. 1. The blanket region is composed of a number of modules, typically ~70 cm in radial thickness and ~30 cm wide. The module shells can be of any structural material, including stainless steel, titanium, aluminum, etc. One end of each module shell faces the plasma, serving in effect as the first wall, while the other end is welded into a backing plate of the same structural material. The backing plate can be cooled by the same circuits that cool the module shells or by separate circuits. Inside the module shells, there is a relatively thick layer of solid material "A," which is maintained in the solid state by imbedded tubes carrying a liquid or gas coolant, (material "B") at a temperature substantially below the freezing point of material "A." A number of these modular-backing plates are attached to a fixed shield around the plasma chamber. A complete blanket assembly for a fusion reactor would require several hundred such modules. The interior of the module has few or no coolant tubes, so that material "A" is liquid in this region. The pressure of material "A," P_A, is maintained at a higher level than the pressure of the coolant, P_B, so that no leaks of "B" can occur into the solid or liquid "A" regions even if cracks develop in the coolant tubes. If cracks develop in the module shells, the solid material "A" will not leak to the plasma chamber. The flow velocity of solid "A" through cracks will essentially be zero, while the vapor pressure of any solid material "A" is sufficiently low that no appreciable plasma poisoning will result from evaporation and transport of "A" vapor through cracks, even if the total crack area is very large (e.g., on the order of hundreds of cm^2).

Table I lists some potential choices for the structural material, material "A" and material "B." Stainless steel and aluminum (SAP) are chosen as the structural materials. The aluminum shells can be extruded SAP (sintered aluminum product) material or aluminum alloy. SAP is more desirable because of its higher operating temperature. It contains a dispersoid of Al_2O_3 powder in an aluminum matrix (typically ~10% by weight of Al_2O_3) and retains good stress rupture strength at elevated temperatures, e.g., ~10 ksi at 400°C. Because of the higher thermal conductivity of SAP, a SAP shell can be thicker than a stainless steel shell.

Among the potential choices of "A"-type materials listed in table Ia, metallic Pb (with a small addition of Li for tritium breeding), LiPb, Li_7Pb_2, fused salts of $LiF{\cdot}BeF_2$, and $2LiF{\cdot}BeF_2$ are promising candidates. For material "B," Heat Transfer Salt (HTS, content 40% $NaNO_2$, 7% $NaNO_3$, 53% KNO_3), Terphenyl and FLIBE (fused salts, $LiF{\cdot}BeF_2$, $2LiF{\cdot}BeF_2$) are the first choices for the anlayses.

A wide range of designs can be developed which will prevent leaks to the plasma chamber, achieve a tritium breeding ratio above one, and a reasonable tritium inventory, and have a good power cycle efficiency. Table Ib lists some promising design combinations for NOEL blankets. In the designs considered, the module shell thicknesses range from 0.5 to 1.0 cm for stainless steel, and 1 to 2 cm for aluminum (SAP). Coolant tube diameters range from 0.75 to 1.0 cm. For blankets where material "A" is a mixture of LiF and BeF_2 salts, the tritium breeding ratios range from 1.0 to 1.1. If material "A" is an alloy of Pb and Li, breeding ratios range from 1.4 to 1.6.

3. THERMAL ANALYSIS

The thermal-hydraulic studies of the NOEL blanket have been carried out, based on the module shell geometry shown in fig. 1. Surface and internal temperatures are determined using the Heating-5 [5] finite difference conduction code. Neutron flux distributions are calculated with a 1-D ANISN model using a P_3S_8 approximation, 100 energy groups, and ENDF B-IV cross sections. Neutron and gamma heating distributions are also computed.

The steady-state and transient temperature distributions of the module shell are obtained using Heating-5. The assumptions are as follows:

1. The module is divided into regions by various materials.
2. Physical properties are uniform for each region.
3. A constant temperature is maintained on the wall of the cooling tubes by the coolant "B."
4. The neutron + gamma heat deposition is constant during the plasma burn and drops to zero during the dwell, between burns.
5. The incident heat flux (Bremsstrahlung radiation) to the first wall is assumed to be 20% of the gross wall load. For example, at a gross wall load of 2.0 MW/cm^2 during the plasma burn and zero during dwell. A 100-sec plasma burn and 20 sec dwell are selected for the calculations.

Six blanket designs have been examined: Nos. 1 and 2 use SAP module shells, while Nos. 3 to 6 use stainless steel module shells. Table II summarizes the materials and dimensions for these blankets.

Thermal calculations have been carried out for the six blankets based on the physical properties given in table III and neutron and gamma heating rates given in table IV. The energy deposition distributions in table IV correspond to a gross wall load of 2.0 MW/m^2.

The steady-state temperature distribution for NOEL blanket No. 1 is shown in fig. 2. A solid layer, 1.3 cm thick, is observed using Li_7Pb_2 as material "A" with only a single set of coolant tubes, the internal temperature climbs well over 1000°C. Placing a second set of coolant tubes 7 cm behind the first wall dramatically reduces the inner temperature; in fact, it results in a completely frozen layer in excess of 10 cm in thickness. This appears too thick for optimum performance, so that the second set of coolant tubes should be placed much further behind the first wall. Figure 3 shows the same blanket with the coolant tubes placed 21 cm behind the first wall. The maximum steady-state temperature is ~900°C, and the liquid zone is approximately 10 cm thick between the two sets of tubes. Figure 3 also shows the transient temperature distribution starting from a completely cold blanket. The approach to steady state requires a relatively long time, on the order of 10^4 seconds. The large latent heat of fusion of Li_7Pb_2 moderates temperature swings resulting from the on-off nature of plasma burns in Tokamak reactors. Figure 4 shows the temperature swings near the solid/liquid boundary in blanket No. 1. This moderating of temperature swings is also employed in the NUWMAK design [6], which also uses a two lead-lithium alloy.

Steady state and transient temperature distributions for NOEL blanket No. 2 are shown in figs. 5 and 6, respectively. The relatively low thermal conductivity of $LiF \cdot BeF_2$ salts (FLIBE) results in very high-temperature gradients in the solid phase (~1000 K/cm for a heat flux of 10 W/cm^2). In order to operate at wall loads of several MW(th)/m^2 with a reasonable solid phase thickness (e.g., 0.5 to 1.0 cm) around the tubes, some method of conductivity enhancement in the solid phase is used. Extended heat transfer surfaces on the coolant tubes (e.g., longitudinal fins or a splined surface) or a honeycomb or plate-type structure (made of metal, graphite, or SiC, etc.) around the tubes appear suitable. Figure 5 also shows that with conductivity enhancement, a solid layer thickness of 0.5 cm is achieved by using 50% SAP in 1-cm-thick region around the cooling tubes. NOEL blanket No. 3 (fig. 7) has a stainless steel module shell and a higher melting fused salt of $2LiF \cdot BeF_2$ (460°C). An even thicker solid layer of ~1 cm is achieved using a 50% SAP region for conductivity enhancement.

Because of the high electrical resistivity of fused salts, fluid material "A" can be readily pumped out of the module to an external heat exchanger to extract the fusion energy deposited in the module interior. Figure 8 shows a solid layer of ~1 cm thickness when the interior liquid "A" in blanket No. 3 is circulated to an external heat exchanger.

NOEL blanket No. 4 uses a stainless steel module shell, Li_7Pb_2, and FLIBE coolant ($LiF \cdot BeF_2$). A frozen layer thickness of ~1 cm (fig. 9) is obtained with a single row of cooling tubes at 0.5 cm behind the first wall. Placing a second set at 6.7 cm greatly increases the thickness, so that both sets are enclosed in a single frozen layer. As in NOEL blanket No. 1, the optimum location is much further behind the first wall.

The analyses for blankets Nos. 1 through 4 assumed 1-D geometry and examined temperature distributions only in the radial direction. Since the module shells have sidewalls, the actual temperature distributions will reflect the necessity of placing coolant tubes along the sidewalls to maintain a frozen layer there also.

4. CONCLUSIONS AND DISCUSSIONS

The results of the thermal analyses and simulated module tests of the NOEL blanket indicate that the concept is feasible; coolant leaks to the vacuum chamber can be prevented, even if through cracks occur in the first wall.

Acceptable temperature distributions and frozen layer thicknesses can be achieved with either metallic (e.g., lithium-lead alloys) or fused salt (e.g., FLIBE) materials for module fillings. The higher thermal conductivity of metallic module fillings allows the extraction of heat without needing to circulate the material from the liquid zone to an external heat exchanger; that is, all of the fusion energy deposited in the module can be removed directly through the coolant tubes that maintain the frozen layer. This eliminates concerns about MHD pressure drop effects associated with moving fluids with high electrical conductivities through strong magnetic fields.

The low thermal conductivity of fused salts, on the other hand, appears to require circulation of material from the liquid zone to an external heat exchanger, if they are used as the material "A" in NOEL blanket modules. Without such circulation, excessive internal temperatures in the liquid interior region would occur. Fortunately, fused salts have sufficiently low electrical conductivities that MHD effects will not be a problem if the liquid interior is circulated to an external heat exchanger.

NOEL blankets have high thermal inertia because of the high latent heat of fusion of the phase change material "A." As a result, coolant temperature changes will be relatively small during a plasma burn cycle of the type expected in Tokamak reactors. The principal effect will be a relatively small oscillation in thickness of the frozen layer during the burn cycle. The high thermal inertia also leads to relatively long times (i.e., several thousand seconds) being required to approach a steady-state temperature distribution after starting up from a cold blanket condition. This does not appear to be a problem. The effects of volumetric changes associated with startup and shutdown were not investigated. In general, there is a large volumetric change associated with melting and freezing, and there will have to be some relief volume built into the module to accommodate it. For stagnant module fillings, this could be a pressurized gas plenum, or a bellows-type coolant tube. For module designs in which material from the liquid interior is circulated to an external heat exchanger, volumetric changes can be accommodated by a pressurizer outside the blanket. Another possibility is the use of phase change materials with essentially zero volumetric change on freezing or melting. Appropriate mixtures of LiF and BeF_2 can achieve this condition, for example, and it may be possible to formulate zero volume change metallic alloys.

The NOEL concept appears to be a very promising approach for fusion blankets. It offers reliable performance, lifetime operation, and minimizes the need for a long, expensive development program on blanket structural materials. If crack-proof materials cannot be developed, it may prove to be the only route to achieving a practical blanket.

6. REFERENCES

[1] YU, W-S. et al., Trans. Amer. Nucl. Soc. 27, 74 (1977).

[2] YU, W-S. et al., 7th Symposium on Engineering Problems of Fusion Research, Knoxville, 25-28 October 1977. Proceedings pp. 1478-82.

[3] FILLO, J.A. and POWELL, J.R., Nucl. Eng. & Design 391, 181 (1976).

[4] CRAMER, B.A. and DAVIS, J.W., McDonnell Douglas Astronautics Report, St. Louis, MO.

[5] TURNER, W.D. et al., Oak Ridge National Laboratory Report, ORNL/CSD/TM-15 (1977).

[6] CONN, R.W., 3rd Topical Meeting on Technology of Controlled Nuclear Fusion, Sante Fe, 9-11 May 1978. Proceedings pp 1049-59.

TABLE Ia

Material Choices for NOEL Blanket

Structural Material [Max oper. temp.]	Material "A" (m.p.)	Material "B" (m.p.) [Max oper. temp.]
Stainless steel [500°C]	Pb[Li] (337°C)	He [500°C]
Titanium [500°C]	PbLi (482°C)	H_2O* [200°C]*
Vanadium [500°C]	Li_7Pb_2 (726°C)	HTS** (143°C) [500°C]
Molybdenium [600°C]	PbF_2 (822°C)	$NaF[BeF_2]_x$ (~340°C) [500°C]
Aluminum [SAP] [400°C]	$LiF.BeF_2$ (360°C)	Terphenyl [350°C]
Aluminum Alloy 70°C]	$2LiF.BeF_2$ (460°C)	$LiF.BeF_2$ (360°C) [500°C]
	BeF_2 (797°C)	$NaF[BeF_2]_x(LiF)_y$ (~300°C)
	LiF (848°C)	[500°C] S (~120°)
	Li_2S (900°)	[500°C] $S[Li_2S]_x$ (~120°C)
	Li_4Si (600°C)	 [500°C]
	PbO (886°C)	

TABLE Ib

Promising Design Options for NOEL Blanket

Structure	Material "A"	Material "B"
Aluminum [SAP]	PbLi or Li_7Pb_2	Terphenyl
Aluminum [SAP]	$LiF.BeF_2$	Terphenyl
Stainless	$2LiF.BeF_2$	HTS
Stainless	Li_7Pb_2	$LiF.BeF_2$
Stainless	PbLi or Li_7Pb_2	HTS

* H_2O limited to ~240°C by maximum pressure in module ($\leq$500 psi).

** HTS = Heat Transfer Salt [40% $NaNO_2$.7% $NaNO_3$.53% KNO_3].

TABLE III

Physical Properties

Structural material	k W/cm-°C	ρ g/cm³	C_p J/g°C	ΔH J/g	m.p. °C
Aluminum (SAP)	1.68	2.75	0.942		
Stainless steel	0.172	7.968	0.437		
Phase change Material "A"					
Li_7Pb_2	0.403	3.63	0.36	250.0	726.0
$LiF.BeF_2$	0.008	1.94	2.35	447.9	363
$2LiF.BeF_2$	0.01	2.214	2.39	447.9	460
LiPb	0.349	6.85	0.261	37.35	482.0

TABLE II

Cooling tubes: o.d. (cm) i.d. (cm)
SAP: [illegible] [illegible]
Stainless steel: [illegible] [illegible]
[illegible] [illegible]

NOEL blanket	Structural material (thickness)	Phase change material "A" (m.p.) (30 cm)	Coolant material "B" (temp.)	Moderator [illegible] graphite [illegible] (30 cm)	Cooling plane (10 cm)	Remarks
1	SAP (1 cm)	Li_7Pb_2 (726°C)	Terphenyl [illegible]	Li_7Pb_2	SAP	With and without additional cooling tubes
2	SAP (1 cm)	$LiF·BeF_2$ [illegible]	Terphenyl [illegible]	[illegible]	SAP	With and without conductivity enhancement
3	Stainless steel (0.5 cm)	$2LiF·BeF_2$ [illegible]	HTS [illegible]	$2LiF·BeF_2$	SS H_2O	With and without conductivity enhancement
4	Stainless steel (0.5 cm)	Li_7Pb_2 [illegible]	$LiF·BeF_2$ [illegible]	Li_7Pb_2	SS H_2O	With and without additional cooling tubes
5	Stainless steel (0.5 cm)	Li_7Pb_2 [illegible]	HTS [illegible]	[illegible] graphite [illegible]	SS HTS	Two-dimensional analysis
6	Stainless steel (0.5 cm)	LiPb [illegible]	HTS [illegible]	[illegible] LiPb	SS HTS	Two-dimensional analysis square cooling channels

NOTE: [illegible]

TABLE IV

Neutron and Gamma Heating Rates, W/cm³
Peak Wall Load = 2.0 MW/m²

Distance from first wall, cm	NOEL Blanket No.					
	1	2	3	4	5	6
0.0	9.685	10.92	20.25	16.46	17.68	12.01
0.13			20.25	16.44	17.08	12.00
0.25	9.685	10.92	19.91	16.07	16.37	10.00
0.50	9.407	10.62	19.25	11.90	15.55	8.90
1.00	8.847	10.03	10.00	10.56	13.36	7.00
2.0	10.78	10.84	9.330	9.910	8.05	6.50
4.0	9.498	9.601	8.614	8.596	7.30	5.50
6.0	7.478	7.741	7.362	6.970	6.50	4.50
8.0	6.173	6.489	6.359	5.892	5.97	3.50
10.0	5.247	5.548	5.544	5.109	5.50	3.20
12.0	4.558	4.793	4.878	4.918	5.00	3.10
14.0	4.038	4.197	4.334	4.071	4.68	3.00
16.0	3.656	3.728	3.980	3.748	4.05	2.80
18.0	3.403	3.379	3.580	3.503	3.83	2.75
20.0	3.311	3.176	3.400	3.574	3.19	2.[illegible]
21.0	3.347	3.136	3.317	3.776	3.08	[illegible]
22.0	3.509	3.254	1.825	1.947	2.98	2.20
24.0	1.760	1.714	1.705	1.862	2.78	2.00
30.0	1.570	1.348	1.449	1.589	2.00	1.55
40.0	1.008	0.757	0.816	0.996	1.20	1.15
50.0	0.319	0.356	0.383	0.419	0.75	0.80
60.0	0.224	0.154	0.140	0.173	0.38	0.70
70.0	0.088	0.065	0.059	0.017	0.18	0.78
71.0	0.015	0.040	0.093	0.016	0.16	0.50
75.0	0.707	0.101	0.088	0.051	0.12	0.40
80.0	0.010	0.016	0.026	0.025	0.076	0.02
82.0	0.010	0.014	0.017	0.017	0.078	0.01

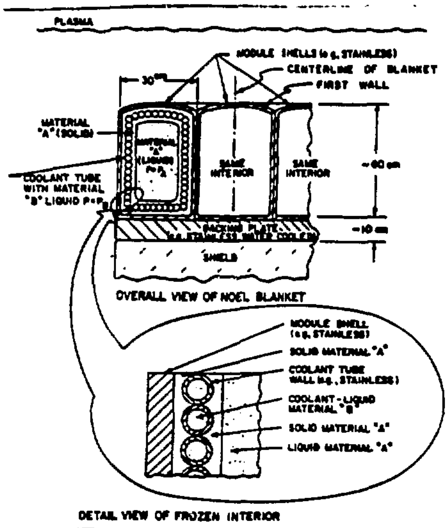

Fig. 1. NOEL blanket

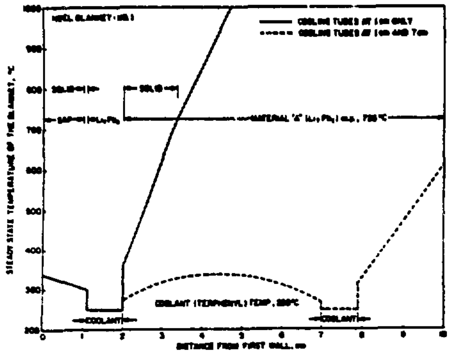

Fig. 2. Steady-state temperature of NOEL blanket

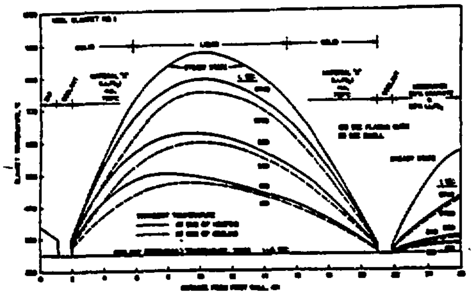

Fig. 3. Transient temperature of NOEL blanket No. 1

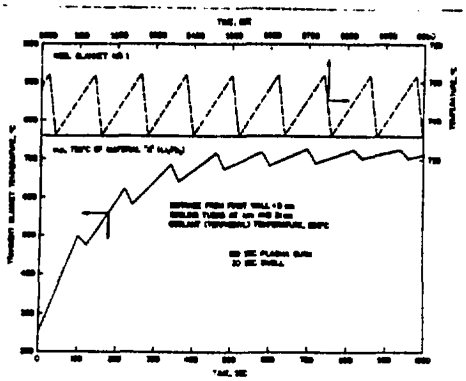

Fig. 4 Transient temperature of NOEL blanket No. 1

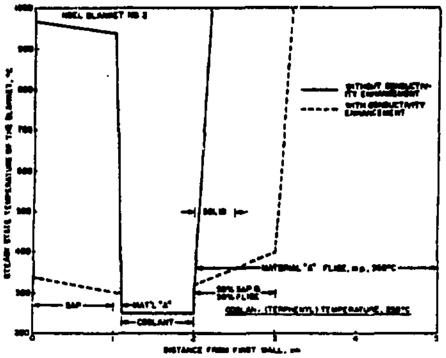

Fig. 5. Steady-state temperature of NOEL blanket No. 2

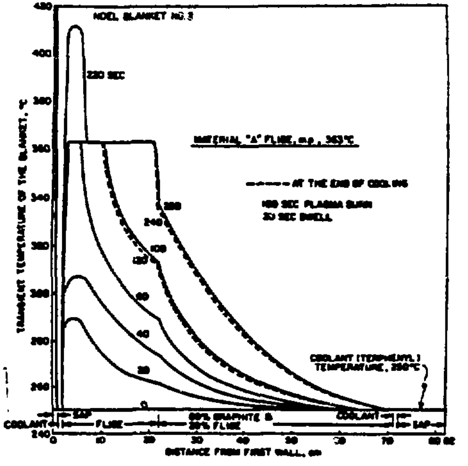

Fig. 6. Transient temperature of NOEL blanket No. 2

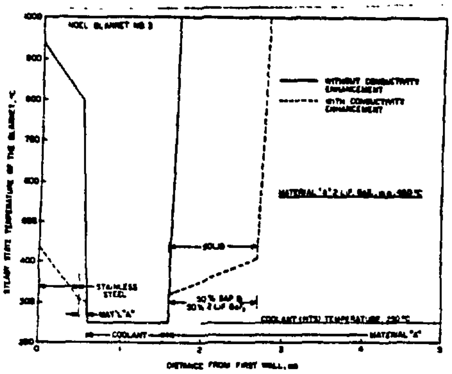

Fig. 7. Steady-state temperature of NOEL blanket No. 3

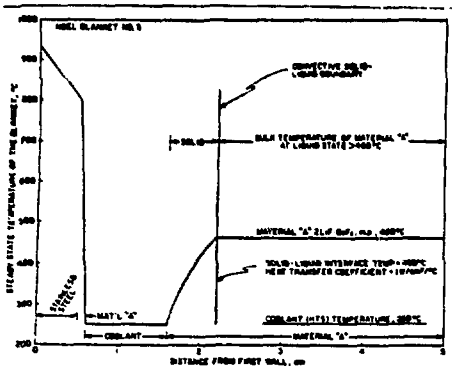

Fig. 8. Steady-state temperature of NOEL blanket No. 3, with convection

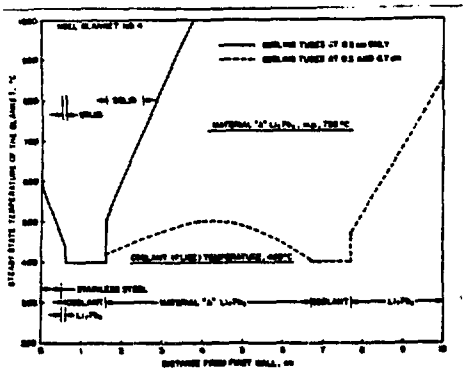

Fig. 9. Steady-state temperature of NOEL blanket No. 4