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ENGINEERING, SAFETY, AND ECONOMIC EVALUATIONS OF ASPIRE*

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ABSTRACT

A preconceptual design of a tokamak fusion reactor concept called ASPIRE (Advanced Safe Pool Immersed REactor) has been developed. This concept provides many of the attractive features that are needed to enhance the capability of fusion to become the power generation technology for the 21st century. Specifically, these features are: inherent safety, low pressure, environmental compatibility, moderate unit size, high availability, high thermal efficiency, simplicity, low radioactive inventory, Class C radioactive waste disposal, and low cost of electricity. We have based ASPIRE on a second stability tokamak. However, the concept is equally applicable to a first stability tokamak or to most other magnetic fusion systems.

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1. INTRODUCTION

The Advanced Safe Pool Immersed Reactor (ASPIRE) is based on a pool reactor configuration improving the safety and simplicity of a fusion reactor. The ASPIRE configuration is depicted in Fig. 1 where it is seen that all of the reactor components including the primary heat exchanger and most or all of the superconducting coils are immersed in a coolant pool. The purpose of the pool is several-fold. The fluid in the pool, a lithium-beryllium fluoride molten salt (Li_2BeF_4--Flibe), serves as the tritium breeding medium, as the first wall coolant, and as the shield for the superconducting toroidal field coils. This eliminates the need for a separate blanket and shield structure. The pool also provides sufficient heat capacity to limit temperature excursions in the event of a loss of coolant flow accident. A submerged pump generates Flibe flow to transfer heat from the first wall and blanket to an intermediate heat exchanger (IHX). If there is a pump failure, natural convection of the Flibe can remove all of the decay heat from the first wall and can also provide several minutes of safe operation with the plasma on.

To estimate system costs, we have established a baseline set of system performance parameters for a 600 MW_e, second stability, steady state tokamak with current drive using the work performed by ANL and TRW on the Tokamak Power Systems Study [2]. The open bore shown in Fig. 1 assumes both current drive and rf-assisted startup. This system is schematically labeled ECRH although a combination of electron cyclotron and lower hybrid heating may be used. The parameters for this reactor are presented in Table 1. It should be emphasized that the system has not yet been optimized and that the design point would be expected to change as further analysis is performed. We believe that the overall system performance would improve relative to the results presented in this paper when these analyses have been completed.

2. ECONOMIC EVALUATION

We have estimated the capital cost and the cost of electricity for ASPIRE using the TRW Tokamak Reactor Systems Code. In this evaluation, a reduction in costs that arise from the inherent safety of the reactor have been included. A summary of the direct costs are given in Table 2. The cost of the blanket and shield systems are seen to be much lower than has been estimated for most commercial reactor studies with a conventional first wall, blanket, and shield. Inherent safety lowers the cost of the plant by eliminating systems that would be needed for safety and by reducing the cost of many systems such as the IHX and the reactor building because they are not required for plant or public safety. Therefore, N-stamp (nuclear grade) construction is not needed for these systems.

To put these costs in perspective, a comparison of ASPIRE with other fusion and fission concepts is shown in Table 3 in 1985 dollars. We use the unit cost, which is unit direct cost +25% include the indirect cost, expressed in $\$/kW_e$ as a figure of merit. Both ASPIRE and MINIMARS,[3] an inherently safe advanced tandem mirror commercial reactor, project significant cost advantages. At a 600 MW_e unit size, these concepts are significantly less expensive than the conventional STARFIRE [4] and MARS [5] concepts at a 1200 MW_e rating. If ASPIRE is scaled to a 1200 MW_e plant, its capital cost would be more than 40 percent lower than either STARFIRE or the Large Scale Prototype Breeder reactor.

The cost of electricity (COE) for ASPIRE is 36.8 mills/kW-hr using levelized costing with zero inflation. This method of costing has been recommended by the Fusion Engineering Design Center for all fusion system studies. If this COE could be obtained, ASPIRE would be competitive with fossil fuel power generation today.

3. ENGINEERING EVALUATION

The second aspect of our evaluation was the engineering of the system. Emphasis was placed on reliability and maintainability issues because this concept was radically different from other fusion reactor systems. Without a more complete conceptual design, it is difficult to make precise quantitative estimates of reliability and availability. However, we have created some figures of merit that indicate potential reliability advantages. These are indicated in Table 4 where it can be seen that the pressure, length of pressurized piping, required leak-free surface area and number of piping welds and connections are significantly smaller than corresponding values for pressurized water and liquid metal fusion reactors as typified by STARFIRE [4] and MARS [5], respectively. We believe that this will result in much higher subsystem reliabilities.

4. SAFETY EVALUATION

In an attempt to quantify the relative safety of the ASPIRE concept a safety evaluation was conducted based on the Blanket Comparison and Selection Study (BCSS) assumptions [6]. Table 5 summarizes the results of this evaluation for tokamak systems concepts. As can be seen from this table the ASPIRE concept scores considerably higher than any of the other concepts. The main areas in which the Flibe pool concept is better than the others depends on the concept chosen for comparison as seen in Table 6. The ASPIRE concept is significantly better than the Li/Li/V concept in the areas of source terms and fault tolerance, however, the Li/Li/V concept is slightly better in the amount of effluents possible from the reactor system. A comparison with the LiPb/LiPb/V tandem mirror concept shows a marked difference in the source term index for the ASPIRE concept, but the effluent, maintenance, and waste management indices for the ASPIRE concept are significantly better by comparison.

The concept of inherent safety involves the level of protection which a reactor concept can provide to the public. Table 7 reveals one concept of inherent safety assurance. The best reactor concepts would achieve level 1 safety assurance which would provide absolute protection to the public and allow no possibility for a release of radioactivity which could cause any acute fatalities. Since the ASPIRE concept has no chemical or thermal transient problems, this implies level 2 safety assurance. In fact, there may not be any plausible pathway for radioactivity mobilization which could be sufficient to cause any acute fatalities and thus ASPIRE could even approach level 1. This is a higher level of safety assurance than any of the concepts studied in BCSS,[6] MARS,[5] STARFIRE,[4], or MINIMARS [3]. The only concepts which are even close to the ASPIRE design are the water pool TITAN [7] concept which appears to be a level 2, and any SiC based concept may be level 1.

Lastly, a unique quality of this concept is that the design may even be safe for a transient with the plasma remaining on for a long period of time, and the high level of inherent safety for ASPIRE with respect to public safety can be directly associated with ensuring the investment protection for the reactor operating utility.

5. ESECOM EVALUATION

A recent report from a Senior Committee on Environmental Safety and Economic Aspects of Magnetic Fusion Energy [8] compares 8 cases of fusion reactor systems. ASPIRE is one of the concepts chosen for comparison and received good overall ratings. Table 8 summarizes the rating of ASPIRE. As can be seen, ASPIRE is rated very high on the safety and environmental aspects. Those ratings are similar to that of D-He_3 and silicon carbide blankets. However, ASPIRE was not rated very well on economics.

There are areas of costing that the ASPIRE team did not agree with the ESECOM team. The main area of differences are:

1. Cost of Flibe: The unit cost recommended by BCSS [6] is \$35/kg. The number used by ESECOM is \$70/kg.

2. The Cost of Heat Transport System: The BCSS [6] recommended \$57M. The number is low due to the low pressure and compact system. ESECOM used \$185M scaling from the thermal power.

3. Cost of the Reactor Building: ASPIRE team recommended \$66M. There is no over-pressure requirement and less shielding requirement for ASPIRE. ESECOM scaled to the volume of the fusion island volume.

4. Availability: The ASPIRE team suggested a higher availability of 75% due to the reason summarized on Table 4. ESECOM used 65% for every system.

5. Coolant Makeup: ESECOM used 2% makeup for every system. For ASPIRE, this will translate into 56,000 kg/yr.

Further work will be required to clarify the difference in the cost estimate between ASPIRE and ESECOM teams. This work is in progress.

6. SUMMARY

A system evaluation of the Advanced Safe Pool Immersed Reactor (ASPIRE) has been carried out. The safety and environmental attractiveness of ASPIRE is generally agreed between the ASPIRE team and the ESECOM team. The ASPIRE concept can be rated as one of the most safe fusion reactor concepts evolved. It is rated similar to that of the D-He_3 and SiC blankets, but requires much less extrapolation of technology. There is a big difference in economic evaluations, and further work is required to clarify the difference.

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Table 1 -- ASPIRE Plant Parameters

Net Electric Power	(MW_e)	582
Fusion Power	(MW)	1425
Major Radius	(m)	4.84
Minor Radius	(m)	0.81
Aspect Ratio		6
Plasma Elongation		2
Beta		0.2
Peak Magnetic Field on Axis	(T)	4.7
Peak Magnetic Field at Coil	(T)	9.4
Neutron Wall Loading	(MW/m^2)	3.8
Plasma Current	(MA)	4.4
Confinement	(s/cm^3)	2.8×10^{14}

Table 2 -- ASPIRE Plant Capital Cost Estimate

Account Number		Description		Cost (M$)
20		Land		5
21		Structures and Site Facilities		162
22		Reactor Plant Equipment		
	22.01.01	First Wall and Blanket	94	
	22.01.02	Shield	43	
	22.01.03	Magnets	63	
	22.01.04	Plasma Heating and Current Drive	36	
	22.01.05	Structure and Support	9	
	22.01.06	Vacuum	5	
	22.01.07	Magnet Power Supplies	0.5	
	22.01.08	Impurity Control	11	
	22.02	Main Heat Transport	57	
	22.03	Cryogenic	5	
	22.04	Rad Waste	5	
	22.05	Tritium Processing	18	
	22.06	Instrumentation and Control	12	
	22.07	Other Reactor Plant Equipment	20	
		TOTAL		379
23		Turbine Plant Equipment		142
24		Electric Plant Equipment		53
25		Miscellaneous		19
		Total Direct Cost		760
		Net Electric Output (MW_e)		582
		Unit Direct Cost ($\$/kW_E$)		1306

Table 3 -- Capital Cost Comparison

Plant Designation	Nominal Plant Rating (MW_e)	Unit Cost ($/$kW_e$)
ASPIRE	600	1633
ASPIRE	1200	1136
STARFIRE	1200	1942
MARS	1200	2055
MINIMARS	600	1483
Large Scale Prototype Breeder	1320	2025
Pressurized Water Reactor	1200	1736

Table 4 -- ASPIRE Reliability Parameters

Index	Unit	ASPIRE	STARFIRE	MARS
Contained Pressure	(MPa)	0.3	15	2
Pressurized Piping Length	(km)	1	200	200
Leak-free Surface Area	(m^2)	400	7,000	5,000
Leak-free Welds/Connections	(#)	100	140,000	11,000

Table 5 -- Safety Evaluation of Various Tokamak Blankets

Score	Tokamak Concept
67.9	Flibe Pool
62.6	LiPb/LiPb/V (for tandem mirror only)
59.8	He/Li_2O/FS
59.7	Li/Li/V
55.3	He/Li/FS
54.1	He/$LiAlO_2$/FS/Be
48.3	He/Flibe/FS/Be
35.7	H_2O/$LiAlO_2$/FS/Be
30.8	NS/$LiAlO_2$/FS/Be

Table 6 -- Safety Indices of Three Different Blankets

	ASPIRE	Li/V	LiPb/V	Perfect
Source Term Indices	14.9	11.9	22.5	30.0
Fault Tolerance Indices	21.4	17.5	21.1	30.0
Effluent Index	14.0	15.2	8.8	20.0
Maintenance Index	7.6	5.6	5.7	10.0
Waste Management Index	10.0	9.5	4.5	10.0
TOTAL	67.9	59.7	62.6	100.0

Table 7 -- Levels of Safety Assurance

1. Total Protection:
   - True Inherent Safety
   - Public Acute Fatalities Impossible

2. Large-Scale Passive Protection:
   - Passive Safety
   - Tolerate Multiple Pipe Failures

3. Small-Scale Passive Protection:
   - Passive Safety
   - Seismic Qualifications of all Safety-Related Components
   - Less Forgiving than Level 2

4. Active Protection:
   - Active Engineered Safeguard Systems

Table 8 -- Summary of ESECOM Rating for ASPIRE

Mass Power Density (kW_e)/tonne	283*
Unit Capital Cost ($/$kW_e$)	2035**
Cost of Electricity (unit/kW hr)	47.9**
Total Radioactive Inventories	
First Wall (MCi)	110*
BOFC (MCi)	220*
Level of Safety Assurance	1 - 2*
Deep Disposal Index (m^3)	9.2*

* Top or near the top.
** Middle of the pack or lower.

LIST OF FIGURES

Figure 1 ASPIRE configuration.
(Sze et al.)

No penetrations in pool boundary

All vacuum vessel penetrations are vanadium, transitions to other metals are outside pool

Everything can be removed from the top