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HELIUM-COOLED LITHIUM COMPOUND SUSPENSION BLANKET CONCEPT FOR ITER*

by

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HELIUM-COOLED LITHIUM COMPOUND SUSPENSION BLANKET CONCEPT FOR ITER[a]

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ABSTRACT

This blanket concept uses a dilute suspension of fine solid breeder particles (Li_2O, $LiAlO_2$, or Li_4SiO_4) in a carrier gas (He) as the coolant and the tritium breeding stream. A small fraction of this stream is processed outside the reactor for tritium recovery. The blanket consists of a beryllium multiplier and carbon/steel reflector. A steel clad is used for all materials. A carbon reflector is employed to reduce the beryllium thickness used in the blanket for a specific tritium breeding ratio. The breeder particle size has to exceed few microns ($\geq$ 2 microns) to avoid sticking problems on the cold surfaces of the heat exchanger. The helium gas pressure is in the range of 2-3 MPa to carry the solid breeder particles through the blanket and the heat exchanger loop. The solid breeder concentration in the helium stream is 1 to 5 volume percent. A high lithium-6 enrichment is used to produce a high tritium breeding ratio and to reduce the breeder concentration in the helium gas. At a lithium-6 enrichment of 90%, the local tritium breeding ratio is 2.03 based on a one-dimensional poloidal model. The total thickness of the helium stream is only 4 cm out of the 50 cm total blanket thickness. The blanket uses a 35 cm of beryllium for neutron multiplication. A simple multi-layer design is employed where the blanket sector has the helium coolant flowing in the poloidal direction. The blanket concept has several unique advantages which are very beneficial for fusion reactors including ITER. The key advantages are listed below:

- The blanket operation can be switched between nonbreeding and breeding modes without hardware changes in the reactor.
- The blanket performance can be adjusted during reactor operation by changing the breeder concentration, lithium-6 enrichment, helium pressure, or helium velocity.
- The blanket has a very low tritium inventory.
- The tritium breeding ratio is adjustable during operation in the range of 0 to 2.03.
- The coolant loop operates at low to medium pressure (2 to 3 MPa).
- The addition of μ-sized solid particles in the helium gas improves its heat transfer and transport properties.
- The blanket can be designed to operate in any temperature range suitable for an optimum structure performance.
- The afterheat source in the blanket is very low because of the low steel fraction and the absence of the solid breeder.
- The blanket has no impact on the reactor configuration and it can be designed for vertical or horizontal maintenance schemes.
- The blanket has very low design uncertainties in its performance.
- The blanket concept has the potential to extrapolate to power reactor conditions.

The main features, key technical issues, and design analyses of this blanket concept are summarized in this paper.

INTRODUCTION

A simple tritium breeding blanket has been developed for fusion reactors including ITER. The blanket uses a dilute suspension of fine solid-breeder particles (Li_2O, $LiAlO_2$, or Li_4SiO_4) in a carrier gas as the tritium breeding stream. About 1% of this stream is processed outside the reactor for tritium recovery. Also, it can serve as the coolant for the blanket (self-cooled) or a separate coolant can be used. The self-cooled option is considered for the current analysis to simplify the reactor configuration. The blanket consists of a beryllium multiplier and carbon/steel reflector. A steel clad is used for all materials (Be and C) in the blanket. The carbon reflector is employed to reduce the beryllium thickness used in the blanket for a specific tritium breeding ratio and insulate the last breeder zone from the cold steel

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behind the blanket.

The current design uses helium as a coolant and carrier for the fine solid-breeder particles. The breeder particle size has to exceed a few microns (≥ 2 microns) to avoid sticking problems on cold surfaces. The helium gas pressure should be in the range of 2 to 3 MPa to carry the solid breeder particles through the blanket and the heat exchanger loop. The solid breeder concentration in the helium stream is 1 to 5 volume percent.

A high lithium-6 enrichment is required to produce a high tritium breeding ratio and to reduce the breeder concentration in the helium gas. At a lithium-6 enrichment of 90%, the local tritium breeding ratio for a multilayer configuration is 2.03 based on a one-dimensional poloidal model. The total thickness of the helium stream is only 4 cm out of the 50 cm total blanket thickness. These dimensions can be changed to adjust the helium velocity or solid breeder concentration in the helium gas without significant impact on the blanket performance or dimensions.

In this blanket configuration the helium coolant is flowing in the poloidal direction from the bottom to the top of the reactor. Tritium recovery is performed outside the reactor by diverting ~ 1% of the tritium breeding stream to the tritium recovery system. The estimated tritium inventory is less than 1 g in the helium stream. The tritium inventory formalism presented in the ITER nuclear design guidelines[1] was used to calculate tritium inventory in the Be multiplier. The results show a tritium inventory of less than 1 g based on the data of Jones and Gibson.[2] These data based on unirradiated arc-cast Be in the temperature range of 300-900°C indicate that the diffusivity of tritium in Be is quite high and the solubility is quite low, consistent with the very low tritium inventory calculated for Be. However, for decreasing test temperatures, increasing fractions of tritium remained in their samples even after 50-100 hours of annealing. This suggests the possibility of chemical trapping due to impurities. Also, it has been observed[3] that Be specimens containing 1-3 wt.% BeO, which have been bombarded by deuterons, release tritium very slowly from room temperature up to ~ 350°C. Using an upper-bound envelop of these two data sets for tritium which may be trapped in Be due to impurities and radiation-induced defects may result in higher tritium inventory up to 800 g at the end of life. Clearly more work needs to be done in this area to characterize tritium retention in Be as a function of impurities and defects.

This blanket concept has several advantages which are very useful for fusion reactors including ITER. The blanket operation can be switched between nonbreeding and breeding modes without hardware changes in the reactor. Also, the blanket performance parameters can be adjusted during reactor operation by changing the breeder concentration in the helium stream, the lithium-6 enrichment of the solid breeder particles, the helium stream pressure, or the helium velocity. The addition of μ-sized solid particles in the helium gas improves its heat transfer and transport characteristics.[4] Similar gas suspension coolants were studied for fission reactors in the 1960's where models and experimental data were obtained.[4,5] The helium coolant with improved characteristics reduces significantly the impact on the reactor configuration relative to pure helium systems and allows the horizontal or the vertical access schemes for the blanket maintenance. For ITER conditions, the blanket can be designed to operate in any temperature range suitable for an optimum structure performance. The low fractions of steel and solid breeder in the blanket results in a very low decay heat source which enhances the reactor safety. The separation of the tritium recovery function from the blanket results in very low design uncertainties in the blanket performance.

CONCEPT DESIGN

The blanket configuration has a simple multilayer design with four helium purge streams. The first wall/blanket/shield design and optimization system (BSDOS)[6] was employed to define the thickness of the different layers which maximize the tritium breeding ratio and limit the total blanket thickness to 50 cm. Table 1 gives the dimensions and the compositions of the different zones as calculated by BSDOS. The one dimensional tritium breeding ratio of this configuration is 2.03. The total thickness of the tritium breeding stream is 4 cm which is adequate from the thermal hydraulics viewpoint to cool the blanket. However, the blanket has adequate flexibility to change these thicknesses without degrading its performance. For example, doubling the tritium breeding stream thickness to reduce the solid breeder concentration in the helium gas by a factor of 2 has a trivial impact on the tritium breeding ratio or the total thickness of the first wall, blanket, and shield.

The addition of the μ-sized solid breeder particles to the helium coolant considerably improves its heat transfer (higher heat transfer coefficient) and transport (higher thermal inertia) properties.[4,5] As a result, the blanket cross section area required to flow the coolant and the manifold size can be

Table 1. Helium-cooled lithium compound suspension blanket configuration[a]

Zone	Thickness, cm	Composition, Volume Fraction
First Wall	0.7	Steel
Helium Breeder	1.0	0.05 Li_2O, 0.95 He
Back Wall	0.3	Steel
Multiplier	13.8	Be (0.8 DF)
Coolant Channel	0.2	Steel
Helium Breeder	1.0	0.05 Li_2O, 0.95 He
Coolant Channel	0.2	Steel
Multiplier	13.9	Be (0.8 DF)
Coolant Channel	0.2	Steel
Helium Breeder	1.0	0.05 Li_2O, 0.95 He
Coolant Channel	0.2	Steel
Multiplier	16.0	Be (0.8 DF)
Coolant Channel	0.2	Steel
Helium Breeder	1.0	0.05 Li_2O, 0.95 He
Coolant Channel	0.2	Steel

(a) Li_2O has a 90% lithium-6 enrichment, Type 316 Stainless Steel is the structure material.

significantly reduced relative to pure helium system. Also, it was reported from the experimental work that the handling of gas-solids suspensions is not difficult and standard type of blowers are suitable for circulating them.[5] The thermal hydraulics characteristics of these suspensions are reproducible.

The sticking of the μ-sized solid breeder particles on the wall surfaces is a potential concern for such systems. However, previous work[4,5] on gas suspension coolants has provided several important conclusions: a) μ-sized particles do not stick on surfaces which are at a higher temperature than a suspension, b) μ-sized particles also do not stick on surfaces which are at lower temperature than a suspension if certain operating conditions are satisfied, and c) these conditions which particles sticking may occur have been theoretically[4] and experimentally verified. The criterion[4] for avoiding the particle deposition on a cooled surface is $F_s/F_t > 1$. Where F_s is the shear force tending to keep the particle in suspension. F_t is the thermal force causing precipitation on a cold surface. For the current configuration with following operating conditions: helium pressure = 2 MPa, helium velocity = 3 m/s, solid volume fraction = 0.05, and helium temperature = 200°C, the particle size has to exceed 2×10^{-6} m to avoid sticking.

The other factor which effects the choice of the particle size is erosion of the steel walls which can be avoided by operating below the erosion threshold.[7] Experimental results on stainless steel[8] show a threshold at ~ 10 m/s for a 40-micron particle size. This threshold is energy sensitive. It allows a higher velocity with smaller particle size as long as the particle energy is constant.

There is also a possible concern about magnetic field effects on the solid breeder particles behavior in the helium coolant. The concern is that the magnetic field may separate solid breeder particles from the helium coolant by driving the particles to the walls. Although high magnetic field strength can polarize even weakly magnetic materials, only a highly nonuniform field can exert strong magnetic forces on dipolar bodies. The magnetic field gradient through the blanket is too small to produce any significant forces on the particles. These magnetic forces, however, may cause a spatially nonuniform distribution of particles in helium flow. On the other hand, the particles should not stick to the walls. It is also important to note that the helium flow is in the turbulent regime and the fluid drag forces should be higher than both gravitational and magnetic forces. However, there may exist some parts in the reactor where the gradient of the magnetic field is relatively high. Then

Table 2. Helium leakage rate per crack
(% of the plasma helium generation rate)

Crack Width/ Crack Opening (μm)	Pressure (atm)		
	1	5	50
400/40	2.18	10.9	108.8
200/20	.27	1.36	13.6
100/10	.03	.17	1.7
10/10	.002	.012	.12

analysis is needed to evaluate the impact of such effects.

Also, there is a general concern about helium leak from the blanket which applies to any helium-cooled concept. The helium flow can be characterized by either viscous flow or molecular flow with a transition region exists between these two types of flow. Viscous type of flow will dominate the gas flow at high pressures, while molecular type of flow will dominate the flow at low pressures. In reactor conditions where there is a large pressure difference between the coolant and the vacuum chamber. All flow conditions can exist and the actual leak rate must then be determined experimentally.

The only experimental data that is directly applicable for comparing theoretical prediction of the gas leak rate is the one given in Ref. 9. Based only on this limited data it is recommended to use molecular flow equations to predict the leak rate of helium through cracks in a vacuum first wall. This conclusion is contrary to a previous study in which it was recommended to use viscous flow to predict leak rates in fusion reactors based on the same experimental data.[9,10]

It is assumed in this study that the critical amount of helium gas leakage should be in the order of helium generation rate from the thermonuclear reaction. This in turn will determine the maximum crack size or the maximum number of cracks corresponding to this critical leakage rate.

Table 2 shows the helium leakage rates as a function of crack dimensions and the helium coolant pressure for a 1 mm thickness wall. These leakage rates are given in the percentage of the helium generation rate for a 700 MW fusion reactor operating at 300°C first wall temperature. Cracks of sizes 100-200 microns in thin structures may be difficult to detect by conventional nondestructive techniques. It can be seen from Table 2 that the leakage through 10-50 cracks of sizes 100-200 micron is equivalent to the helium generation atm. Cracks existing in weldments or cracks created during operation (fatigue) in the complex structure could also have a serious impact on the successful operations of a helium-cooled reactor.

The analysis given above is only based on the few experimental data available. More experiments are needed to confirm the analytical predictions. If, however, other experimental data show that the helium leakage rate is controlled by viscous flow rather than molecular flow, the leakage rate can be even much higher than those predicted in this study.

KEY TECHNICAL ISSUES

The helium-cooled lithium compound suspension blanket makes use of current technology and data bases. However, several key issues require further investigations to provide extra confidence in the design and to insure a satisfactory blanket performance. Helium leakage through micro-cracks and weldments is a main concern for this concept. Also, the erosion threshold of the type 316 stainless steel requires and experimental confirmation to insure a satisfactory blanket performance. The data base for tritium retention in Be is inadequate, leading to a large uncertainty in the upper-bound estimate of tritium inventory. Experimental work is required to characterize tritium retention as a function of impurities, defects, and operating conditions. Another design issue is the sticking of fine solid breeder particles on cold surfaces. It does require experimental confirmation using the solid breeder particles.

CONCLUSIONS

The main conclusion from this study is that a helium-cooled lithium compound suspension blanket concept is a very promising concept for ITER. This concept has several advantages including adequate tritium breeding for ITER operation without an external tritium source and the lowest first wall coverage.

REFERENCES

1. U.S. ITER Nuclear Group, "ITER Shield and Blanket Work Package Report," ANL/FPP/88-1, Argonne National Laboratory (1988).

2. P.M.S. JONES and R. GIBSON, "Hydrogen in Beryllium," J. Nucl. Mater., 21 353 (1967).

3. W.R. WAMPLER, "Retention and Thermal Release of Deuterium Implanted in Beryllium," J. Nucl. Mater., 122&123, 1598 (1984).

4. M.T. WOODCOCK and N.G. WORLEY, "Gas-Solids Suspensions as Heat Transfer Media," Proc. Instr. Mech. Engrs. (London), Vol. 181, Part 3-I (1966-1967).

5. The Babcock & Wilcox Company, "811/208-GAS Suspension Coolants Study," Rep. 1/62/57 (1962).

6. Y. GOHAR et al., "First Wall/Blanket/Shield Design and Optimization Systems," paper presented at the International Symposium on Fusion Nuclear Technology, Tokyo, Japan (1988).

7. S. MAJUMDAR and A. SARAJEDINI, "A Review of Solid Particle Erosion of Engineering Materials," ANL/FE-88-1, Argonne National Laboratory (1987).

8. C.A. YOUNGDAHL, W. PATER, and M.J. GORSKI, "Erosive Wear and Design Evaluation of a Stainless Steel Cyclone on the Coal Gasification Pilot Facility at Morgantown," Proceedings of 1979 conference on the properties and performance of materials in coal gasification environments ASM, page 709 (1980).

9. R.H. JONES and S.M. BRUEMMER, "Damage Analysis and Fundamental Studies Quarterly Report, DOE/ER-004614, p. 65 (1980).

10. R.H. JONES, R.W. CONN, and R.F. SCHAFER, "Effect of First Wall Flaws on Reactor Performance," Nuclear Engineering and Design/Fusion, 2, 175-188 (1985).

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