



## Design Considerations for the SIRIUS-M ICF Materials Test Facility

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October 1987

UWFDM-732

Presented at the 12th Symposium on Fusion Engineering, 12-16 October 1987, Monterey CA]. [Presented at the 12th Symposium on Fusion Engineering, 12-16 October 1987, Monterey CA.

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## DESIGN CONSIDERATIONS FOR THE SIRIUS-M ICF MATERIALS TEST FACILITY

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### Summary

SIRIUS-M is a fusion materials test facility designed to duplicate the time-dependent radiation damage structure unique to ICF systems in order to provide the technology base for an ICF demonstration facility. Single shell ICF targets with a gain of 13.4 are symmetrically illuminated by 92 beams of a KrF laser with a total energy of 1 MJ. The impact of tritium breeding and self-sufficiency on the design and economics of SIRIUS-M has been examined. The analyses indicate that tritium self-sufficiency can significantly reduce the total lifetime cost without adverse impact on the testing capability of the facility. The impact of target yield on cavity design and overall costs has also been examined. It is shown that no economic advantage is gained by using higher yield (100 MJ) targets. Various shielding options have been examined in order to minimize radiation streaming to the laser building through the 92 beam ports. It is shown that this can be achieved using a beam crossover between the last two optical elements.

### Introduction

The development of inertial confinement fusion (ICF) using symmetrically-illuminated direct drive targets has been pursued by the U.S. Department of Energy as a backup approach to the first-line indirect-illumination schemes which are being developed by the national laboratories. As part of this program, the Fusion Technology Institute of the University of Wisconsin (FTI) in collaboration with the University of Rochester's Laboratory for Laser Energetics (LLE) and in consultation with the Naval Research Laboratory (NRL) has been conducting a study of the critical issues related to symmetrically illuminated direct drive ICF systems. In the first year of the study ('83-'84) the emphasis was on general critical issues of a symmetrically illuminated commercial reactor SIRIUS. Since then ('84-'87) the effort has concentrated on the critical issues and a scoping study of a materials test facility SIRIUS-M.<sup>1</sup>

The need to test structural materials under realistic fusion reactor conditions has been discussed for both magnetic confinement fusion (MCF), and inertial confinement fusion (ICF). Irradiating small size materials samples in a neutron flux can be accomplished in fission reactors or small DT neutron source facilities. However, the restricted temperature range and small individual test volumes, along with serious neutron energy spectral differences, make complete testing of fusion reactor materials in these facilities impossible.

Large differences exist between the damage conditions in ICF and MCF environments. These differences, which arise from geometrical, spectral, and temporal effects, make it necessary to develop a dedicated ICF materials test facility. To this end, the SIRIUS-M facility has been designed to duplicate the time-dependent radiation damage structure unique to ICF systems in order to provide the technology base necessary for an ICF demonstration facility.

This paper provides an overall description of the SIRIUS-M facility. Attention has been focussed on three issues: (1) impact of tritium breeding and self-sufficiency on the design and economics of SIRIUS-M, (2) unique shielding requirements for ICF facilities, in general, and symmetrical illumination systems, in particular, (3) cavity design optimization for enhanced target performance. Details may be found in reference 2.

### Facility Description and Design Parameters

Table 1 lists the main design parameters for the SIRIUS-M facility. The base case parameters as well as parameters for enhanced target performance discussed later are given in the table. Single shell ICF targets with an estimated gain of 13.4 are symmetrically illuminated by 92 beams of a 1 MJ KrF laser uniformly distributed around a 2 m radius cavity. The beam arrangement is based on surrounding the spherical cavity with 12 pentagonal and 80 hexagonal blanket modules with a beam at the center of each module as indicated in Fig. 1. An earlier design of SIRIUS-M utilizing 32 beams has been deemed inadequate because of the strict requirements on target illumination uniformity.

Table 1. Summary of Key SIRIUS-M Parameters

	Base Case	Enhanced Target	
		Constant Power	Constant Wall Load
Number of Beams	92	92	92
Target Gain @1 MJ	13.4	100	100
Repetition Rate (Hz)	10	1.34	5.36
Fusion Power (MW)	134	134	536
Cavity Radius (m)	2	4	4
Neutron Wall Load (MW/m <sup>2</sup> )	2	0.5	2
Tritium Breeding Ratio	1	1	1
Lifetime (CY)	10	10	10
Availability (%)	50	50	50
Overnight Cost (M\$)	838	933	1018
Lifetime Cost* (M\$)	1220	1231	1394
FOM (M\$/peak dpa)	12.8	52	14.6

\*Based on COE of 30 mills/kWh

Reasonably achievable values of target gain, 13.4, and repetition rate, 10 Hz, are assumed so that a total fusion power of 134 MJ is obtained. The explosions are contained in a 2 m radius cavity which results in a neutron wall loading of 2 MW/m<sup>2</sup>. The cavity is filled with xenon gas at a pressure of 1 torr in order to protect the first wall from the x-rays and ions produced by the explosions. The entire cavity is placed within a xenon filled, 22 m radius, 3 m thick concrete containment building (Fig. 2).

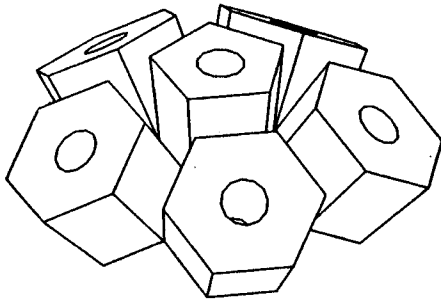


Fig. 1. A cluster of one pentagonal and five hexagonal modules

The first wall consists of water cooled graphite faced tiles attached to the ninety-two blanket modules surrounding the cavity (Fig. 3). Eighty hexagonal tiles and twelve pentagonal tiles approximately 50 cm on edge are used. The tiles consist of a water cooled 2 cm thick austenitic stainless steel (PCA) base structure with a 1 cm thick graphite layer brazed to its front surface. The graphite layer has a collar which extends into the base structure collar and serves as a beam port for each of the 92 beams.

#### Tritium Breeding and Self-Sufficiency

In order to simplify the design of the SIRIUS-M facility and reduce its capital cost, its mission was originally limited to materials and blanket testing; tritium breeding and high temperature recovery of thermonuclear energy were excluded. However, since the tritium costs represented nearly

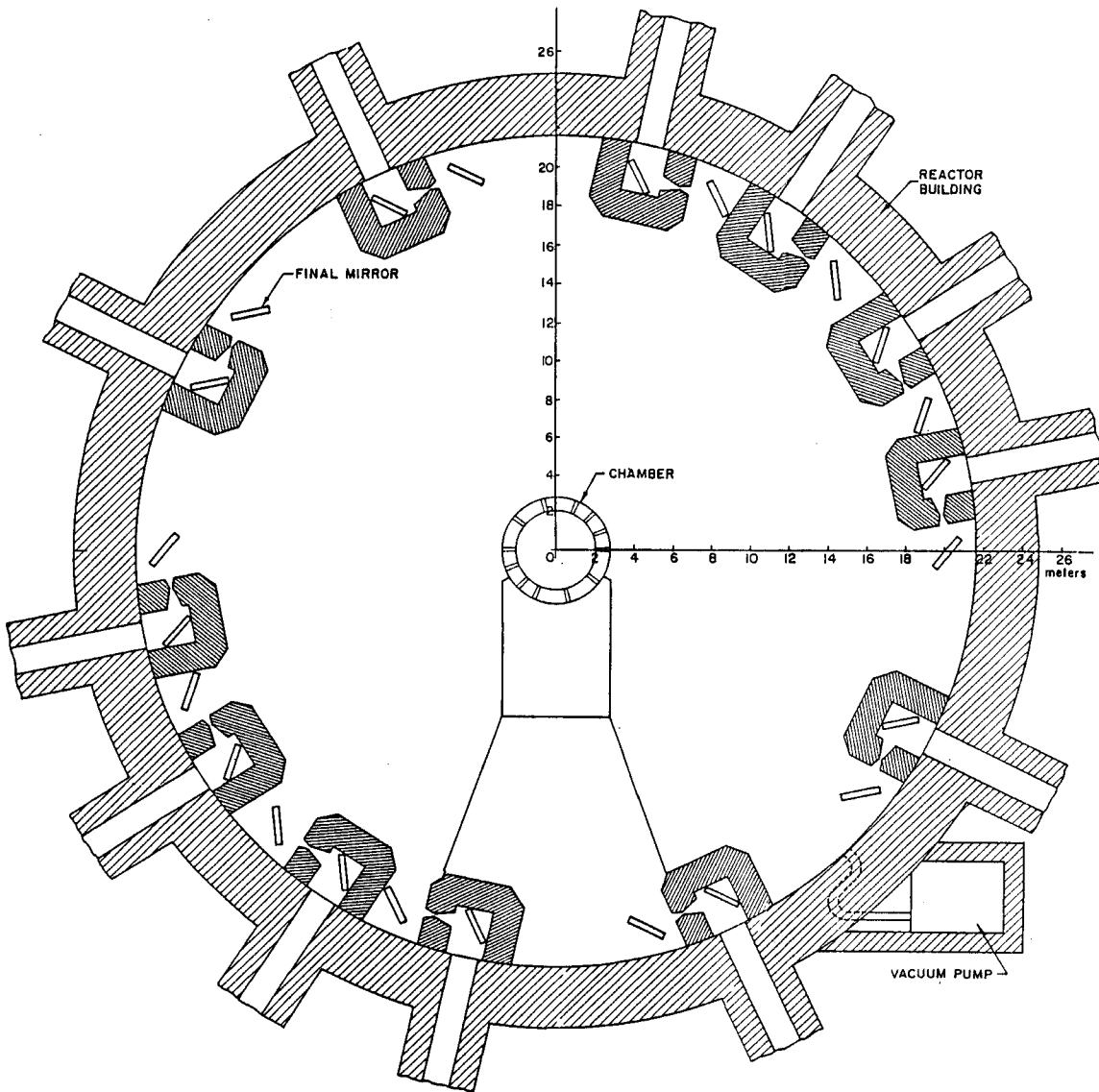


Fig. 2. Cross section of SIRIUS-M reactor building with 92 symmetrically distributed beams

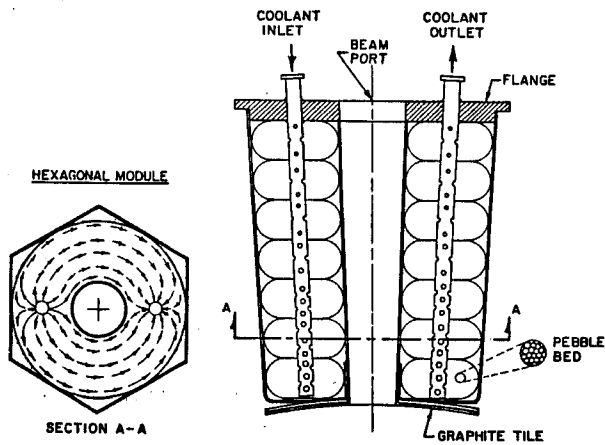


Fig. 3. SIRIUS-M prototypical blanket module design.

50% of the annual operating costs of the facility, it was decided to examine the impact of tritium breeding and self-sufficiency on the design, performance, and economics of the facility. Table 2 lists the various options examined in that regard; option 1 is the reference case without tritium breeding. Values of the tritium breeding ratio (TBR) and the relative displacement per atom (dpa) in the materials test modules normalized to the value for the non-breeding reference design (option 1) are given. Breeding is accomplished by dissolving a small amount of lithium nitrate in the water coolant.

Table 2 indicates that by dissolving  $\text{LiNO}_3$  into the coolant with a concentration of  $20 \text{ g}/100 \text{ cm}^3$ , increasing the coolant fraction in the steel zone from 10% to 20% and trading off 10 cm of Pb multiplier for steel reflector increases TBR from 0.668 to 0.792 while the dpa is reduced by 2.7%. In option 5, the graphite tiles are replaced with Be increasing TBR to 0.85 with almost no loss of dpa. The difference between option 6 and option 4 is that the  $\text{LiNO}_3$  concentration is increased to  $80 \text{ g}/100 \text{ cm}^3$  (the saturation limit at  $30^\circ\text{C}$  is  $89.8 \text{ g}/100 \text{ cm}^3$ ). This increases TBR from 0.792 to 1.077 while sustaining a minor loss of dpa. This option suffers from the fact that at this  $\text{LiNO}_3$  concentration the corrosion will be higher. Option 7 is similar to 6 with the difference that the lead zone is separately cooled with an aqueous  $20 \text{ g}/100 \text{ cm}^3$   $\text{LiNO}_3$  solution. The TBR is 1.132 but is accompanied by an 18% loss in dpa. The last

two cases utilize Be multiplier instead of Pb. Thicknesses of the multiplier/steel zones are varied holding the sum of the two constant. A TBR of 1.4 is achieved with almost no loss of dpa over the Pb multiplier case (option 7).

The costs of the SIRIUS-M facility with and without tritium breeding have been estimated. The results indicate that minor differences in the design (self-cooled vs. separately cooled Pb zone) give slight variations in the direct costs and the total overnight costs. However, the total lifetime cost shows a decrease of 385 M\$ for the breeding case, a 27% reduction over the non-breeding case. From the standpoint of the price of damage as shown by the figure of merit, M\$/dpa, the reduction is only 5%.

In conclusion,  $T_2$  self-sufficiency can be achieved by the simple dissolution of  $\text{LiNO}_3$  in the cooling water and utilizing a front multiplier zone of either Pb or Be. Options 7 and 8 would be the best choices with a slight edge for the Be multiplier (option 8) case, because of a reduction in weight and an easier design. Further, a substantial savings over the lifetime costs can be realized by making the design self-sufficient with respect to  $T_2$ .

#### Impact of Target Performance

As indicated earlier, a conservatively low value of target gain, 13.4, has been assumed in the base case design for SIRIUS-M. It has been suggested that higher target gains (~100) may be possible. Therefore, the impact of enhanced target performance on the design and economics of SIRIUS-M has been examined.

The thermal response of the graphite tiles to the surface heat flux emitted by the cavity gas and unattenuated x-rays following a 100 MJ explosion has been determined. The analysis is performed for different size cavities ranging from 3 to 5 m in radius. The corresponding compressive stresses at the front surface are then determined. By comparing the stress values with the compressive strength of the material, the necessary cavity radius to contain the 100 MJ explosion is determined. Figure 4 shows that a cavity radius of approximately 4 m is needed to contain such high yield target explosions.

An economic analysis has been performed to compare the base case design with designs using the higher yield targets. Two cases are examined; in the first the fusion power is assumed to remain constant and equal to 134 MJ so that a lower repetition rate would be needed (1.34 Hz). For the second case, the

Table 2. Impact of Blanket Design on TBR and Testing Capability

Option	Tile Material	Multiplier Material	Multiplier Zone Thickness (cm)	Steel Zone Thickness (cm)	% $\text{H}_2\text{O}$ in Steel Zone	$\text{LiNO}_3$ Concentration ( $\text{g}/100 \text{ cm}^3$ )	Overall TBR	Relative dpa Rate in Test Module
1	C	Liquid Pb	40	30	10	0	0	1
2	C	Liquid Pb	40	30	10	20	0.668	0.991
3	C	Liquid Pb	40	30	20	20	0.786	0.991
4	C	Liquid Pb	30	40	20	20	0.792	0.973
5	Be	Liquid Pb	30	40	20	20	0.850	0.991
6	C	Liquid Pb	30	40	20	80	1.077	0.964
7	C	Solid Pb	30	40	20	20	1.132	0.795
8	C	Be	15	55	20	20	1.077	0.787
9	C	Be	30	40	20	20	1.399	0.790

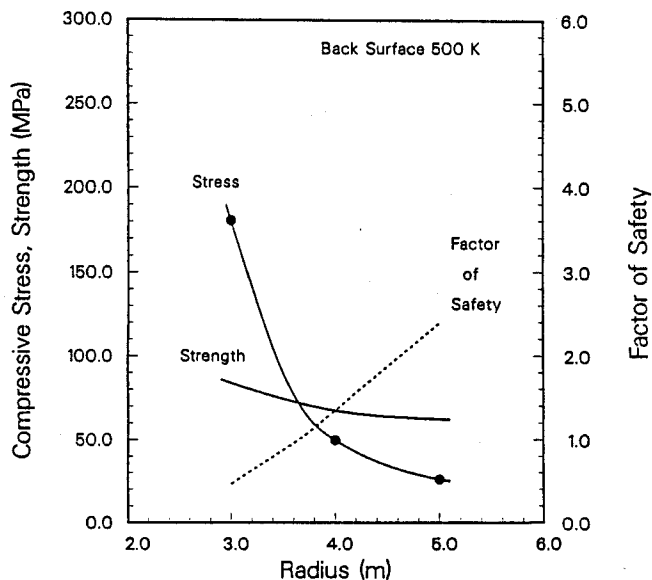


Fig. 4. Compressive stress in graphite tiles as a function of cavity radius with back temperature at 500 K and 1 torr of xenon gas

neutron wall loading is assumed to remain constant and equal to  $2 \text{ MW/m}^2$  so that a repetition rate of 5.36 Hz would be required. The design parameters for these two cases are given in Table 1. Tritium breeding is assumed in both cases. Credit is taken for an excess tritium production at a rate of  $10^4$  \$/g by assuming that a market need will exist. The M\$/dpa figure of merit is a factor of 4 higher for the same power and 8% higher for the same wall loading. The results indicate that for the same wall loading the bare direct and overnight costs will be higher than those for the base case by 21%; the lifetime costs will be only 14% higher due to the reduction of purchased electricity cost resulting from the reduced repetition rate. Based on these results, it is clear that there is no incentive to use a more advanced higher yield target in the SIRIUS-M test facility.

#### Shielding Requirements

One of the major problems facing an ICF reactor designer is the need to reduce neutron streaming through the beam tubes to the laser building and limit damage to the vacuum windows separating the laser building from the containment. While this problem is common for all ICF reactors, it is particularly difficult for symmetric illumination systems where a large number of beams is involved.

Several design options have been examined for SIRIUS-M. The selected design involves the use of a beam crossover point between the two last optical elements in each beam (see Fig. 2). The main uncertainty involved in this approach is the possibility of breakdown of the containment gas (1.0 torr xenon) at the focal point with attendant beam quality degradation.

The final design selected (Fig. 2) utilizes a beam point crossover with a 10 cm diameter orifice at the crossover point. For this case, neutron streaming through the optical window is nearly  $2.5 \times 10^{-14}$  neutrons/cm<sup>2</sup> per source neutron. This value is nearly

three orders of magnitude lower than streaming rates for design options without a crossover point. The dose rate in the SiO<sub>2</sub> laser building windows is  $4.6 \times 10^4$  rad/FPY. This corresponds to an end of life dose of about 0.23 Mrad. This results in a density reduction of less than 0.01% with very little optical degradation expected.

For xenon at 1.0 torr and a KrF laser (0.25 μm) the threshold for multiphoton absorption or tunneling occurs at  $2 \times 10^{13} \text{ W/cm}^2$  and for cascade breakdown at  $2.5 \times 10^{15} \text{ W/cm}^2$ . A 1 MJ laser using a 1 ns pulse and 92 beams will have  $10^{13}$  per beam and if focused to an area of 1.0 cm<sup>2</sup> will have a power density of  $10^{13} \text{ W/cm}^2$ . On the basis of this preliminary determination we would not expect breakdown to occur.

Increasing the number of beams to 92 and reducing the crossover port from 10 cm diameter to 2 cm diameter reduces the dose to the window by a factor of 25 with an end of life dose of ~0.01 Mrad.

#### Conclusions

Based on the results of the SIRIUS-M study the following conclusions can be made:

(1) Inertial confinement fusion offers the opportunity to build a low power, high-performance materials test facility at a reasonable cost. The design includes a 1 MJ short wavelength laser, low-gain targets, large materials test volume, a small fusion reactor cavity, and an efficient geometry for neutron multiplication.

(2) Tritium breeding and self-sufficiency can be easily achieved in the SIRIUS-M facility by adding a small amount of lithium nitrate to the water coolant. This will significantly reduce the total lifetime cost of the facility without adverse impact on the materials testing capability.

(3) No economic advantage can be gained by using higher-yield targets (100 MJ) in such a materials test facility.

(4) Radiation streaming to the laser building and damage to the optical windows represent a major design problem for ICF reactors in general, and symmetrically illuminated systems, in particular. It is shown that this can be considerably reduced by using a beam crossover between the last two optical elements.

#### Acknowledgment

Support was provided by the U.S. Department of Energy. Computing support has been provided by the National Science Foundation through the San Diego Supercomputer Center.

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