The Economic Analysis of SIRIUS-M, A Symmetrically Illuminated, Inertial Confinement Fusion Engineering Test Reactor (Continuation of UWFDM-708)

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FUSION TECHNOLOGY INSTITUTE

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Introduction

We have looked at the cost of SIRIUS-M and compared the direct cost, annual costs and figure of merit (FOM) for various 13.4 MJ and 100 MJ ETR (engineering test reactor) designs. The differences in the designs considered (apart from the target yield) are due to the presence or absence of tritium breeding. Tritium breeding will improve the figure of merit because it rescinds the significant annual fuel cost which can be quite large in the case of a 100 MJ facility. We have also considered the case where the thermal power of the ETR is converted into electricity to supply part of the laser input power needed (100 MW). In the end, we considered the case of a 100 MJ, 10 Hz demo reactor that would produce electricity and have a design similar to the one considered for a 100 MJ test facility with breeding.

This report is a continuation of UWFDM-708, "The Economic Analysis of SIRIUS-M, A Symmetrically Illuminated Inertial Confinement Engineering Test Reactor," in which the base case of a 13.4 MJ, 10 Hz test facility without tritium breeding was considered.

A 100 MJ Facility -- An Example

In order to understand the cost differences between the base case of a 13.4 MJ, 2 m test reactor and this new case of a 100 MJ test reactor (without tritium breeding), Table 1 has been prepared. It compares the cost of the items affected for the two facility designs. There are other cost components that are not affected by the switch to a higher yield target and a larger radius cavity. In this example, the rep rate is kept constant at 10 Hz, so the cavity radius is increased to 5.5 m in order to conserve the wall loading.

Because the constant rep rate is associated with a higher target yield, the fusion power of the new case goes up in proportion to the target yield.

Table 1. Comparison of a 100 MJ and a 13.4 MJ Design Without Breeding

$E_0 = 13.4$ MJ $\quad E_1 = 100$ MJ

$r_0 = 2$ m $\quad r_1 = 5.5$ m

$\nu_0 = 10$ Hz $\quad \nu_1 = 10$ Hz

	Affected Item	Direct Costs ($M) Before	Now	Scaling Law [1]
1)	Cooling system structures	4.6	7.3	$\$9.05\ M \times (Pg/1000)^{0.3}$
2)	Heat rejection	6.0	20.4	$\$145\ k \times Pg^{0.8}$
3)	Part of electrical plant	3.9	29.1	$C_{ref} \times P_{aux}/P_{ref,aux}$
4)	Miscellaneous plant	23.2	33.6	$\$5.05\ M \times Pg^{0.3}$
5)	I&C	13.6	22.0	$\$2.52\ M \times P_{th}^{0.3}$
6)	Maintenance equipment	22.1	35.8	$\$4.1\ M \times P_{th}^{0.3}$
7)	Graphite	4.1	30.6	$4520/kg
8)	Pb	1.9	14.2	$4.5/kg
9)	PCA	11.8	88.1	$50/kg
10)	Pb pumps	2.7	20.1	$\$27.45\ M \times \dot{m}/3.2 \times 10^8$ kg/hr
11)	Pb heat exchangers	4.2	31.3	$\$81.2\ M \times P_{th,Pb}/2081$ MW
12)	Pb cleanup	3.3	24.6	$7.5/kg
13)	H_2O pumps	3.6	26.9	$\$264\ k/1.0 \times 10^5$ kg/hr
14)	H_2O heat exchangers	3.3	24.6	$\$31.8\ M \times P_{th,w}/730$ MW
15)	Auxiliary cooling	0.9	6.7	$C_{ref} \times P_{aux}/P_{aux,ref}$
		$109.2 M	$415.3 M	

$\Delta = \$306.1$ M

$BDC_0 = \$452$ M

$BDC_1 = \$758$ M (+67.7%)

The dependence of cost on the fusion power and the cavity radius can be separated, because the cost of certain items depends only on fusion power, while the cost of some other items (cavity materials) depends exclusively on the cavity radius; the rest of the cost items are independent of these two parameters. Table 1 presents the breakdown in cost for the items that are affected by this change in the facility design and compares the bare direct cost of the whole facility between the 13.4 MJ and the 100 MJ cases.

Parametric Studies of Direct Cost of a 100 MJ Facility Without Breeding

Figure 1 presents the results of parametric studies of direct cost for a 100 MJ facility without tritium breeding. It presents the direct cost as a function of rep rate, with the cavity size as a parameter. Since the direct cost of the facility C can be written as:

$$C = C_0 + C_1(R^2) + C_2(\nu)$$

where: R = cavity radius

ν = rep rate

then the dependences on R and ν can be separated from each other. The dependence on the rep rate is approximately linear for $\nu > 3$ Hz and the dependence on the cavity size is approximately quadratic, as can be seen from the figure. Also shown in Fig. 1 are the boundaries (in dashed lines) imposed by the condition that the wall loading, Γ, should be between 2 MW/m^2 and 3.6 MW/m^2. From other considerations, the minimum cavity size for a 100 MJ target yield should be about 4 m. In order to satisfy the wall loading considerations, we are interested in the section of the 4 m curve in Fig. 1 that is between the 2 MW/m^2 and 3.6 MW/m^2 dashed lines. Therefore the rep rate should be between 5.36 Hz and 9.65 Hz and the corresponding bare direct cost (BDC) of the 100 MJ

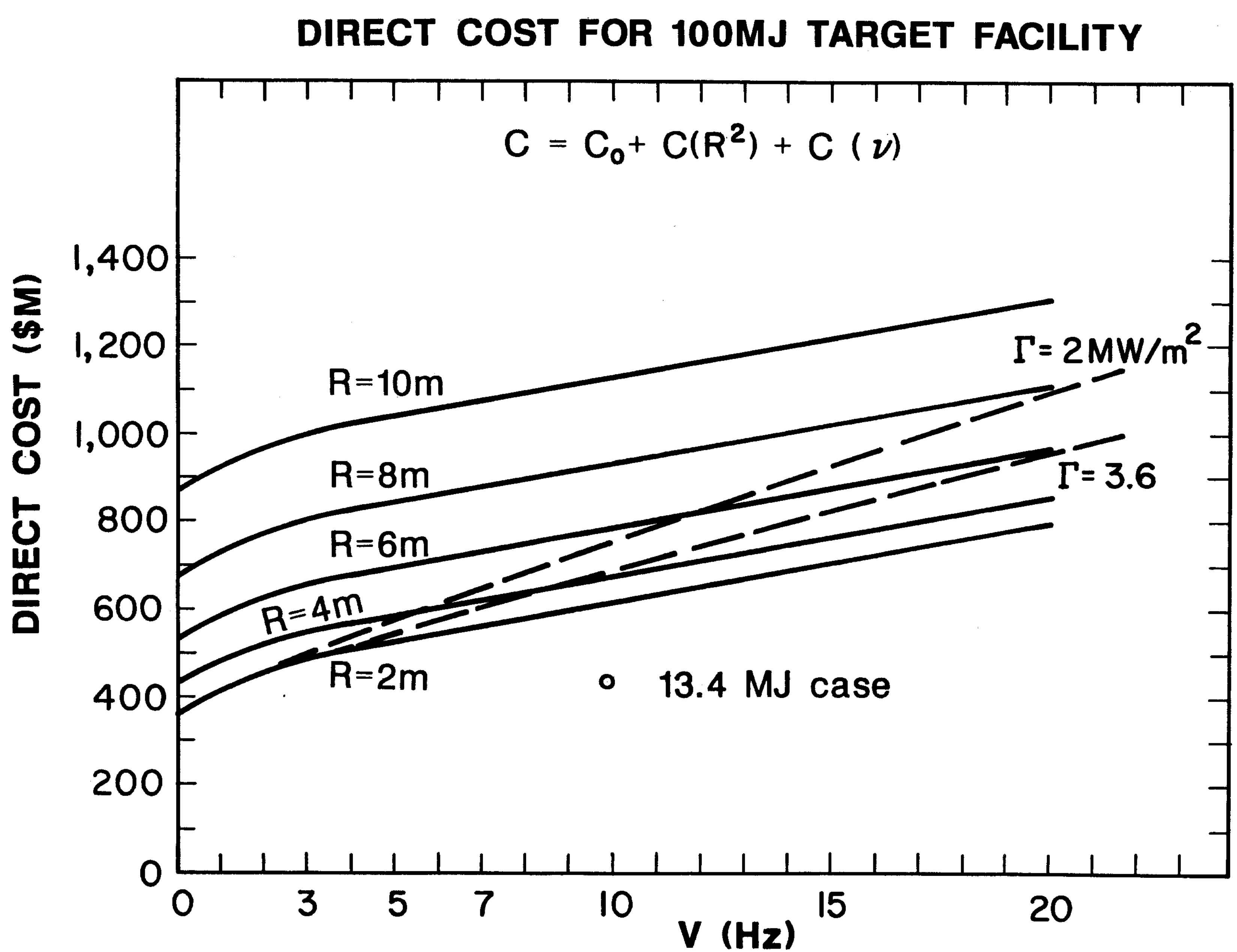


Fig. 1. Parametric study of cost with respect to cavity radius and rep rate for the 100 MJ facility

facility lies in the range of \$590 M - \$670 M (for the 13.4 MJ facility the BDC was \$452 M). Therefore the increase in cost over the base case is substantial (30.5% to 48.2%). The data used in generating Fig. 1 are shown in Table 2.

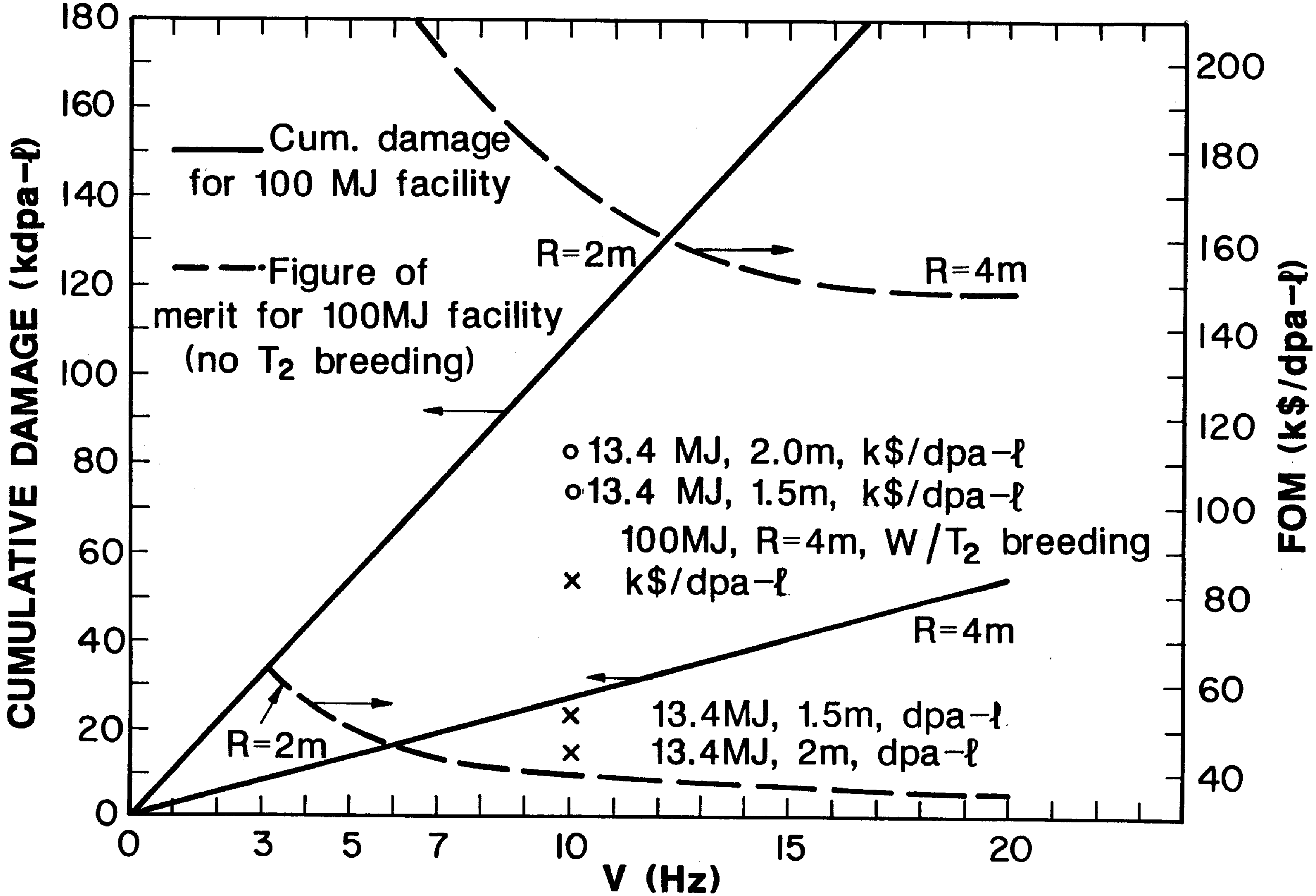
Figure 2 presents the figure of merit (FOM) and the cumulative damage (in dpa-ℓ) for the 2 m and the 4 m 100 MJ reactor without breeding as a function of rep rate. Also shown on the same graph are the data for our base case (2 m, 13.4 MJ target). The solid lines show the cumulative damage function for these two cases (the corresponding ordinate is on the left) and the points marked "X" show the cumulative damage (in dpa-ℓ) for the 2 m base case and for the 1.5 m 13.4 MJ case. The dashed curves show the figure of merit (FOM) for the 2 m and 4 m 100 MJ reactor costs. The FOM is a decreasing function of rep rate because the cumulative damage increases with fusion power. The FOM is defined as the ratio of the total lifetime cost (total overnight cost plus the sum of all the annual costs over the life of the plant) and the cumulative damage. Points marked "O" on the figure are the FOMs for the two 13.4 MJ cases. As can be seen, at 10 Hz the 100 MJ, 4 m reactor has a much worse FOM than our base case. However, this FOM is improved substantially (and is actually better than the FOM for the base case design) if tritium breeding is included in the design (point marked "*"). The reason for this is that due to the increase in the fusion power, the fuel requirements, and consequently the fuel cost, of the 100 MJ 10 Hz facility is enormous (a cost of \$271 M per year for fuel alone). This drives up the total annual cost and hence the FOM. On the other hand, with tritium breeding equipment, this cost drops to zero in exchange for ~ \$10 M in additional bare direct cost. Therefore, this option cuts the FOM of the 100 MJ, 4 m, 10 Hz reactor by 52%.

Table 2. Parametric Studies for a 100 MJ Yield

Direct Costs Shown in $M

Hz		$\nu = 0$	3	5	7	10	15	20
m	Dependence	$R = 0$	2	4	6	8	10	
1) Cooling system structures	ν	0	5.4	6.1	6.7	7.3	8.2	8.9
2) Heat rejection	ν	0	9.3	12.8	16.1	20.8	28.1	34.9
3) Part of elec. plant	ν	0	8.7	14.6	20.4	29.1	43.7	58.2
4) Miscellaneous plant	ν	0	26.0	28.7	30.8	33.6	37.2	40.2
5) I&C	ν	0	16.3	18.5	20.3	22.4	25.2	27.3
6) Maintenance eq't.	ν	0	26.5	30.1	33.0	36.4	41.0	44.4
7) Heat transfer equipment	ν	0	32.9	54.9	76.8	109.7	164.6	219.4
Subtotal	ν	0	125.1	165.7	204.1	259.3	348.0	433.3
Reactor Cavity Total	R	0	21.1	84.4	189.9	337.6	527.5	
Rest: $342.8 M								

Fig. 2. Parametric study of cumulative damage and figure of merit with respect to cavity radius and rep rate for the 100 MJ facility.



Comparison of Cases With Tritium Breeding

In this section we will compare the costs and the FOM of the 4 m, 100 MJ reactor designs with the original base case (13.4 MJ, 2 m) and the base case with T_2 breeding included. It was decided that 4 m was the best radius for the 100 MJ facility.

Figure 3 shows a representative geometry for the 2 m 13.4 MJ cavity. The first wall made of graphite tiles is at 2 m from the target. Its thickness is 1 cm and is followed by 1.5 cm of cooling channels. Next comes the zone containing the neutron multiplier and/or T_2 breeding material. The final zone again contains the steel structure and cooling channels. The thicknesses of the last two zones vary in such a manner that the final radius of the reactor stays constant at 270 cm. The breeding material can be either 90% enriched $LiNO_3$ dissolved in the cooling water (in all three zones) or LiPb that replaces water in zone 3 (multiplier zone). The $LiNO_3$ concentrations in water are either 20 g/100 cc or 80 g/100 cc of water. The base case (no breeding) had liquid lead in zone 3 (40 cm) followed by 30 cm of steel and water. In the breeding scenarios, the multiplier is either Be balls, or lead (solid or liquid). Be in the third zone tends to decrease the damage rate in the test modules by 15-20% due to forwardly peaked scattering of neutrons and a softer neutron spectrum. In addition, if there is breeding material in that zone, the neutrons are absorbed in Li.

The 6 representative breeding configurations for the 2 m, 13.4 MJ cavity are shown in Tables 3 and 4. In Table 3, the cases identified and presented are the total tritium breeding ratio (TBR), energy multiplication and loss in the damage rate in the test sample due to the effects discussed above. Also presented are the adjustments in the direct cost of the reactor chamber that

Table 3. 2 m Cases With Breeding

	Case	Fuel Revenue ($M)	TBR	Energy Multiplication	Dpa Loss (%) (total dpa-ℓ)	Cost of $LiNO_3$ ($M)	Cost of Be ($M)	Cost of LiPb ($M)	Cost of Pb ($M)	Cost of PCA
ΔBe, 30 cm 20 g/100 cc $LiNO_3$	1	14.44	1.399	1.33	20.9 (11,232)	0.62	9.43	0	-1.25	-0.33
ΔBe, 15 cm, 20 g/100 cc $LiNO_3$	2	2.75	1.077	1.30	21.3 (11,175)	0.62	3.99	0	-1.25	-0.33
30 cm, liq. Pb, 80 g/100 cc $LiNO_3$	3	2.79	1.077	1.35	3.6 (13,689)	0.81	0	0	-0.35	+0.28
30 cm, solid Pb, 20 g/100 cc $LiNO_3$	4	4.78	1.132	1.35	20.5 (11,289)	0.62	0	0	-0.62	-0.33
Be + LiPb, no salt, 25 cm	5	5.57	1.154	1.38	15.6 (11.985)	0	7.54	1.06	-1.25	-0.33
Be + LiPb, no salt, 30 cm	6	10.72	1.296	1.37	15.6 (11,985)	0	9.43	1.32	-1.25	-0.33

Table 4

Case	Reactor Cavity, ΔC ($M)	Breeding Equipment, ΔC ($M)	HT eq't, ΔC ($M)	Total, ΔC	Fuel Credit
1	8.47	7.2	-15.9	-0.2	14.44
2	3.03	7.2	-16.2	-6.0	2.75
3	0.74	7.2	-4.9	+3.0	2.79
4	-0.33	7.2	-15.6	-8.7	4.78
5	7.02	7.2	-6.7	+7.5	5.57
6	9.17	7.2	-4.9	+11.5	10.72

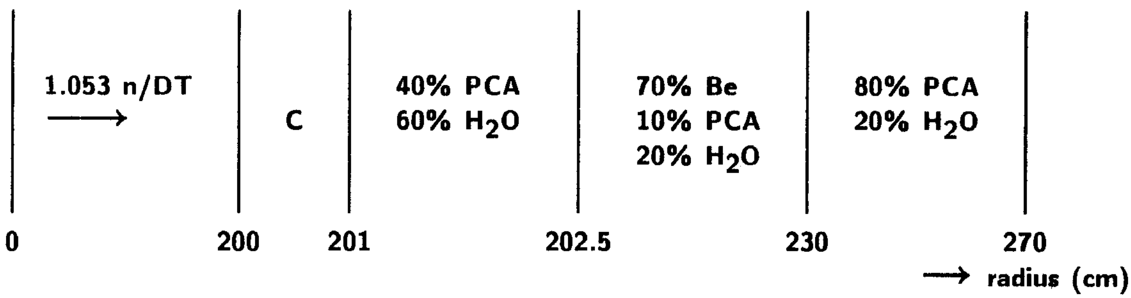


Fig. 3. Representative case of a 2 m SIRIUS-M cavity with T_2 breeding, showing compositions and thicknesses of various zones. Not drawn to scale.

need to be made over the base case. These adjustments are due to the cost of additional materials ($LiNO_3$, Be, LiPb, PCA) and displaced materials (Pb, PCA). In Table 4, the adjustments are combined to give the total difference in cost of the reactor cavity. The cost of additional breeding equipment is also shown ($2.2 M for isotope separation, TSTA figures,[2,3] $5 M for extraction of T_2 from breeding material). Adjustments in the cost of the heat transfer equipment need also be made because we are replacing expensive liquid metal cooling by water cooling to a varying degree. (There are also slight differences in energy multiplication.) This information yields the total difference in direct cost which can be either positive or negative. For case 1, Be balls in zone 3 with 20 g/100 cc dissolved $LiNO_3$, this total cost difference is almost zero. The huge negative difference caused by replacing all of the liquid lead cooling by water cooling is offset by putting a lot of expensive Be in the reactor chamber. This case also has the highest fuel credit due to the high TBR of 1.399 (shown in the last column and assuming that a T_2 price of $10,000/g can be maintained). Case 4 has the lowest direct cost, because the lower cost of H_2O cooling is not offset by an increase in reactor cavity cost (there is no Be and $LiNO_3$ cost is offset by a decrease in the cost of Pb and PCA displaced). This case has a medium fuel credit. Case 6 has the highest net gain in direct cost (most of liquid Pb cooling is replaced by LiPb cooling which costs the same, only a fraction is replaced by cheaper water cooling). The increase in reactor cavity cost is high due to the cost of Be and 90% enriched LiPb. This case has a relatively high fuel credit, too. Similar calculations were done for these 3 cases for the 100 MJ, 4 m design.

The 100 MJ and the 13.4 MJ designs with various breeding scenarios are shown in Table 5 and Table 6. Table 6 assumes zero fuel credit for T_2 bred.

Table 5. Comparisons in Costs and FOM Among Various Breeding Alternatives for the 13.4 MJ, 2 m and 100 MJ, 4 m Designs

$FOM_1 = 0.277\ BDC + AC$

Type Cost ($M)	Original 2 m	1	2	3	4	5	6	1	4	6	1	4	6
		2 m With Breeding						100 MJ, 4 m, 1.34 Hz With Breeding			100 MJ, 4 m, 5.36 Hz With Breeding		
BDC	452	452	446	455	443	460	464	528	493	542	573	538	620
TOC	855	855	844	861	838	870	878	999	933	1025	1084	1018	1173
O&M	25.5	25.5	25.2	25.7	25.0	26.0	26.2	30.0	28.0	30.8	32.5	30.5	35.2
Fuel	36.3	-14.4	-2.75	-2.8	-4.8	-5.6	-10.7	-14.4	-4.8	-10.7	-57.6	-19.2	-42.8
Electricity	13.2	13.2	13.2	13.2	13.2	13.2	13.2	1.8	1.8	1.8	7.1	7.1	7.1
Total Annual	75.	24.3	35.6	36.1	33.4	33.6	28.7	17.4	25.0	21.9	-18.0	18.4	-0.5
Total Lifetime	1605	1098	1200	1222	1172	1206	1165	1173	1183	1244	904	1202	1168
Cum. Damage dpa-ℓ	14200	11232	11175	13689	11289	11985	11985	2808	2822	2996	11232	11289	11985
FOM (k$/dpa-ℓ)	113	97.8	107.4	89.3	103.8	100.6	97.2	418.	419.	415.	80.5	106.5	97.5
FOM_1 ($M)	200	149	159	162	156	161	157	164	161	172	141	167	171

Table 6. Comparisons in Costs and FOM Among Various Breeding Alternatives for the 13.4 MJ, 2 m and 100 MJ, 4 m Designs; No Fuel Credit Given

$$FOM_1 = 0.277\ BDC + AC$$

Type Cost ($M)	Original 2 m	1	2	3	4	5	6	1	2	3	4	5	6
		2 m With Breeding						4 m, 100 MJ, 5.36 Hz With Breeding					
BDC	452	452	446	455	443	460	464	573	550	586	538	604	620
TOC	855	855	844	861	838	870	878	1084	1040	1108	1018	1143	1173
O&M	25.5	25.5	25.2	25.7	25.0	26.0	26.2	32.5	31.2	33.0	30.5	34.3	36.5
Fuel	36.3	0	0	0	0	0	0	0	0	0	0	0	0
Electricity	13.2	13.2	13.2	13.2	13.2	13.2	13.2	7.1	7.1	7.1	7.1	7.1	7.1
Total Annual Cost, AC	75.	38.7	38.4	38.9	38.2	39.2	39.4	39.6	38.3	40.3	37.6	41.4	43.6
Total Lifetime Cost	1605	1242	1228	1250	1220	1262	1277	1480	1423	1511	1394	1557	1609
Cum. Damage dpa-ℓ	14200	11232	11175	13689	11289	11985	11985	11232	11175	13689	11289	11935	11985
FOM (k$/dpa-ℓ)	113	111	110	91	108	105	106	132	127	110	123	130	134
FOM_1 ($M)	208	164	162	165	161	167	168	198	191	203	187	209	215

The 100 MJ cases shown are for the rep rate of 5.36 Hz (which keeps the wall loading at 2 MW/m^2) and 1.34 Hz (which keeps the fusion power at 134 MW, the same as the 2 m base case though the wall loading may be below the required value). Shown are the bare direct cost (BDC), total overnight cost (TOC) and components of the annual cost (operations and maintenance, fuel and electricity). The fuel credit in Table 5 is given at the same rate that the fuel cost is charged -- at 10,000/g of T_2. The total lifetime cost is defined as the sum of the TOC and the annual costs summed over the life of the facility (10 yr). The FOM is then the ratio of the total lifetime cost and the total cumulative damage in dpa-ℓ. An alternative figure of merit, which more truly reflects the cost of borrowed money under the assumptions used, is also shown. This FOM doesn't incorporate the cumulative damage, because a certain minimum wall loading (~ 2 MW/m^2) is required and the damage rate (in dpa/y) is proportional to the wall loading. This FOM is the annual cost (including borrowed money) of owning and operating the facility.

Based on the old figure of merit, the best configuration is for the 100 MJ, 4 m, 5.36 Hz design with 30 cm multiplier zone with Be balls and H_2O cooling with 20 g/100 cc dissolved $LiNO_3$ as the breeder; this is followed closely by the 2 m, 13.4 MJ, 10 Hz design with the liquid Pb zone with H_2O shield and first wall cooling containing 80 g/100 cc $LiNO_3$. If the alternative FOM is used, then the best case is the same as above (100 MJ, 4 m, 5.36 Hz, 30 cm Be zone and 20 g/100 cc $LiNO_3$) followed very closely by the 13.4 MJ, 2 m, 10 Hz case with the same cavity configuration. If no fuel credit is allowed for bred T_2, and if a minimum wall loading of ~ 2 MW/m^2 is required, then by far the best case is the 13.4 MJ, 2 m, 10 Hz design with 30 cm solid lead multiplier zone cooled by H_2O with 20 g/100 cc dissolved

$LiNO_3$ as the breeder. If there is no market for bred T_2, then the object is to reduce the amount of T_2 produced and the best case is the 13.4 MJ, 2 m, 10 Hz design with 30 cm liquid lead zone and H_2O cooling elsewhere with 80 g/100 cc dissolved $LiNO_3$ for the breeder. However, in that case the price of T_2 purchased would probably be low, and if we don't want to introduce any additional T_2 into the economy, then the base case (2 m cavity without breeding) is the only case to be considered.

The cost of T_2 produced in the breeding options for SIRIUS-M can be legislated as has been done above (at $10,000/g or $0./g) or it can be calculated as will be shown here.

The cost of producing T_2 will have several components:

a) The cost of raw material, which in this case will be the cost of burned Li. Assuming we have 90% enriched Li as the worst case, we know that the cost of this is $1200/kg. For each g of T_2 produced, approximately 2 g of Li are consumed. If we are producing 10 kg of T_2 (about the upper limit for the SIRIUS-M options considered), then we are consuming 20 kg of Li/year and the cost is only $24,000/y. Therefore, raw material cost is a very minor item.

b) Cost of additional (breeding) equipment levelized (depreciated) over plant lifetime. If we charge just the cost of the breeding equipment to the selling price of T_2, and charge the other option-dependent costs in Table 4 to the operation of our basic facility, and with the economic assumptions used in this study [1], this item comes out to $2.0 M/y.

c) The cost of operating and maintaining this additional equipment, given these economic assumptions is about $0.4 M/y.

Therefore the total cost of T_2 production would be \$2.4 M/y. The selling price of T_2 produced (assuming no profit margin for this government owned facility) would depend on the amount produced. This price is given in Table 7 for the various design options considered. It is shown that the selling price of a T_2 producing ETR can be substantially less than the currently prevailing price of \$10,000/g.

Table 7. Selling Price of T_2 in \$/g

	2 m, 13.4 MJ Facility		4 m, 100 MJ Facility		
Case from Table 2.2-1	TBR	Price @ 10 Hz	Price @ 1.34 Hz	5.36 Hz	10 Hz
1	1.399	1767	1767	442	237
2	1.076	9251	9251	2313	1240
3	1.077	9118	9118	2280	1222
4	1.132	5322	5322	1331	713
5	1.154	4567	4567	1142	612
6	1.296	2373	2373	593	318

An ETR With Electricity Production

It may be economically viable to produce part (or all in the 100 MJ case) of the laser input power requirements by adding electric conversion equipment. The cost impact of this option on the affected facility items is shown in Table 8 for the 13.4 MJ, 2 m, 10 Hz design. The added cost is relatively modest, \$31 M, in order to supply about 60% of laser input requirements (for a

Table 8. Cost Difference, ΔC for Affected Items in the 13.4 MJ, 2 m, 10 Hz Facility

Item	ΔC, $M
Electric plant	+13.8
Turbine plant	+19.3
Heat rejection	- 1.5
Cooling structures	- 0.4
	+31.2

10% efficient, 1 MJ laser). This will result in the decrease in the cost of electricity charged to the facility and a slight increase in the O&M cost. The plan should go ahead if the difference in the FOM is below zero, because then the savings in the electricity cost outweigh the additional O&M cost and the additional prorated capital cost (which is defined differently for the alternative FOM discussed above). The results are presented in Table 9 for the two cases of the cost of electricity (3¢/kWh and 6¢/kWh) and the two figures of merit used (the alternative FOM is FOM_1). Negative figures show annual savings in $M in operating and ownership costs. We see that for 6¢/kWh, the electric conversion equipment should be included (for a yearly savings of ~ $6 M in case of of FOM_1, ~ $9 M in case of FOM_0). In case of 3 ¢/kWh electricity, FOM_0 decision gives very small advantage to electric conversion, whereas FOM, does not; this may change (in favor of electric conversion) if laser waste heat is used for feedwater heating, thus increasing the amount of electric power available.

Table 9. Δ FOM Table

Cost of Electricity ¢/kWh	FOM_0 Logic	FOM_1 Logic
3	-0.58	+2.2
6	-8.8	-6.1

Demo Plant

A 100 MJ, 4 m, 10 Hz demo plant has been costed using a design similar to the base case 13.4 MJ, 2 m, 10 Hz with breeding. We can start by calculating the direct cost of a 100 MJ, 4 m, 10 Hz ETR from Figure 1 and including breeding. Table 10 presents the difference in cost of affected items between the 100 MJ, 4 m, 10 Hz ETR and the demo. The change in assumptions is that now the availability is assumed to be 75%, construction time is 6 years and plant lifetime is 20 years. This demo produces 366 MWe of net power.

Table 11 shows the new bare direct cost (BDC), total capital cost (TCC), annual costs and the cost of electricity produced (COE).

Upgrade Demo vs. a Greenfield Demo

In a previous section we have looked at a 2 m, 13.4 MJ, 10 Hz ETR with electricity production.

Similarly, the corresponding information for a 100 MJ, 4 m, 10 Hz ETR is shown in Tables 12 and 13. In this case, all of the laser input power is supplied by the electric conversion equipment and a substantial amount of electric power is sold outside the facility. It can be seen that in this case, too, it is economically advantageous to convert to electric power on site, because of the high electricity demand of the laser input power equipment.

Table 10. Cost Difference, ΔC in $M for Affected Items for the Demo

Item	4 m, 100 MJ, 10 Hz ETR	Demo	ΔC	
Electrical plant	62.9	80.6	17.7	
Turbine plant	0	96.6	96.6	
Heat rejection	28.2	21.4	- 6.8	
Cooling structures	8.2	7.4	- 0.8	
TOTAL			+106.7	(+15.7%)

Table 11. Various Costs for the Demo Plant

Item	Value
BDC ($M)	787
TCC ($B)	1.93
Annual Costs in $M	
(Investment return	138.)
O&M	44.7
Fuel	0
COE, with investment return, ¢/kWh	7.6
COE, w/o investment return, ¢/kWh	1.9

Table 12. Cost Difference, ΔC for Affected Items in the 100 MJ, 4 m, 10 Hz Facility

Item	ΔC, \$M
Electric plant	+ 14.6
Turbine plant	+ 113
Heat rejection	- 10.4
Cooling structures	- 1.3
	+ 115.9

Table 13. ΔFOM Table for the 100 MJ, 4 m, 10 Hz Facility

The figures represent the reduction (if negative) or increase (if positive) in yearly cost of owning and operating the facility (in \$M) depending on which figure of merit (FOM) is used.

Cost of Electricity ¢/kWh	FOM_0 Logic	FOM_1 Logic
3	-33.1	-22.9
6	-94.6	-84.4

The Advantages of a 4 m ETR and Upgrade Demo vs. a 2 m ETR and a Greenfield Demo

It has been decided that a 2 m, 13.4 MJ, 10 Hz ETR with breeding will be the base case for the SIRIUS-M facility. Similarly we have looked at the cost estimate of a 366 MWe Demo plant, assuming a similar configuration (except for larger cavity), T_2 self-sufficiency and also comparing the direct cost to that of a 4 m, 100 MJ ETR. It can be seen in Tables 5 and 6 that, if uncertainties in cost estimates are neglected, some 4 m design options can compete with a 2 m ETR based on our figures of merit. It will be shown here, that if the total cost of an ETR and a subsequent Demo are considered, it may be advantageous to start with a 4 m, 100 MJ ETR and upgrade it to a Demo, rather than to have a 2 m, 13.4 MJ ETR and subsequently build a separate Demo.

In previous discussion on cost dependence on cavity radius and rep rate (see Fig. 1), it was shown that a 4 m, 100 MJ ETR with a rep rate of ~ 10 Hz was possible, and it can be seen that it is economically advantageous to go to higher rep rates because the FOM decreases (the lower the FOM the better); see Fig. 2. This will also have an impact on the total life of the ETR facility, because the required cumulative damage will be achieved in a much shorter time (about 5 years instead of 10 years), so the schedule for a Demo can be advanced.

It has been shown above that it is economically advantageous to add electric power conversion equipment to a 100 MJ, 10 Hz ETR. In addition, it can be said that the electric power conversion equipment won't add to engineering uncertainty of the facility, and won't significantly add to its unavailability (availability of this equipment is on the order of 90% from conventional plant experience, and assumed availability of SIRIUS-M ETR is ~ 50%).

Therefore, we can look at a 100 MJ, 4 m, 10 Hz ETR that, after retirement and after certain equipment is replaced becomes a Demo. This combination will cost less than building a 2 m ETR and a Demo separately.

The equipment to be replaced at the end of life will be the following:

The reactor cavity, due to damage, new knowledge gained from operating the ETR and a possibly different cooling/breeding medium.

Breeding equipment due to different breeding medium and extraction method of T_2. In this case, just the equipment responsible for extraction of T_2 is replaced.

+ Laser power supply due to wear and tear of the high voltage, high total pulse number equipment.
+ Laser optics, due to radiation damage.
+ Possibly heat transfer equipment if the ETR is using H_2O cooling and the Demo is using liquid metal cooling (we are looking at the worst case here). H_2O cooled Demo is the base case.

Excluded is the normal replacement of equipment that is included in the ETR's and Demo's annual O&M costs.

The direct cost of these items is shown in Table 14. The items that will not need replacement are the buildings, the heat rejection plant, the electrical plant exclusive of the laser power supply, the turbine plant, miscellaneous plant, part of the laser excluding the optics, the target factory, the pellet injector (a minor item), the vacuum system, isotope separation and storage, Xe recycle equipment, fuel storage, any water cooling outside the first wall and the reflector, instrumentation and control and maintenance equipment [1].

Table 14. Items to be Replaced at End of 100 MJ, 4 m, 10 Hz ETR Life

Item	Direct Cost ($M)
Reactor Cavity	~ 140
Breeding Equipment (extraction of T_2)	5
Laser Power Supply	31.7
Laser Optics	33
Heat Transfer Equipment	102.8
Total	313
ΔTOC	592

Table 15 shows the comparison of a 4 m, 100 MJ 10 Hz ETR and a 2 m, 13.4 MJ, 10 Hz ETR. Note that credit is given for excess electricity produced in the former. Also, there are two lifetime costs for the 100 MJ, 4 m ETR: one corresponding to the original 10 year lifetime and the other corresponding to the 6 year lifetime whereby credit is taken for the higher damage rates of the enhanced target facility and the slightly lower availability due to the electric power conversion equipment. Also given are the total lifetime costs of the ETR + Demo combinations; separate ETR and Demo in case of the 2 m, 13.4 ETR and a Demo built on an earlier ETR in case of the 4 m, 100 MJ ETR. It can be seen that this latter case has a much lower lifetime cost and therefore should be seriously considered. Even if we compare just the two ETR's, we can see that if the cost of electricity is 6¢/kWh or higher, the

Table 15. Comparison of Enhanced Target (4 m) ETR Plus Upgrade Demo and a Baseline (2 m) ETR Plus Greenfield Demo Combinations

Type Cost	Value for 4 m ETR ($M)	Value for 2 m ETR ($M)	
BDC	787	450	
TOC	1488	850	
O&M	45	25	
Fuel	0	36[c]	0
Electricity[a]	-48 (-96)[a]	13	
Total Annual Cost	~ 0 (-50)[a]	75[c]	38
Total Lifetime Cost			
N = 10 y	1488(1000)[a]	1605[c]	~ 1200
N = 6 y[b]	1488(1188)[a]		
Total Lifetime Cost			
ETR + Demo	2080(1780)[a]	3100[c]	2700
		(3000)[c,d]	(2600)[d]

(a) Electricity sold at 3¢/kWh (6¢/kWh); bought at 3¢/kWh for the 2 m ETR.

(b) Includes reduction in availability due to electric conversion equipment and an increase in the damage rate due to enhanced target and 10 Hz rep rate.

(c) This case assumes no breeding of T_2 for the 2 m ETR. The next column includes breeding.

(d) Numbers in parentheses assume electricity production to meet part of the laser demand in the 2 m ETR case.

enhanced target ETR is less expensive over the lifetime than our baseline ETR. This is due to the substantial credit from electricity sold outside the facility.

Acknowledgement

Support for the work has been provided by the U.S. Department of Energy.

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APPENDIX A

The Economic Model

This appendix will explain the basic facts about our economic model. The model has been described in greater detail elsewhere [10-12,14]. The model has been implemented on the IBM-PC computer, employing user friendly, menu-driven input. In short, the model takes plant parameters from the user, applies the scaling laws (discussed below) to arrive at the direct cost of individual accounts, combines the accounts to arrive at the total direct and indirect cost of the facility and calculates the total overnight cost, total capital cost and annual levelized cost items (operations and maintenance, fuel, electricity and return on capital) based on the values of economic parameters (inflation rate, cost of money, etc.) input by the user. The results are given both in constant and in then-current dollars. To familiarize the reader with the terminology, we will first give some definitions and then present the default values of economic parameters used in this study.

Definitions

Cost in constant dollars. This is the cost that assumes the value of the dollar doesn't change in time, i.e. zero inflation. The cost is given in the dollars of the reference year input by the user, usually the year of the start of construction or the year of the study.

Cost in then-current dollars. This cost item takes into account the inflation rate (which must be assumed by the user) and the reference year is the finish of construction (or startup of the facility). So, if the construction was to start in 1986 and last 4 years, the total capital cost (i.e., the money that the investor would have to pay back) in current dollars would be given in 1990 dollars. Similarly, the then-current dollar cost of operating the plant would be given in the dollars of the first year of operation (1990 in this case). The return on investment, for example, would be summed up over the life of the plant and divided up so that it's levelized in the reference year dollars (1990 in this case).

Direct cost. The direct cost of an item (e.g., the laser) includes the cost of hardware and the cost of installing that hardware, if the purchasing and installation were to happen instantaneously and on a cash basis. In other words, indirect costs (administrative, design and field engineering, cost of ownership and project contingency allowance) are not included; neither is the cost of borrowing the money nor the cost of escalation and interest during construction. The items mentioned above can multiply the cost of an item multifold (3-4 times in our base case) to arrive at the real cost of that item. The "bare" direct cost doesn't include the uncertainty in the design and the fact that some spare equipment will be needed. When the design and spare allowances are included, we talk about the total direct cost (TDC) of the facility.

Indirect cost. Explained in the discussion of direct cost above. Usually calculated as some fixed fraction of the total direct cost and called total indirect cost (TIC) of the facility.

Total overnight cost (TOC). This is the sum of total direct cost and the total indirect cost and represents the cost the facility would incur if it were built and paid for instantaneously (or "overnight").

Total capital cost. This is the bottom line cost that every utility or investor building something is interested in. It represents the money that is owed at the end of construction. Usually, a project cannot be paid out of pocket, so the money is borrowed (by selling ownership in the company as in the case of preferred and common stock, or by borrowing money by sale of bonds, which can be done by either a private investor or by the government, if it is financing the project). The interest on the money borrowed to pay for some equipment at a point during construction accumulates for the remainder of construction. Both the interest and the principal are inflated in current dollars (but not in constant dollars) until the end of construction. Also, the direct and indirect cost of equipment that hasn't been purchased increases in time until the time of installation of that equipment. This increase is due to both inflation (loss in the value of money) and escalation (which is caused by scarcity of natural resources and therefore represents a real increase in the price of an item, in constant and in current dollars). It can be seen that short construction times, and spending most of the money as early in the construction as possible, are important in holding the line on the total capital cost (TCC). In this study we have assumed a relatively short construction time of 4 years, although other cases have also been run. There are some indications that a test facility like this (e.g., FMIT) may take as long as 10 years [15]. The total capital cost is paid off over the life of the plant by charging the users of the facility a certain fee each year. Usually, the fee due at the end of the first year of operation is given, either in constant or in then-current dollars. Other costs of operating the facility (operations and maintenance, fuel and electricity) are added to arrive at the total annual cost of the facility. For a government owned facility, and in an era of federal budget deficits, the money for construction will be borrowed just as in the case of a private investor, but at a lower rate of return (no stock sales involved). These bonds would probably be long term. They would be serviced after the end of construction, but the annual fee that the government would be charged for return on investment would be "lost" in the huge national debt and would not be directly traceable to the facility in question. Therefore, this fee will not be shown in the annual cost of operating SIRIUS-M. In case of federal budget surplus, there would be no need for the government to borrow money, so we would have to worry only about the appreciation of the overnight cost of each piece of equipment that is installed.

Default Values of Economic Parameters

This section will present the economic parameters used in the base case scenario, and assuming government ownership. Some of these parameters were later varied: cost of electricity (up to 6 ¢/kWh), tritium cost (down to $7100/g), salvage fraction (up to 20%), general inflation rate (3-12%), cost escalation rate (3-12%), construction time (2-10 y), plant life (up to 20 y) and cases were run for private financing (not much change in this instance due to short construction time assumed).

Availability of the facility (50%) was given as a design parameter, so it wasn't varied.

Table A.1 shows the values of economic parameters used in our base case calculations.

Some of the more obscure entries in the table will now be explained.

Operations and maintenance cost fraction. This is the fraction by which the total overnight cost is multiplied to arrive at the annual O&M cost of running the facility (in this case the cost excludes the cost of fuel and electricity) excluding return on capital.

Table A.1. Default Values of Economic Parameters

Description	Default value
Cost of purchased electricity, ¢/kWh	3.0
Facility availability	50%
Cost of tritium, $/g	10,000.
Operations and maintenance cost fraction	0.03
Salvage fraction	0.00
TEFRA number of years	10.
General inflation rate	6.0%
Average cost escalation rate	6.0%
Construction time in years	4.0
Plant life in years	10.0
Construction factor, f91	0.15
Home office factor, f92	0.15
Field office factor, f93	0.15
Owner's cost factor, f94	0.05
Project contingency factor, f95	0.10
Interest rate on debt	0.09
Fraction of capital from debt	1.00
Total income tax rate	0.00
Investment tax credit rate	0.00
Property tax rate	0.00
Levelized interim replacement cost fraction	0.01
Reference year of cost	1986
Construction completed, year 1	0.25
Construction completed, year 2	0.25
Construction completed, year 3	0.25
Construction completed, year 4	0.25
Construction completed, year 5 through 12	0.00

Salvage fraction. This is the fraction of the total capital cost that can be recovered at the end of the facility life (e.g., by selling the buildings and some of the equipment).

10 year TEFRA accelerated tax depreciation. The utilities are allowed to depreciate their investment over a 10 year or a 15 year period for tax purposes. Depending on the period chosen for accelerated depreciation (10 y or 15 y), the company each year depreciates a given, fixed fraction of its investment. Since we are interested in a government owned facility, this number is irrelevant because all taxes are set to zero and the annual return on investment is of no interest to us.

f factors. The construction factor, f91, the home office factor, f92, the field office factor, f93, the owner's cost factor, f94, and the project contingency factor, f95, are the quantities used in calculation of the total indirect cost (TIC) of the facility. These factors' values are taken from recommendations on a typical ICF electricity-producing facility [12] and they may be different for an engineering test facility like SIRIUS-M.

Levelized interim replacement cost fraction. This item refers to the cost of replacing worn-out components each year of operation.

The Scaling Laws

The scaling laws relate some design parameter of a piece of equipment to that equipment's bare direct cost. For instance, the direct cost of a building is proportional to its free volume raised to a certain power, whereas the direct cost of a pump is related to the mass flow rate of the fluid. Table A.2 represents the scaling laws used in this study. These laws were drawn from several sources, because as of this writing there is no source for

Table A.2. Scaling Laws for Direct Costs

Account Item	Scaling Law
LAND	
Land and land rights [6,1,16]	\$5600/acre
BUILDINGS AND SITE	
Site improvements [16,17]	\$10M
Reactor building (1.5 m wall) [18]	$\$0.0038M * V^{0.8}$
Concrete work [6]	$\$523/m^3$
Tritium treatment building [18]	$\$0.00496M * V^{0.8}$
Control building [18]	$\$0.00182M * V^{0.85}$
Maintenance building [18]	$\$0.0018M * V^{0.7}$
Radwaste building [18]	$\$0.00496M * V^{0.8}$
Administration building [5]	\$1.5M
Diesel generator building [5]	\$0.5M
Cooling system structures [19]	$\$9.05M * (P_g/1000.)^{0.3}$
Hot cell building [1]	\$7.1M
Laser hall, in "Laser equipment"	NA
Rest of the buildings [1]	\$3.4M
HEAT REJECTION PLANT	
Heat rejection equipment [17,6]	$\$145K * P_g^{0.8}$
ELECTRICAL PLANT W/O ELECTRIC CONVERSION	
Elec. plant, ground and cathodic protec.	$C_{ref} * A/A_{ref}$
Elec. plant, rest w/o laser pwr. supp. [6]	$C_{ref} * P_{aux}/P_{ref,aux}$
Laser power supply [6]	$\$31.7M * P_{in}/100.$
ELECTRICAL PLANT WITH ELECTRIC CONVERSION	
All of electrical plant [17]	$\$5.7M * P_g^{0.2} * P_{in}^{0.3}$
TURBINE PLANT (IF EXISTS)	
All of turbine plant [17]	$\$0.35M * P_{th}^{0.8}$
MISCELLANEOUS PLANT	
Miscellaneous plant equipment [17]	$\$5.05M * P_g^{0.3}$
LASER EQUIPMENT	
KrF laser [20,21,9]	$\$100.M * E_d^{0.7}$
TARGET FACTORY	
Target factory equipment [20]	\$100.M

Table A.2. Scaling Laws for Direct Costs (continued)

Account Item	Scaling Law
REACTOR EQUIPMENT	
1st wall graphite [6]	$4520./kg
Lead reflector [6]	$4.5/kg
PCA reflector [6]	$50./kg
Pellet injector [1]	$0.75M
Last mirror shield [1]	$2.11M
Reactor vacuum Roots blower (3000 l/s) [6]	$13.5k/unit
Vacuum exhaust duct [6]	$15.1k/m
Exhaust circulation, 1 atm [4]	$316K
Fuel cleanup [4]	$2.01M
Hydrogen isotope separation [3]	$250.k
Uranium storage beds [4]	$107.k
Xe recycle (cryogenic separation from He) [4]	$3.14M
Xe inventory [2]	$10.20/l
Radwaste (gas, solid, liq.) system [19]	$1951. * P_{th}
Fuel storage cryogenics , 3 kW @ 4.2 K [6]	$2.71M
Fuel storage tank, 40 kg DT capacity [6]	$121.k
Pb cooling, pumps and motor dr. [7]	$27.45M * m/3.2E+8 kg/h
Pb cooling, SS piping (50 cm) + insulation [6]	$339.k/m
Pb cooling, heat exchangers [7]	$81.2M * $P_{th,Pb}$/2081 MW
Pb cooling, cleanup system (Na system) [6]	$7.5/kg coolant
Pb cooling, dump, makeup, hot storage tanks, 400 m^3 [6]	$1433/$m^3$
Water cooling, pumps and motor drives, 1E+05 kg/hr [6]	$264.k/unit
Water cooling, SS piping (50 cm) + insulation [6]	$12.1k/m
Water cooling, heat exchangers [7]	$31.8M * $P_{th,w}$/730 MW
Water cooling, tanks, 400 m^3 capacity [6]	$173./$m^3$
Auxiliary cooling [6]	C_{ref} * $P_{aux}/P_{aux,ref}$
Laser power supply cooling [6]	$4.5/kWth
Instrumentation and control [17]	$2.52M * $P_{th}^{0.3}$
Maintenance equipment [17]	$4.1M * $P_{th}^{0.3}$

scaling of ICF reactor equipment (although several references exist for KrF laser scaling rules). These references are noted in the table after the name of each item. The references are from several different years, ranging from 1978 to the present, so care must be exercised to quote all costs in the same year dollars. We have escalated these scaling laws to the 1986 values in this table employing the consumer price index (CPI). The CPI should measure both the effects of the escalation and the inflation; however, it is really applicable to average consumer products and not to the products and services required in building a fusion test facility. However, the CPI has been used to adjust the costs in another study [11]. The CPI has risen at the following rates in the period 1976-1986 [13]: 5.16% (1976-1977), 6.73% (1977-1978), 9.40% (1978-1979), 13.92% (1979-1980), 11.71% (1980-1981), 8.45% (1981-1982), 3.75% (1982-1983), 4.13% (1983-1984), 3.57% (1984-1985) and 3.89% (1985-1986). These numbers are based on January figures for each year, and they give us a total multiplication of 1.60 in the period 1979-1986 (many scaling laws are from 1979) and 1.12 in the period 1983-1986. Comparison was made in the few accounts where scaling laws exist for both 1979 and 1986. Some of these items have escalated by approximately a factor of 2 in this period, according to the scaling laws, which is consistent with an annual inflation rate of 6% and an annual escalation rate of 6% (12.4% total annual escalation). This escalation could be due to both economic effects (inflation and escalation) and, perhaps to a more realistic appraisal of cost. Nevertheless, all items for which no 1986 figures exist have been escalated based on CPI. Where no appropriate scaling laws exist, we tried to base our estimate on the SOLASE design. Sometime the best that could be done was to take the SOLASE cost directly and escalate it to 1986, and that was the case wherever the SOLASE report was referenced in this table. In some cases, the same was done with the TASKA-M costs [5]. In the scaling laws, the following variables are used:

- V is the building volume.
- $\dot{m}$ is the mass flow rate of the coolant in question (liquid lead).
- E_d is the driver energy on target.
- P_{efth} is the facility's effective thermal power, calculated as explained in UWFDM-708 [24].
- P_g is the effective gross electric power as explained in UWFDM-708, Chapter 2.
- P_{th} is the facility's total thermal power.
- $P_{th,Pb}$ is the thermal power absorbed in the lead.
- $P_{th,w}$ is the thermal power absorbed in the water.
- P_{aux} is the total auxiliary power (excluding the laser power supplies). Since no figures are available for this item, it is assumed to be proportional to the facility's total thermal power.
- P_{in} is the laser input power (100. MW in the base case).
- A is the total plot size (i.e., ground floor area) of the facility.
- A_{ref} is the total plot size of the reference facility (SOLASE [1] in this case). See the comment in Chapter 2 of UWFDM-708.
- C_{ref} is the cost of an account item in the reference facility's design (escalated to the proper year, i.e., 1986).

All the volumes are in m^3, areas are in m^2, powers are in MW, the driver energy is in MJ and the mass flow rates are in kg/hr.

The costs in this table are given in dollars (1986), unless otherwise stated (k stands for \$1000., M stands for a million dollars).

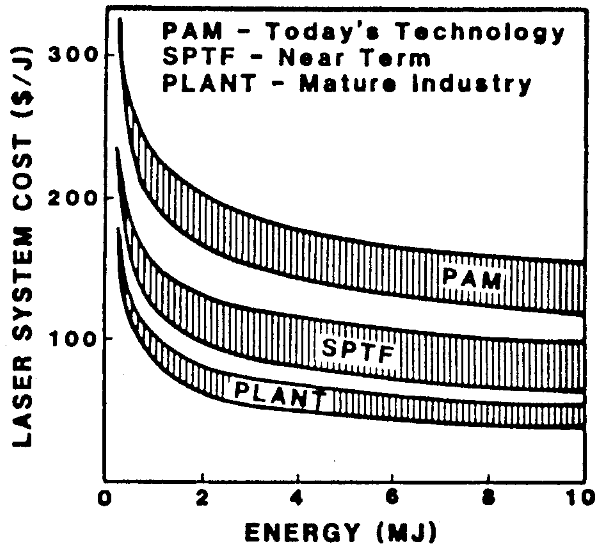
There may be considerable uncertainty and lack of consistency in some of these scaling laws. For instance, there is discrepancy in scaling laws of some items between the mirror and the tokamak programs (some buildings, blanket and 1st wall, etc.). While there may be some justification for the mirror reactor building costing twice as much as the tokamak reactor building (due to a different shape?) it is hard to see why some of the other buildings are so different as well as some of the other items [16-18]. In this study, in absence of the scaling laws for the inertial confinement fusion facilities (except for the laser and target factory costs), we relied on scaling laws from both of these programs, among others. Because the scaling laws used may be different, it may be meaningless comparing facilities whose costs were arrived at by employing different scaling laws.

For the land and land rights, the scaling law is stated but is not used, because siting on government owned land is assumed.

For the site improvements, we used half the value suggested in the references for reasons stated above (government owned site, with probable prior activity, including roads, site characterization, etc.).

For the tritium treatment and radwaste buildings, we used the scaling laws for the more expensive portion of the glovebox building [18]. For the "rest of the buildings" we used the costs from SOLASE directly, escalated to 1986 and including the buildings described in Chapter 2 of UWFDM-708. For the 1st wall graphite, we used the most expensive and the densest graphite. For the PCA structures in the reactor, we used the scaling for the most expensive stainless steel work [6]. For the Xe recycle, we used the cost of the cryogenic distillation column from the TSTA [4], although the application (D-T separation) and temperature are much different (much lower temperature in case of D-T separation, than for the Xe-He separation). For the Pb cooling we used data from the MARS study [22], and scaled according to the mass flow rate (pumps and motor drives) or the thermal power removed by the coolant (heat exchangers) [6]. The exception is the item SS piping and insulation (which includes associated valves) where the scaling law was taken directly from Ref. [6] for lack of better data (this scaling law applies to liquid sodium piping and insulation).

The laser equipment cost includes everything from the front end to the last mirror. It includes the laser hall, but it excludes the power supplies and the last mirror. However, it also includes certain indirect costs which probably roughly equal the last mirror costs. The scaling law for the laser equipment given in the table assumes a mature laser industry and ICF electricity producing power plants. Figure A.1 [9] gives one an idea what laser costs may be expected for various scenarios. It can be seen that for a near term technology, laser costs of the order of $250M can be envisaged for a 1 MJ laser. This may be more representative of the SIRIUS-M laser, because it is a more near term facility than a power plant. Other references [8] quote a cost of $300/J for a near term laser (if 300-kJ amplifier modules can be built and if optical fluences of 3 J/cm^2 are possible), and $680/J for a 100 kJ system using today's technology (this is less than 20% of the cost of the Nova laser operating in the triple frequency mode). A large fraction of the cost (33%) goes toward the optical components, so anything that reduces their size (e.g., increasing the fluence threshold) will help bring down the cost. We have assumed a 10 ns target illumination time, because as Fig. A.2 shows, anything much shorter than 5 ns results in a significant cost increase of the



Figs. A.1 Single-pulse KrF laser system cost.

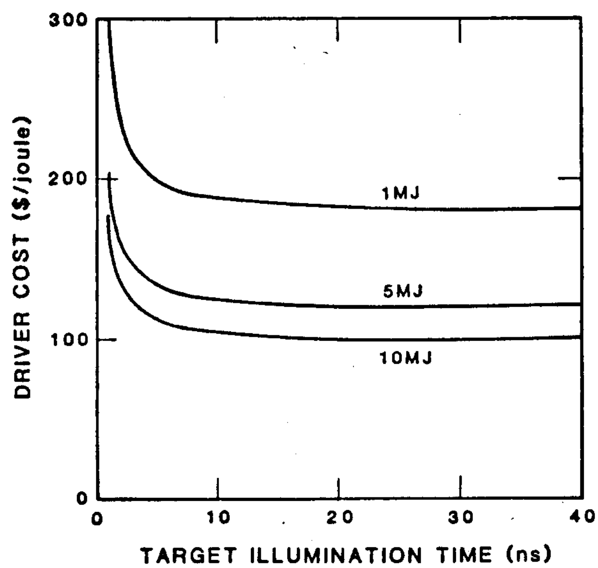


Figure A.2 10 Hz KrF laser system cost scaling vs. illumination time.

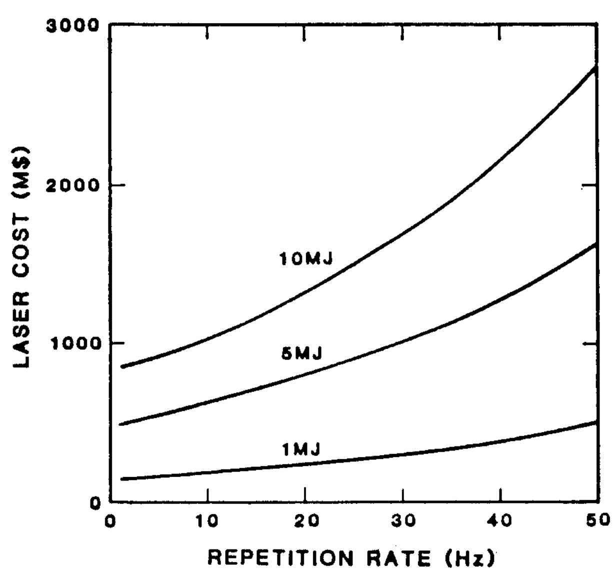


Figure A.3 KrF laser cost scaling vs. repetition rate for a 10-ns system.

laser [9]. Figure A.3 shows the increase in cost with repetition rate (Fig. A.1 refers to a single-pulse laser) [9]. Another source [8] quotes the cost of \$50/J to be added to the cost of the single-pulse laser system, to obtain the cost of a power-plant rep-rateable laser. The added cost is due mainly to the gas circulation and handling system and associated heat transfer equipment. The same source suggests using the laser waste heat for feedwater heating in a power plant, thereby utilizing a significant fraction of the input energy (up to 40%) and significantly lowering the cost. Obviously, we cannot do that in the case of the non-power producing SIRIUS-M.

For the target factory cost, flat direct costs of \$100.M [20], \$200.M [23] and \$250.M [1] have been cited. The latter two costs are given in 1981 and 1979 dollars respectively. The \$100.M cost is based on comparison with the semiconductor industry, where a factory turns out a large number of very small items (IC chips). For the base case, the \$100.M value was adopted.

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