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ABSTRACT

The IPFR (Integrated Pool Fusion Reactor) concept is to place a fusion reactor into a pool of molten FLiBe. The FLiBe will serve the multiple functions of breeding, cooling, shielding, and moderating. Therefore, the only structural material between the superconducting magnets and the plasma is the first wall. The first wall is a stand-alone structure with no coolant connection and is cooled by FLiBe at the atmospheric pressure. There is also no need of the primary coolant loop. The design is expected to improve the safety, reliability, and maintainability aspects of the fusion system.

INTRODUCTION

The basic configuration of a fusion reactor blanket and shield has not been changed in the past three decades, as shown in Fig. 1. To protect the superconducting magnets, layers of structure material, including the first and/or second wall, blanket, reflector, and shield are located between the plasma and the magnets. Each subsystem has its own unique function and, therefore, unique design and possibly different structural material and coolant. For most cases, each subsystem is cooled by miles of high pressure coolant in small sized, thin-walled tubes. Very high reliability is required by each subsystem. This arrangement is logical for superconducting magnet protection. However, the first wall and the front part of the blanket requires regular replacement. The first wall replacement requires the disconnection and removal of all layers behind, either collectively or individually. Such first wall/blanket/shield system will be difficult to engineer, operate, and maintain.

Figure 1. Typical D-T fusion-reactor configuration employing magnetic confinement (from Rose).

During the past few years, a number of innovative ideas have been developed to remove or combine reactor systems to simplify the reactor design. This is necessary to improve the attractiveness of fusion. The developed innovative concepts are:

1. IBC;¹ combining the function of blanket and coil.
2. Self-pumped limiter;² combining the function of vacuum pumping, impurity control and/or blanket function.
3. Fast wave current drive;² combining plasma start-up and current drive.
4. Integrated blanket and shield;³ combining the coolant of first wall, blanket, and shield.

The integral pool fusion reactor has been developed with the similar spirit. The basic principle is to use the FLiBe (Li_2BeF_4) to

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serve the multiple function of cooling, breeding, shielding, and moderating. If such a system can be engineeringly designed, there would be significant improvements on the simplicity of the reactor systems. Also, the safety, reliability, and maintainability of the nuclear island can also be improved.

CONCEPT DESCRIPTION

The IPFR reactor system concept has been developed based on a pool reactor configuration. The nuclear island, including only the first wall and the superconducting magnets, is submerged under a molten Flibe pool as shown in Fig. 2. The Flibe will fill the space between the first wall and the superconducting magnets and will provide the necessary magnet protection. Therefore, the Flibe serves the multiple functions of breeding, cooling, moderating, and shielding thus eliminating the requirement of a structural blanket, reflector, and shield. The thickness requirement of the Flibe is ~ 130 cm for superconducting mag-

net protection, which is acceptable. Therefore, the only structural layer remaining between the plasma chamber and the TF coil is the first wall.

The Flibe-to-Flibe intermediate heat exchanger (IHX) is also located in the pool, either at the center of the torus or at the outer edge, depending upon the availability of space. The IHX is needed for safety and tritium containment reasons. Since the working fluid is Flibe on both sides of the IHX, the IHX can continue to operate with small leaks. A pump(s) is also submerged in the pool to generate a Flibe flow upward around the first wall and downward through the IHX for the purpose of heat transport. By such design, the need of a primary loop can also be eliminated.

First wall cooling and the tritium control are the two most critical issues of this concept. If these issues can be resolved for the system described above, the reactor system then becomes very attractive. The reliability

Figure 2. IPFR Configuration

of the blanket, maintenance of the first wall, cost and mass utilization, and the safety features may all give significant advantages over the more conventional blanket configurations. The IPFR concept is attractive because:

1. By eliminating the blanket, shield, and the primary loop, the cost of the system can be significantly reduced.
2. After draining of the FLiBe, the first wall is exposed. The replacement of the first wall is easy. The amount of radioactive waste to be disposed is low.
3. There is no coolant connection in the reactor. The IHX is from FLiBe-to-FLiBe and, therefore, can operate with leaks. The reliability of the blanket is high.
4. A pool type reactor is inherently safe.
5. The steam generator is outside the reactor building and is radiation free. Hands on maintenance is feasible.

Some key critical issues have been evaluated and will be discussed.

MATERIAL SELECTION

The key material to be selected is the breeding material. FLiBe is chosen due to its low induced activation, low electrical conductivity, high temperature stability, low electrical conductivity, and inertness toward air and water. However, some critical issues exist for using FLiBe. It has been generally accepted that FLiBe will not breed without a neutron multiplier. Recent calculation by Cheng⁴ concluded that by careful material selection, FLiBe can have a breeding ratio of 1.2. Another critical issue associated with FLiBe is corrosion and tritium containment. It is felt that either corrosion or tritium containment problems can be handled, but it may be difficult to solve both at the same time. However, since the goal of TPSS is to improve the attractiveness of fusion, FLiBe is picked as the breeding material. The possible solution for tritium and corrosion have been developed.

High nickel alloy is the structural material for Molten Salt Breeder Reactor (MSBR);⁵ it is a logical choice for the structural material here. Unfortunately, high nickel alloy cannot be used in the fusion environment due to radiation damage. Therefore, the high nickel alloy is used outside the neutron environment, such as magnet casing, IHX, etc.

The preferred first wall material requires high operating temperature, long life time, low neutron absorption cross-section, and low activation. V-alloy is chosen for the

first wall because it fulfills most of the requirements.

Due to the selection of the materials and the pool reactor configuration, some unique problems arise. The issues to be discussed are: Be resources, first wall cooling, and corrosion/tritium problems.

BE RESOURCE

The U.S. and world reserve of beryllium have been recently estimated and are listed in Table 1.⁶ The total beryllium inventory, based on the ANL TPSS configuration,² is 290 tons. The beryllium burn rate is 18 kg/y for a 1000 MW fusion reactor.⁴ The FLiBe in the reactor does not need to be reprocessed; thus, the only make up is the burn rate. Therefore, there is sufficient beryllium in the U.S. reserve for hundreds of 1000 MW reactors for a very extended period of time.

Table 1
Be Resources (For TPSS)

Total Volume of FLiBe	1600 m ³
Total Mass of FLiBe	3200 tons
FLiBe Cost	120 x 10 ⁶
Be Required	290 tons
	<u>U.S. Resource</u> <u>World Resource</u>
USBM	73,000 (250)* 1,185,000 (3800)
USGS	282,000 (970) 678,000 (2330)

* Number of reactors that can be built with the total resource.

Klein pointed out that one of the problems in estimating the beryllium reserve is caused by the small demand.⁷ The known reserve is disproportionately small compared to the abundance of the material. Erickson⁸ reports that the potential recoverable resource for most elements in the earth's crust should approach

$$R = 2.45 A \times 10^6$$

where A is the abundance of material in the earth's crust in wppm, and R is the potential resource in metric tons. Table 2 lists the reserves and potential resources for different materials. For the most sought after material, the ratio is close to 1. For beryllium, the ratio is ~ 100. Therefore, there is reason to speculate that at least 10 times more beryllium than the reserve number may be available. If this is the case, there will be sufficient beryllium for fusion economy.

Table 2
Abundance-Reserves-Resources Relationship in U.S. and Earth Crust⁴

Element	United States			World		
	Reserve ^a (MTx10 ⁶)	Recoverable Resource Potential ^c (MTx10 ⁶)	Ratio of Potential to Reserve	Reserve ^b	Recoverable Resource Potential ^c	Ratio of Potential to Reserve
Lead	31.8	31.8	1.0	0.54	550.0	1000
Copper	77.8	122.0	1.6	200.0	2120.0	10
Zinc	31.6	198.0	6.3	81.0	3400.0	42
Silver	0.05	0.16	3.2	0.16	2.75	18
Gold	0.002	0.0086	4.1	0.011	0.15	14
Molybdenum	2.83	2.7	1.0	2.0	46.6	23
Beryllium	0.073	3.7	50.0	0.016	64.0	4000
Beryllium	0.025 ^d	3.7	148.0	0.38 ^d	64.0	170

^aU.S. Bureau of Mines (1970).

^bU.S. Bureau of Mines (1970), does not include U.S. reserve.

^cRecoverable resource potential = $2.45 A \times 10^6$ (abundance A expressed in g/mt).

^dU.S. Bureau of Mines (1982).³

MATERIAL COMPATIBILITY AND TRITIUM CONTAINMENT

The problems associated with corrosion and tritium containment may be resolved by formation of a Mo coating on the surfaces of the structural component. The formation of the coating has been demonstrated at ORNL by dissolving MoF₆ in the Flibe.⁹ Table 3 lists the free energy of formation of different fluoride compounds. It can be seen that MoF₆ is the most unstable (or Mo is the most stable) of all the listed materials. Therefore, V, Ni, and tritium will react with MoF₆ to form VF₄, NiF₂, and TF respectively. In reaction with V or Ni, the Mo is precipitated out and forms a continuous coating to prevent further reaction. If MoF₆ concentration is carefully monitored, this coating is self-healing. The formation of TF will greatly reduce the mobility of tritium and prevent it from permeation.

The pressure ratio of TF to that of T₂ can be calculated by the free energy of formation and is summarized in Table 4. If 1 ppm of MoF₆ is dissolved in Flibe, the P_{T₂} = 10⁻¹⁰ Torr and the tritium permeation becomes a non-issue. If MoF₆ concentration is higher, the situation is more favorable. The total tritium inventory in the reference design is 6 g which can be relaxed by a factor of 10.

Table 3
Free Energies of Formation of Fluorides

	ΔG_f^{1000K} (kcal/g-atom of fluorine)
MoF ₆ (g)	-50.2
WF ₆ (g)	-56.8
NiF ₂ (d)	-55.3
VF ₅ (g)	-58.0
VF ₄ (cr)	-66.0
HF(g)	-66.2
FeF ₂ (d)	-66.5
NbF ₅ (g)	-72.5
CrF ₂ (d)	-75.2
TaF ₅ (g)	-82.2
TiF ₄ (g)	-85.4
LiF(l)	-125.2
BeF ₂ (l)	-106.9

Table 4
Tritium Summary

X MoF ₆	1 PPM
P _{TF}	10 ⁻¹ Torr
P _{T₂}	1.3 x 10 ⁻¹⁰ Torr
Tritium inventory	5 g
Tritium leakage rate	4 curie/day
Purge gas flow rate	~ 10 ⁴ liter/sec

FIRST WALL COOLING

The first wall cooling is an inherent problem associated with pool configuration. It is difficult to push the coolant to the first wall in such an open geometry. The work on finite elements calculation of heat transfer on the pool configuration with an unrestricted first wall is in progress with some encouraging initial results.¹⁰

A baffled first wall can also be used to enhance the first wall coolant, as shown in Fig. 3. The concept involves a first wall channel with a 1 cm gap. This first wall channel rests on a supporting structure with flow restriction device to limit the coolant flow to the back of the blanket. Therefore, coolant flow to the first wall channel is preferred by pressure balance. Table 5 lists the thermal hydraulics parameter for the first wall region, and it can be seen that sufficient cooling for the first wall can be provided for the reference design of TPSS.

OTHER DESIGN CONSIDERATIONS

Neutronic performance of the blanket system has been performed⁴ and the results are summarized in Table 6. The breeding performance and shielding capability are both acceptable. The afterheat in the reactor system is so small that inherent safety can be assured.

Figure 3. First Wall Cooling Concept

Table 5
Parameter of Baffled First Wall

Surface heat flux	1.3 MW/m ²
Volumetric heat	150 MW/m ³
First wall channel width	1 cm
First wall channel length	2 m
Coolant temperature	550/600°C
Coolant velocity	2.23 m/s
Heat transfer coefficient	1.37×10^4 W/m ² -°C
Coolant pressure drop	.03 MPa
Maximum interface temperature	690°C
First wall thickness	1.5 mm

Table 6
Summary of Neutronic Calculations

Tritium Breeding Ratio	1.2
Blanket Energy Multiplication	1.30
Total Blanket Thickness	
120 cm Flibe + 10 cm Pb	
or 130 cm Flibe + 14 cm Nickel Alloy	
Maximum Blanket Temperature Rise (LOFA)	<10°C

The reliability, maintenance, and economic issues of the reactor system have not yet been studied. It is expected that the reactor system has the potential to be significantly better compared to the conventional design due to its simplicity, low pressure, and reduced number of components.

CONCLUSIONS

A pool reactor concept for a fusion reactor system has been developed as part of the ANL TPSS work. The philosophy of the concept is to reduce the number of components in the fusion reactor system and thus reduce its complexity. The concept is expected to have significant improvements on reactor safety, maintainability, reliability, and, therefore, cost. Flibe is chosen for the breeding material because of its unique material properties. However, many critical issues arise due to both using Flibe and the reactor geometry. A number of critical issues have been investigated here, and it appears that theoretical solutions exist in all of them.

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