CONF-771029--171

Submitted to Seventh Symposium on Engineering Problems of Fusion Research
Knoxville, Tn. - Oct. 25-28, 1977

HIGH TEMPERATURE BLANKETS FOR THE PRODUCTION OF SYNTHETIC FUELS

BNL-23414

J. R. Powell, M. Steinberg, J. Fillo, and H. Makowitz
Department of Nuclear Energy
Brookhaven National Laboratory
Upton, NY 11973

Summary

The application of very high temperature blankets to improved efficiency of electric power generation and production of H_2 and H_2 based synthetic fuels is described. The blanket modules have a low temperature (300-400°C) structure (SS, V, Al, etc.) which serves as the vacuum/coolant pressure boundary, and a hot (>1000°C) thermally insulated interior. Approximately 50-70% of the fusion energy is deposited in the hot interior because of deep penetration by high energy neutrons. Separate coolant circuits are used for the two temperature zones: water for the low temperature structure, and steam or He for the hot interior. Electric generation efficiencies of ∿60% and H_2 production efficiencies of ∿50-70%, depending on design, are projected for fusion reactors using these high temperature blankets.

Introduction

The high energy neutrons from DT fusion reactions can penetrate very deeply into materials before their kinetic energy is transformed to heat. This unique feature of fusion energy, and the fact that ∿80% of the energy released per DT fusion reaction is carried by 14 MeV neutrons, can dramatically increase the efficiency of electric power generation, as well as produce H_2 and H_2 based synthetic fuels at high efficiency.

This deep penetration of the primary neutrons makes two temperature region blankets feasible. In this concept, a relatively low temperature metallic structure is the vacuum/coolant pressure boundary, while the interior of the blanket, which is a simple packed bed of non-structural material, operates at very high temperatures. Separate coolant circuits are required for the two temperature regions, as well as a thermal insulator between them.

These types of blankets have been extensively investigated in connection with BNL's program on minimum activity aluminum blankets.[1,2,3] To achieve good thermal cycle efficiency with aluminum structure, where the aluminum must operate at relatively low temperature (e.g., ∿200-400°C) the interior of the blanket operates at ∿800°C with He coolant. Approximately 70% of the fusion energy release can be extracted from the hot interior. Figure 1 shows a cross section of such a blanket, where several modular structural shells are held on a cool structural backing plate. The complete assembly of modular shells, thermal insulators, hot interiors, and backing plate is termed a "module". A number of these modules, typically ∿200, form the complete blanket. Individual modules can be removed through small access ports at the outside of the blanket/shield assembly (Figure 2).

Materials for the hot interior are capable of much higher temperatures than the 800°C HTGR type conditions assumed in previous designs. Further, the coolant for the hot interior need not be helium, but can be a process fluid like steam or CO_2. This direct heating feature eliminates the transfer of high temperature heat across a metallic primary heat exchanger, which could severely limit the maximum temperature and choice of coolant.

Table I shows the melting point of some candidate high temperature refractory materials for the hot

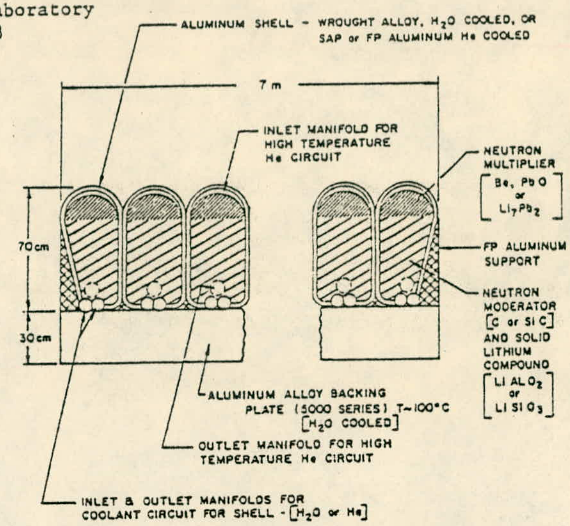

Fig. 1
CROSS SECTION OF ALUMINUM MODULE FOR HIGH WALL LOAD FUSION REACTOR
[UWMAK SIZE PLASMA]
54 SIDEWALL MODULES

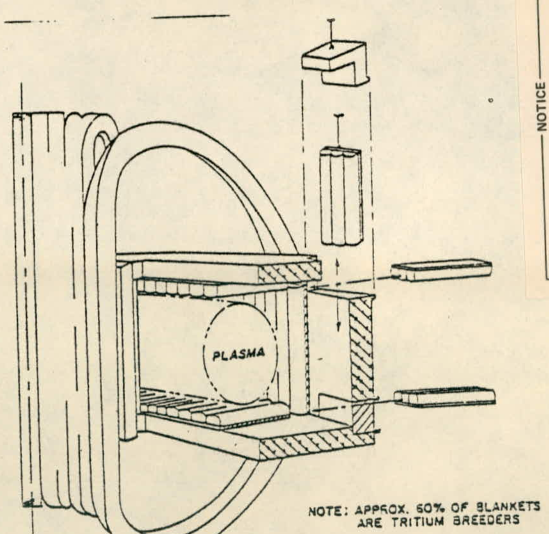

Fig. 2
Schematic Showing Module Removal

interior. All appear compatible with helium or argon coolant. Only the oxide refractories, and perhaps some carbides (e.g., SiC), would be compatible with steam or CO_2 coolant. The hot interior probably would be a packed bed of small diameter (1-2 cm) rods or balls. The low peak power densities (∿10 MW/m^3) and the large surface area in the blanket should result in relatively low temperature differences (on the order of 100°C) between the coolant and the packed bed.

Studies have been made of the application of the two temperature blanket concept to advanced power cycles using inert gas coolants, involving MHD generators [4] and high temperature direct cycle helium turbines.[5] Substantial efficiency gains have been projected, but the technology is undeveloped, and the fusion energy released in the low temperature structure is not available for the advanced power cycle. A

Work performed under the auspices of The Department of Energy.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

Table I

Melting Points of Some High Temperature Refractories

Carbides	M.P.(°K)	Oxides	M.P.(°K)	Nitrides	M.P.(°K)
HfC	4161	ThO_2	3573	TaN	3361
TaC	4148	MgO	3098	BN	3273
NbC	3773	HfO_2	3085	TiN	3205
ZrC	3533	ZrO_2	2973	ZrN	3203
TiC	3523	CaO	2843		
SiC	3100	BeO	2725		
VC	3083	Al_2O_3	2323		

better approach is the FAST (Fusion Augmented Steam Turbine) cycle,[6] where the steam is superheated directly in the hot interior of the module. Open cycle gas turbines presently operate at much higher inlet temperatures than the conventional steam turbine. The latter has been held at an inlet temperature of ∿1100°F for many years because of material temperature limitations in the steam generator/superheater. The present inlet temperature for gas turbines is ∿2000°F (1090°C) with a projection of ∿2400°F (1320°C) by the early 1980's.[7] With direct superheating of steam in fusion blankets, overall cycle efficiency can be raised from the ∿38% level achieved in fossil fuel steam plants to a level of ∿60% assuming that the turbine inlet temperature is 2000°F (1090°C).

High temperature turbine cycles based on the combustion of hydrogen and oxygen have been extensively investigated,[8,9] with projected turbine inlet temperatures up to 3000°F. Operation at these temperatures will require development of water cooled or ceramic blades. This would increase the efficiency of the FAST cycle to ∿70%; however, the increase may not warrant the major turbine development program that would be required.

Oxide refractory materials that are compatible with high temperature steam, such as MgO, Al_2O_3, or BeO, can be used for the hot interior of the blanket module. This application and the associated blanket is discussed in the following section.

The second major application of high temperature blankets is the generation of high grade process heat. There are many potential uses for this process heat, such as steel making, calcination, etc., but the largest and most important appears to be generation of hydrogen through same type of water splitting process. The H_2 could then be used directly as a synthetic fuel, or could be reached with some form of carbonaceous feed stock to make hydrocarbon fuels or methanol.

There are a variety of candidate water splitting processes, including pure thermochemical, hybrid electro-thermochemical, direct thermal decomposition, and high temperature electrolysis. These are discussed in some detail in a panel study[10] on fusion synfuels production. One of the most promising is high temperature electrolysis, in which a combination of high temperature thermal and electric energy are used to split water. This application and the associated blanket designs are discussed in a later section.

High Temperature Blankets and the FAST Cycle

Figure 3 shows a flow sheet for the FAST cycle. Approximately 30-50% of the steam in the turbine circuit flows through the blanket, emerging at a high temperature, typically 1500-1800°C. It then mixes

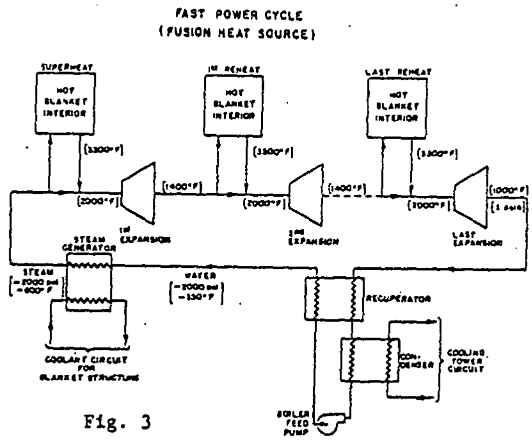

Fig. 3

with the main steam flow; the resultant mixed temperature is controlled to the desired turbine inlet temperature by the relative flow proportions. Bypassing most of the steam flow around the blanket reduces blanket pressure drop, flow velocity, piping dimensions, and the carry over of blanket fines. Figure 4 shows the efficiency of the FAST cycle as a function of turbine

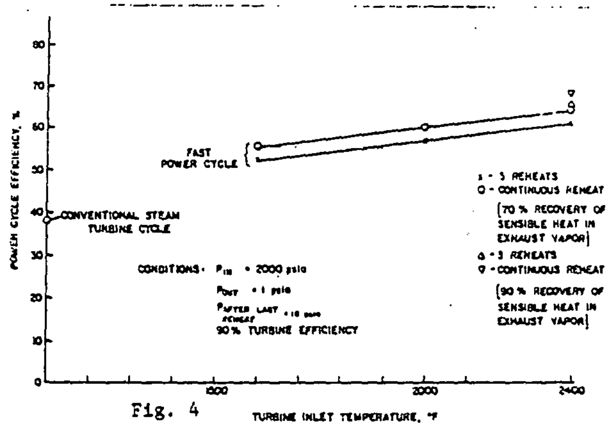

Fig. 4

inlet temperature from 1600°F (870°C) to 2400°F (1320°C), for the case of three reheats and the limiting case of with continuous reheat, turbine inlet pressure of 2000 psia (1.38×10^7 N/m^2) and exhaust pressure of 1 psia (6.88×10^3 N/m^2). The FAST cycle efficiency of ∿60% which could be achieved with essentially developed turbine technology, can be very important for fusion. It will greatly reduce unit $/ KW(e) capital costs for a fusion power plant, as well as reduce the thermal pollution levels per KWH by a factor of 3, as compared to an LWR.

An additional feature of the FAST cycle is the efficient use of the hot/cool energy splits in the blanket. The fusion energy from the cool structure produces high pressure saturated steam, and the high temperature heat from the interior superheats it. Alternate advanced power cycles that only use the high temperature need very high efficiency to match the FAST cycle, since the low temperature heat from the structure only produces ∿33% efficiency in a separate conventional steam cycle. For a 70/30 hot/cool split, an alternate cycle would require an efficiency of 70% to achieve an overall average efficiency of 60% for the reactor.

Table IIa shows the principal neutronic features of illustrative blanket designs using MgO, Al_2O_3 and BeO for the hot interior and stainless steel or V for the cool structure, at a gross wall load of 2.8 MW(th)/m^2. The thermal insulator is a low density block or fibrous layer of the same material as the hot interior. The

Table IIa

Steam Cooled Modules for FAST Cycle or HTE Heat

Blanket Interior	MgO			Al_2O_3	BeO	
Blanket Structure	SS	V	SS	SS	SS	V
% of Fusion Energy in Hot Interior	55	58	49	59	45	44
T/N (0=No $LiAlO_2$)	0	0	0.48	0	0.95	1.00
Energy Per Fusion, MeV	21.6	20.5	20.0	22.0	23.3	22.1
Peak Heating in Shell (W/cm^3 at 2.82 MW(th)/m^2	34.6	26.8	27.8	31.8	28.7	20.3
Thickness of Multiplier Region, CM	--	--	--	--	70	70
Thickness of Shell, cm Temperature, °C	0.75	0.75	0.75	0.75	0.75	0.75
Hot Interior	2000	2000	2000	1500	2000	2000
Cold Structure	400	400	400	400	400	400

neutronic analyses used a 1-D 100 group ANISN model with ENDF-B-IV cross sections. A P_oS_4 approximation was used in most cases, with some P_3S_8 analyses as checks. Generally, the P_oS_4 analyses predicted breeding ratio fairly closely, but tended to underestimate the energy deposition in the hot interior.

For the blankets investigated, the total fusion reaction energy, Q, ranges from ∿20 to ∿23 MeV, depending on the degree of neutron multiplication and the amount of energy released by neutron capture. The fraction of total fusion reaction energy deposited as heat in the hot interior ranges from ∿50% to ∿70%, depending on blanket materials and geometry. The remainder is deposited as heat in the cool structure as a result of bremsstrahlung, ion impacts, neutron and gamma heating, and neutron absorption.

In previous high temperature blanket designs, tritium was bred in a solid lithium compound (e.g., $LiAlO_2$) in the high temperature interior. The characteristic holding time for release into the inert gas coolant was only a few minutes, from which it was recovered. With steam coolant, however, this mode of tritium breeding is not feasible, since the tritium cannot be readily extracted from the steam circuit. Instead, a solid lithium compound can be placed on the outer surfaces of the module. The bred tritium will then diffuse the vacuum chamber and be recovered from the plasma exhaust. Breeding ratios of ∿0.4 to ∿0.6 can be achieved with MgO or Al_2O_3 interiors, but breeding ratios of ∿1.0 require BeO interiors. This is an important constraint on the FAST cycle. The FAST concept requires either that the Be resource base be adequate for a large fusion economy, or that makeup tritium be bred in other modules or reactors with high breeding ratios.

Blankets for High Temperature Electrolysis of Steam

Figure 5 shows a simplified flow sheet for a fusion reactor producing H_2 by the high temperature electolysis (HTE) of steam. Ceramic electrolyzers have operated satsifactorily at ∿1000°C for long periods, and it appears possible to significantly increase their operating temperature. At 1400°C ∿30% of the input energy is process heat, with the balance electricity. At 1800°C, the total input is essentially the same, but ∿50% is process heat. Figure 6 shows the overall efficiency of H_2 production as a function of electrolysis temperature. Efficiency is defined as output H_2 combustion energy divided by input fusion energy. H_2 generation efficiencies of ∿70% appear possible using the FAST cycle for electric generation, and ∿55% using a conventional power cycle.

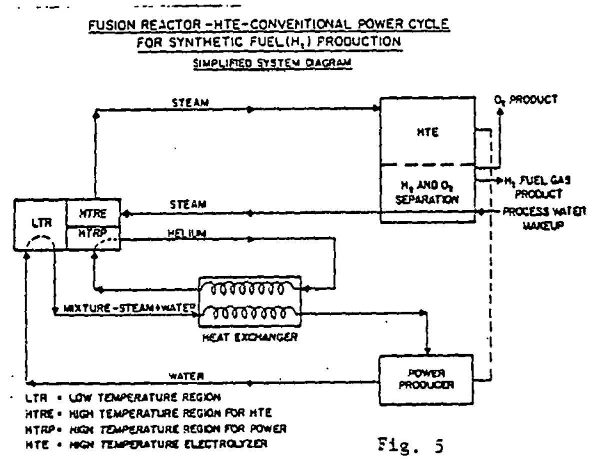

Fig. 5

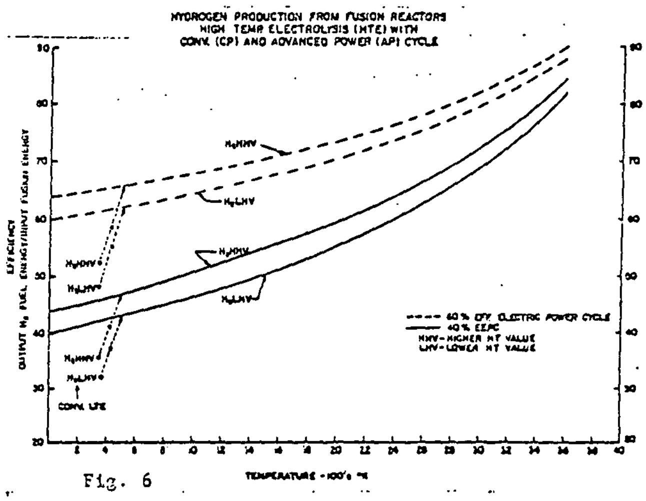

Fig. 6

The flow sheet in Figure 5 shows a balanced fusion synfuels plant in which all of the electricity produced is consumed in the electrolyzers. Two types of blanket modules are required. The modules producing high temperature steam process heat for the electrolyzers will be similar to these described for the FAST cycle. The modules producing heat for electricity generation could either be of the FAST cycle type and produce electricity at ~60% efficiency or could use helium or other inert gas coolant for the hot interior. In the latter case, the inert gas would superheat steam in a conventional power cycle to produce electricity at ~40% efficiency. Table IIb lists the principal neutronic features of these helium cooled modules using SS or V structure, with a hot interior of graphite, $LiAlO_2$ and a neutron multiplier (PbO or Be). As in the other module designs, a separate water coolant circuit is used to maintain the structure at a relatively cool temperature, i.e., ~300 to 400°C.

Table IIb

He Cooled Modules for Electricity Generation

PbO-C		Be-C	
SS	V	SS	V
68	72	73	77
1.29	1.39	1.79	1.87
20.2	18.9	25.2	24
24.0	12.6	21.2	11.5
20	20	20	20
0.75	0.75	0.75	0.75
700	700	800	800
400	400	400	400

Table III shows the fraction of the total blanket occupied by the HTE modules, and the tritium breeding ratio required in the electric generation modules if the reactor is to be self-sufficient in tritium (i.e., average T/n for the reactor = 1.0), as a function of tritium breeding ratio on the HTE module, power cycle efficiency, and the split between process heat and electricity in the HTE units. The reactor can easily be self-sufficient in tritium if a conventional power cycle is used. With the FAST cycle, BeO must be used for the hot interior of the HTE and FAST cycle modules, or makeup tritium must be supplied from another fusion reactor.

The design of the blanket and the HTE system is described in more detail elsewhere.[11]

Table III

Tritium Breeding Requirements for Fusion Modules

	Tritium Breeding HTE Heat Modules (BR = 0.7)		Non-Breeding HTE Heat Modules (BR=0.0)	
Percentage of HTE Energy as Process Heat	30	50	30	50
Fraction of Blanket Occupied by HTE Heat Modules				
E_{ELEC} = 0.40	0.15	0.28	0.15	0.28
E_{ELEC} = 0.60	0.205	0.38	0.205	0.38
Tritium Breeding Ratio for Electricity Prod.				
E_{ELEC} = 0.40	1.05	1.12	1.18	1.39
E_{ELEC} = 0.60	1.08	1.18	1.26	1.61

Conclusions

It appears feasible to generate very high temperatures, approaching 2000°C, through neutron and gamma heating of the interior zone of a fusion blanket. Depending on blanket design, ~50-70% of the total fusion energy can be extracted as high temperature heat from this zone. The remainder of the fusion energy is extracted from a relatively cool (~300-400°C) metallic structure composed of a number of modular shells, which serve as the first vacuum wall and container for the hot interior. The cool structure can be cooled by water, fused salt, etc., while the hot refractory interior (e.g., MgO, Al_2O_3, etc.) is cooled by an inert gas or process fluid, e.g., steam or CO_2. Use of such high temperature blankets can increase electric power cycle efficiency to ~60%, as well as producing H_2 at high efficiency by water splitting processes. A high temperature electrolysis process, for example, should generate H_2 from H_2O at an overall efficiency of ~50-70%, depending on design, where efficiency is defined as H_2 combustion energy divided by input fusion energy.

References

1. J. R. Powell, et al, BNL 18236 (1973).
2. J. R. Powell, et al, BNL 19565 (Dec. 1974).
3. R. F. Benenati, et al, Nuc. Eng. Design 39, 165 (1976).
4. R. Rosa, Evaluation of a Blanket Coupled Fusion MHD Power Generation System, AVCO (Jan. 1975).
5. F. Biancardi, Evaluation of a Fusion-Powered Closed Cycle Gas Turbine Power Generating System, UARL N-951865-1 (June 1974).
6. J. Powell, The FAST Power Cycle for Fusion Reactors, BNL Report (in preparation).
7. C. H. Armstrong, Effect of Recent Advancements in Gas Turbine Technology on Combined Cycle Efficiency, ASME Paper 74-PWR-8, Joint Power Generation Conf., Miami Beach (Sept. 1974).
8. J. H. Kelley and E. A. Laumann, Hydrogen Tomorrow, NASA/JPL Study (Dec. 1975).
9. W. Hausz, et al, Hydrogen Systems for Electric Energy, GE TEMPO Report 72-TMP-15 (May 1972).
10. L. Booth, et al, Fusion Energy Applied to Synthetic Fuel Production, DOE Report (in preparation).
11. J. Fillo, ed. Synthetic Fuel Production from Fusion Reactors - High Temperature Electrolysis, DOE Report (in preparation).