CONF-860652--23

Received by OSTI

AUG 19 1986

FUSION BLANKET INHERENT SAFETY ASSESSMENT*

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CONF-860652--23

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To be Presented at the
**Seventh Topical Meeting on the
Technology of Fusion Energy**

Reno, Nevada

June 15-19, 1986

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ABSTRACT

The inherent safety aspect of TPSS reactor blankets has been investigated. The idea is to design the blanket so safe that cost savings can be realized such as through non-nuclear grading construction. If the blanket materials are carefully selected, inherent safety is feasible for fusion reactor blankets up to 5-10 MW/m² neutron wall loading.

I. INTRODUCTION

Recently, the focus of safety design efforts for nuclear power plants has been dramatically changing. The reactor safety issue is one of the main factors behind the public resistance to fission energy. This issue has caused runaway escalation in design complexity, cost, and construction delay. Not to repeat the mistakes of the fission industry, recent design work in fusion has been emphasized on inherent safety as a design goal.^{1,2,3,4} Rather than continue the safety design approach of the current fission plants (operating or under construction), the goal is to design a fusion plant in which the ultimate inherent safety is embodied in the reactor itself rather than achieved by add-on systems that must be activated by external means in emergencies.

The overall figure of merit for power plants is COE (cost of electricity). Safety alone will not increase the attractiveness of fusion if safety has no impact on the COE. However, by demonstrating the inherent safety, the regulation requirement and time for construction can be reduced significantly. In addition, to gain public support and avoid litigation, inherent safety is essential. Therefore, it is expected that inherent safety reactors can go a long way to reduce the COE,

even compared to an identical power plant which is not inherently safe.

The definition of inherent safety, the achievability of different levels of inherent safety, as well as the potential benefit and penalty for achieving inherent safety have been subjected to numerous discussions recently. It has been generally concluded that, by careful design, inherent safety can be achieved for fusion and is desirable. However, what the impact of inherent safety has to the cost saving, such as removing the nuclear grade requirement for reactor components, is subject to discussion.

II. NEUTRONIC CALCULATIONS

The neutronics issues to be addressed for the safety/decay afterheat analysis include:

1. impact of varied neutron wall loads;
2. difference of loss-of-flow and loss-of-coolant accidents;
3. impact of reflector designs, i.e., Fe1422-base design versus V15Cr5Ti-base design; and
4. comparative study of the three reference blanket designs, viz., the self-cooled liquid-lithium blanket, the self-cooled FLIBE blanket, and the helium-cooled solid-Li₂O blanket.

Regarding Item 4 mentioned above, Fig. 1 describes the system dimensions and materials compositions used for the analysis. In all cases the neutron transport computation was performed by making use of a one-dimensional discrete-ordinates codes, ANISN⁵ with the VITAMIN-C⁶ data library. The subsequent radioactivity analysis was carried out using the RACC⁷ code with the associated RACCLIB and RACCDLIB⁸ data libraries.

*Work supported by the U.S. Department of Energy, Office of Fusion Energy.

(A) Li/Li/V15Cr5Ti

Plasma	Scrape Off	First Wall	Blanket	Reflector	Shield	Thickness (cm)
		1	40	30	30	

First Wall: 100% V15Cr5Ti
Blanket: 5% V15Cr5Ti + 95% Li (# natural Li)
Reflector: 10% V15Cr5Ti + 10% Li (# natural Li) + 80% Fe1422
[Alternate Reflector: 90% V15Cr5Ti + 10% Li (# natural Li)]
Shield: 80% Fe1422 + 20% H₂O

(B) FLiBE/FLiBE/V15Cr5Ti

Plasma	Scrape Off	First Wall	Blanket	Shield	Thickness (cm)
		0.3	80	30	

First Wall: 100% V15Cr5Ti
Blanket: 8% V15Cr5Ti + 92% FLiBE (# natural Li)
Shield: 80% Fe1422 + 20% H₂O

(C) Li₂O-Be/He/V15Cr5Ti

Plasma	Scrape Off	First Wall	Blanket-1	Blanket-2	Plenum	Shield	Thickness (cm)
		6	45	12	22	30	

First Wall: 12% V15Cr5Ti + 88% He/void
Blanket-1: 8% V15Cr5Ti + 81% (7Li₂O-3Be) (# 80% TD; natural Li) + 11% He
Blanket-2: 29% V15Cr5Ti + 63% (7Li₂O-3Be) (# 80% TD; natural Li) + 8% He
Plenum: 20% V15Cr5Ti + 80% (7Li₂O-3Be) (# 80% He/void)
Shield: 80% Fe1422 + 20% H₂O

Fig. 1 System dimensions and material composition of the three reference designs used for decay afterheat.

A. Effect of Neutron Wall Load

The effects of neutron wall load to the afterheat are calculated.

Figure 2 illustrates the time-dependent behavior of decay afterheat in the first wall of a reference blanket. The time-dependent variations shows that, up to ~1000 s after shutdown the decay heat varies linearly with wall load. However, at ~1 h, for instance, the 5.0 MW/m² case yields a heating rate three times higher than the 2.5-MW/m² case due to the gradual contributions from long-lived isotopes. The difference becomes even larger by a factor of five or more beyond ~1 mo after shutdown and thereafter.

Fig. 2 Effect of neutron wall load on decay heating in first wall; Li/Li/V-15Cr-5Ti design.

B. LOFA and LOCA

Table 1 lists a set of results for LOFA with Li/V blanket. Similar calculations have been done for other accidents and different blankets. The complete tabulation of the calculations can be found in Ref. 1. This heating rate provides the source term for blanket temperature calculation.

C. Impact of Reflector Design

The major decay-afterheat sink in the liquid lithium blanket is the Fe-1422-based reflector. In addition, the Fe-1422 alloy itself is a major source of decay gamma. If an alternative reflector material can be used, the afterheat may be significantly reduced. Figure 3 shows the afterheat in the Fe-1422 reflector and V-alloy reflector. The difference can be a factor of 10.

The impact of using an alternative reflector design is not limited only to the decay heat. The overall blanket performance on tritium breeding ratio (TBR) and system energy multiplication factor (EMF) can be compared as follows:

	TBR	EMF
Fe1422-base reflector	1.26	1.27
V15Cr5Ti-base reflector	1.35	1.22

Fig. 3 Effect of reflector designs on decay heating in reflector; material V-15Cr-5Ti (system: Li/Li/V-15Cr-5Ti).

Namely, the alternative reflector design enhances tritium production due to the less parasitic neutron loss in V-15Cr-5Ti than in Fe-1422, while the energy multiplication is sizably lowered in return.

Table 1
[Li/V15Cr5Ti] LOFA/SPECIFIC DECAY AFTERHEAT (MW/m³)
@ 2.5 MW-4 YR/m² WALL LOAD

REGION	0	1 MIN	10 MIN	1 HR	TIME AFTER SHUTDOWN 6 HR	1 DAY	1 WEEK	1 MO	6 MO	1 YR
[V15CR5Ti]										
FW	4.45E-01	3.90E-01	1.67E-01	9.29E-02	7.85E-02	6.07E-02	2.05E-02	1.41E-02	8.61E-03	5.53E-03
BLK1	3.49E-01	3.04E-01	1.30E-01	7.26E-02	5.79E-02	4.36E-02	1.48E-02	1.02E-02	4.21E-03	3.96E-03
BLK2	2.73E-01	2.38E-01	1.00E-01	5.63E-02	4.02E-02	2.87E-02	9.93E-03	7.01E-03	4.28E-03	2.72E-03
BLK3	2.34E-01	2.04E-01	8.88E-02	5.11E-02	3.10E-02	2.01E-02	7.55E-03	5.53E-03	3.43E-03	2.18E-03
REF1	2.18E-01	1.93E-01	9.13E-02	5.60E-02	2.74E-02	1.43E-02	6.61E-03	5.19E-03	3.30E-03	2.12E-03
REF2	2.21E-01	2.00E-01	1.19E-01	8.18E-02	2.78E-02	8.41E-03	6.46E-03	5.83E-03	3.88E-03	2.52E-03
REF3	1.30E-01	1.18E-01	7.31E-02	5.07E-02	1.47E-02	2.17E-03	1.90E-03	1.75E-03	1.17E-03	7.55E-04
	6.83E-02	6.25E-02	3.87E-02	2.68E-02	7.31E-03	5.32E-04	4.43E-04	4.09E-04	2.65E-04	1.69E-04
[L1]										
BLK1	2.73E-02	1.05E-02	6.27E-03	4.07E-03	3.88E-03	2.93E-03	1.02E-03	7.24E-04	4.55E-04	2.93E-04
BLK2	1.77E-02	8.30E-03	4.95E-03	3.76E-03	2.67E-03	1.90E-03	6.70E-04	4.82E-04	3.02E-04	1.93E-04
BLK3	1.33E-02	7.36E-03	4.59E-03	3.46E-03	2.07E-03	1.32E-03	5.01E-04	3.73E-04	2.36E-04	1.51E-04
BLK4	1.14E-02	7.40E-03	5.14E-03	3.93E-03	1.87E-03	9.87E-04	4.45E-04	3.53E-04	2.25E-04	1.47E-04
REF1	1.10E-02	8.90E-03	7.82E-03	6.22E-03	2.08E-03	6.03E-04	4.71E-04	4.27E-04	2.85E-04	1.86E-04
REF2	6.31E-03	5.40E-03	4.83E-03	3.86E-03	1.11E-03	1.56E-04	1.36E-04	1.26E-04	8.45E-05	5.50E-05
REF3	3.40E-03	2.85E-03	2.59E-03	2.04E-03	5.55E-04	3.71E-05	3.11E-05	2.88E-05	1.89E-05	1.22E-05
[FE1422]										
REF1	2.52E-01	2.46E-01	2.21E-01	1.76E-01	5.48E-02	1.20E-02	9.32E-03	8.42E-03	5.56E-03	3.40E-03
REF2	1.46E-01	1.43E-01	1.32E-01	1.05E-01	2.94E-02	3.12E-03	2.72E-03	2.51E-03	1.67E-03	1.02E-03
REF3	7.53E-02	7.41E-02	6.84E-02	5.42E-02	1.46E-02	7.65E-04	6.21E-04	5.72E-04	3.73E-04	2.40E-04

NUCLEAR HEATING (MW/m³) DURING OPERATION

MAT.	FW	BLK1	BLK2	BLK3	BLK4	REF1	REF2	REF3
V-	1.26E+01	9.91E+00	7.31E+00	5.66E+00	4.59E+00	2.79E+00	1.15E+00	5.28E+01
LI		8.18E+00	5.59E+00	4.06E+00	3.13E+00	2.29E+00	1.23E+00	7.76E+01
FE						4.00E+00	1.62E+00	7.30E+01

111. TRANSIENT TEMPERATURE CALCULATIONS

With the afterheat calculated as a function of time after reactor shut down and location, the transient behavior of the blanket can be calculated for various accident scenarios. The main uncertainty is how to define the boundary conditions. For being conservative, it is assumed here that the blanket, reflector shield and ambient are completely separated. Thermal radiation is the only heat transfer mode between these regions. The emissivity used is 0.3. This conservative assumption can be relaxed as more detailed system configuration becomes available in the future.

A finite difference computer code has been set up to do this calculation. The iterative method is based on energy balance for each zone during one time step. This equation is in the form of

$$T_i = T_i + \sum_j [\text{COND}_{ij}(T_j - T_i) + V_i Q_i] \frac{\Delta\theta}{(\rho C_p V)_i},$$

in which

T_i is temperature after time step $\Delta\theta$
 T is temperature before time step $\Delta\theta$
 COND is the conductivity

$$[\equiv \frac{kA}{x} + \sigma \epsilon A (T_j^2 + T_i^2)(T_j + T_i)]$$

V is volume

Q_i is heat generation rate

ρC_p is volumetric thermal inertia

and

$\Delta\theta$ is the time step which is defined by

$$\Delta\theta \leq \frac{(\rho C_p V)_i}{\sum_j \text{COND}_{ij}} \text{ min.}$$

By knowing the initial condition, the entire transient of the blanket can be calculated by each time step $\Delta\theta$ iteratively. The time step is defined by the convergence criteria of the iteration process.

Three types of accident conditions are evaluated for two blankets. The blankets evaluated are self-cooled V/Li blanket and self-cooled V/Flibe blanket. The accident conditions evaluated are:

1. Loss of flow accident: At time = 0, the coolant flow stops for both blanket, reflector and shield.
2. Loss of coolant accident: At time = 0, the coolant is drained from the blanket, reflector and shield.
3. Partial loss of coolant accident: At time = 0, one blanket module loses coolant, while the other blanket modules remain in

normal operation.

The plasma is assumed to be quenched at time = 0 for all the cases.

The allowable temperature limitations for the V-blanket structure with no pressure load is not clear. It is believed that if temperature exceeds 1200°C, the blanket configuration may change so that normal maintenance scheme may not be usable. Therefore, 1200°C is picked as the allowable upper temperature limit.

The temperature responses of the V/Li blanket for LOFA and LOCA are shown on Figs. 4 and 5, respectively, with different neutron wall loadings. The LOCA is the more serious accident because the thermal inertia of the blanket becomes much reduced. The maximum allowable neutron wall loading is about 2.7 MW/m² for the maximum allowable temperature of 1200°C. As discussed before, the reflector material is Fe-1422 and the after heat there is very high, as can be seen of Fig. 3. This high after heat causes the relatively low allowable wall loading for inherent safety. If V reflector is used, the allowable loading will be higher, but the blanket energy multiplication will be reduced. The detailed trade off between safety and economics has to be carried out.

The temperature responses of the V/Flibe blanket for LOFA, LOCA, and partial LOCA are shown on Figs. 6, 7, and 8 respectively. Again, the LOCA is the most serious case due to the same reason. However, a very respectable 5 MW/m² neutron wall loading is acceptable for this case. The main reason is that there is no reflector for this design. The afterbeat due to the V-alloy in blanket is low. For the other accident cases, a wall loading of ~ 10 MW/m² is allowable.

Figure 9 shows the blanket temperature response when plasma is on for 10 seconds after the accident occurs. The heat generated in the blanket during this 10 second period is small compared to the total afterbeat for a very long period of time (10⁴ ~ 10⁵ seconds). Therefore, the effect that the time plasma is on has only a very minor effect on the long time scaled temperature transient.

IV. CONCLUSIONS

Inherent safety can be designed for the fusion reactor blanket with a careful material selection and reasonable neutron wall loading. The blanket is so designed that it will provide sufficient performance compared to the more conventional blanket. Therefore, inherent safety should be a design goal for fusion reactor blankets. How to use this safety characteristic to reduce the COE has to be further examined.

Fig. 4. Temperature Response of LOCA Li/V Blanket

Fig. 5. Temperature Response of LOFA Li/V Blanket

Fig. 6. Temperature Response of LOFA Flibe/V Blanket

Fig. 7. Temperature Response of LOCA Flibe/V Blanket

Fig. 9. Temperature response of LOCA, Li/V Blanket

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