The Economic Analysis of SIRIUS-M

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FUSION TECHNOLOGY INSTITUTE

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Chapter 1

Introduction

This report describes the economic cost model and resulting capital and operating costs for the SIRIUS-M facility. The base case capital cost is \$1016 M in 1986 dollars. This corresponds to the total direct cost of \$519 M, and the total overnight cost (including direct and indirect costs) of \$855 M. The base case annual cost of running the facility (excluding the capital recovery) is \$74 M. The types of assumptions included in these numbers are as follows: default values for economic parameters (such as escalation and inflation rates, cost of money, contingency allowance, construction time, availability), government financing, cost of electricity, cost of fuel and the scaling laws for the direct cost of facility hardware, which are not well known at this time (especially the laser cost and efficiency and the target factory cost).

The organization of this report is as follows:

Chapter 2 deals briefly with the SIRIUS-M facility design. Chapter 3 describes the economic model and default values for the economic parameters. Chapter 4 presents the scaling laws used for each account item and the sources of scaling laws. The resulting costs (direct, indirect and capital) are discussed in Chapter 5. The operating costs are presented in Chapter 6. The total lifetime cost and the cost per dpa-l (measure of damage in the test modules) are shown in Chapter 7 for the two cases: the present 2m reactor cavity, which is reflected light limited, and a hypothetical 1.5m reactor cavity, which would be target debris limited.

Chapter 2

Facility Design

2.1 Land and Land Rights

A 1000 acre site is postulated. This is realistic when compared to the SOLASE facility [1] and nuclear power plants [2], [3], all of which have a 1000 acre site. Since the facility will be situated on federal land, there will be no cost associated with this item.

2.2 Buildings

-Site improvements. We assume that the amount of site improvements will be about half of what would be required for a commercial power plant, because the site will be on federal land and already partially characterized and developed (roads in place, etc.).

-Reactor building. This building is spherical, with a radius of 21.6 m, and wall thickness of 3.2 m, for radiation protection (Fig. 2.1). This size accommodates the 20 m target-last mirror distance. It is evacuated to 1 torr pressure and filled with Xe gas that also fills the reactor cavity at the same pressure. Since the interior of the building is open to the reactor cavity, the building is also tritiated. The inside is lined with 1cm

Table 2.1: Critical locations and tritium amounts

Location	Volume (cu m)	Tritium mass (g)	Radioactivity (Ci)
Fuel box[a]	.18[b]	529.	5.2E+06
Dryer beds [c]	1.0 [5]	57.	5.5E+05
Isotope separation[c]	1400. [6]	57.	5.5E+05
Storage beds[c]	3.4 [6]	399.	3.9E+06

[a] assuming a week's supply of fuel to limit losses due to tritium decay

[b] assuming a void fraction of .43 and a 2 mm diameter target [5]. The tritium amounts are from the SIRIUS-M report [5].

[c] These are items from the tritium treatment system, which may be put in a separate building (see below).

thick stainless steel to prevent leakage of radioactivity through the walls. The building is a Class I seismic structure, that can resist external events such as tornado missiles, explosions and high winds. Internal loads during an accident would be relatively mild, due to use of Pb for transporting away most of the heat generated (liquid lead will not react chemically with water or concrete [4]). The radioactivity of volatile T_2, except for about 10,000 Ci in the building atmosphere, is mostly localized and confined to a relatively few small-volume spaces within the plant. These spaces can be cheaply reinforced such that any release scenario is extremely unlikely. The locations and tritium amounts are given in Table 2.1.

We can compare our reactor building size, construction and cost to that of the boiling water reactor secondary (outer) containment. While the SIRIUS-M reactor building volume is about half that of the BWR reactor building, and the wall thickness is about 3 times greater, the type of construction (except for the presence of stainless steel superstructure, Fig. 2.2, and the building shape) and the cost should be similar, because of similar mission and expected loads. The inner BWR containment (drywell around the reactor and wetwell including the suppression pool) is built around the reactor itself and is made of prestressed concrete, except for top of drywell (steel) and base mat (reinforced concrete) [7]. There have been accepted designs and/or actual plants where even the primary containment would be made wholly of reinforced concrete [8]. The inner surface of primary containment, as in PWRs, is lined with stainless steel for leak-tightness. The primary containment is designed to contain the forces and radioactivity generated in a LOCA (loss of coolant accident). The purpose of the secondary containment (reactor building), which is also a Class 1 seismic structure, is to further limit radioactive emissions and to contain outside loads (tornadoes, high wind, missiles). It is built out of reinforced concrete up to the level of the spent fuel pool. The superstructure is built out of construction steel [7], [2] (Fig. 2.2). This double containment concept is somewhat similar to the 1300 MWe PWRs (pressurized water reactors) built in France. These have a 0.9 m thick (42 m diameter) cylindrical primary containment made of prestressed concrete for LOCA loads, followed (after a 2 m air gap) by the 0.6 m thick outside containment made of reinforced concrete for external loads [8]. The inner containment doesn't have the customary steel liner. The Super-Phenix (1200 MWe operating LMFBR in France) reactor building is a single containment built entirely of reinforced concrete (66 m in diameter, 90 m high and 0.9-1 m thick, with a 5.5 m base mat). The pressure rise due to uncontrolled burning of sodium calculated for the Clinch River Breeder Reactor in the United States is very mild (a few psig [9]). That the LOCA loads (high pressure steam, hydrogen explosions, internal missiles) are the limiting factor in the LWR reactor building design can be seen by the fact that all the PWR containment buildings in the United States are of similar construction (3.5 to 4 foot thick prestressed concrete walls) [10], [3], [11]. This includes reactors in the earthquake region (San Onofre) and the ones that had to consider aircraft impact (Three Mile Island). The prestressed concrete containment is somewhat better for earthquake protection, due to its uncracked state which resists membrane shear generated in earthquakes [8]. However, the reinforced concrete containment is better for protecting against other external events. Since SIRIUS-M will not have appreciable internal loads, the reactor building need only meet the standards for the outside containment buildings mentioned above. Because of the reasons cited above (low and localized radioactivity, liquid lead coolant), these standards should be lower than the ones for reactor buildings for fusion power reactors (MFE tokamak scaling laws were used here, due to lack of data from BWRs).

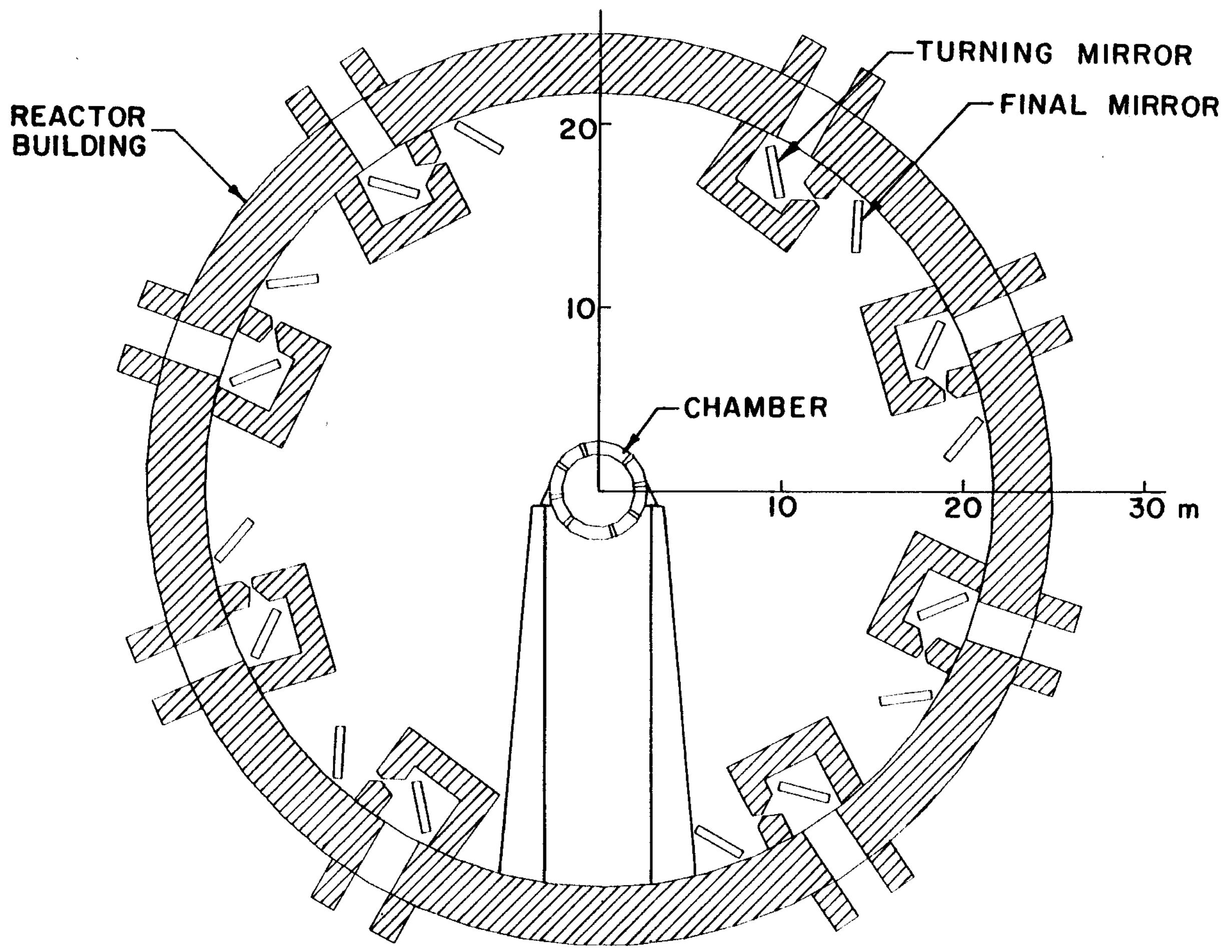


Figure 2.1: SIRIUS-M reactor building with last mirrors

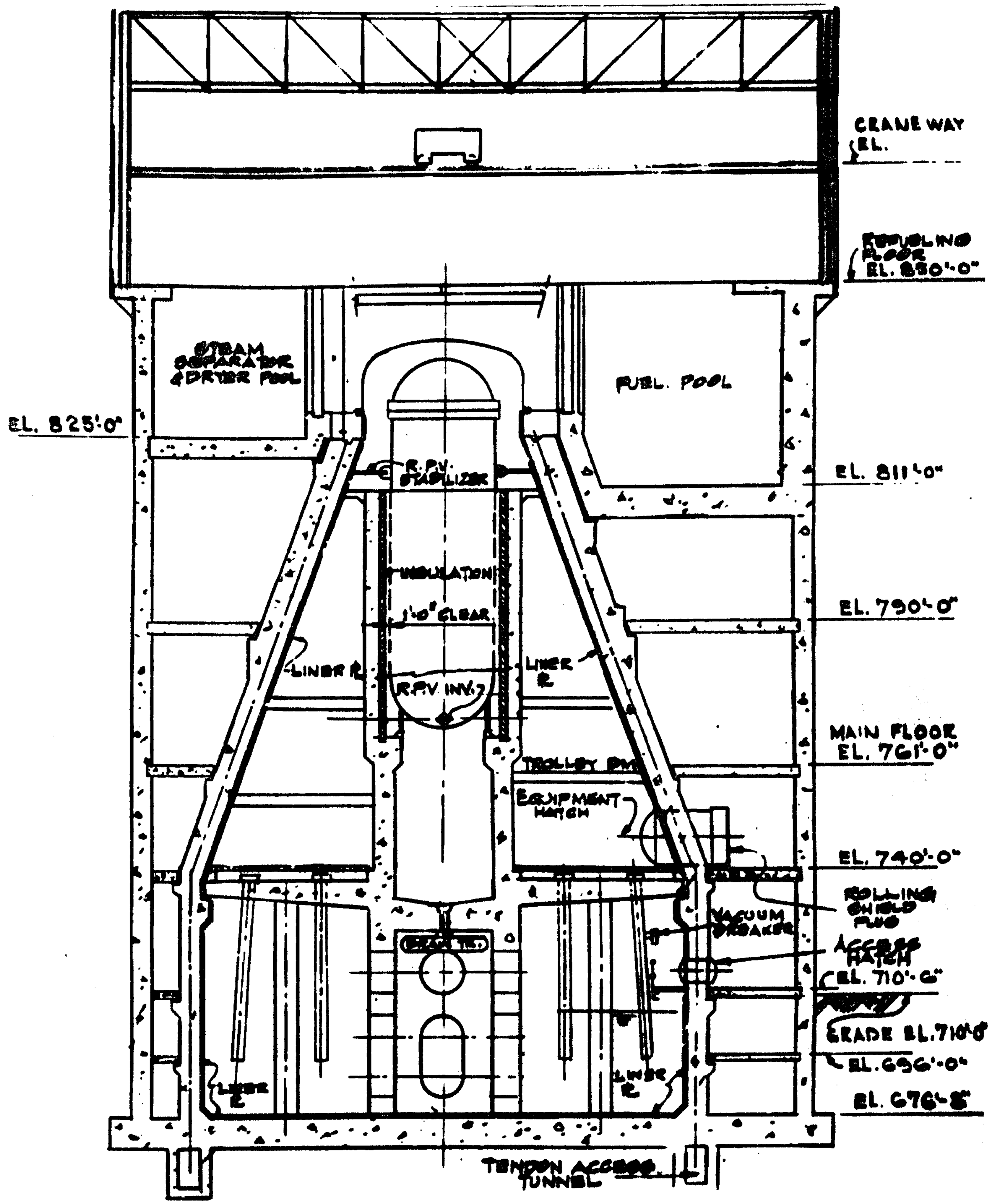


Figure 2.2: BWR primary and secondary containment [7]

Table 2.2: Tritium treatment equipment and volume occupied

Equipment type	Dimensions (m)	Volume (m^3)
Transfer pumps	0.9*6.1*1.2	6.8
Fuel cleanup	0.9*6.1*1.2	6.8
Isotope separation (palladium gas chromatograph)	15.2*15.2*6.1	1416.
Storage beds of activated U	0.9*3.1*1.2	3.4
Gas analysis	0.9*6.1*1.2	6.8

-Tritium treatment building. We can elect to put all the tritium treatment equipment in its own, separate building, apart from the reactor building. This will simplify the task of reinforcing the reactor building against possible tritium releases. In order to determine the volume of the TTB, we have to know the type and effective volume of the tritium treatment equipment. Table 2.2 gives us that information [12], [6].

This gives us the total TTB volume of 1440 m^3.

-Control building. We assumed the same volume of the control building as that in the TASKA-M report [13], for lack of better data. Although TASKA-M is based on a completely different confinement concept (magnetic mirror), it has a similar mission as SIRIUS-M (an engineering test facility for materials irradiation) and a somewhat lower power level. One might argue that the level of control and instrumentation could be about the same. Therefore, the control building volume is 4500 m^3.

-Maintenance building. Using the same reasoning as for the control building, we again assume the same volume as that in the TASKA-M report (12000 m^3).

-Radwaste building. Same as above (12000 m^3).

-Administration building. Same as in TASKA-M: 15000 m^3.

-Diesel generator building. Same as in TASKA-M: 5000 m^3.

-Cooling system structures. This item (recirculating structures and cooling tower earthwork [14]) scales with plant thermal power, not with volume like most other building structures. In this case, the plant thermal power is the sum of effective laser thermal power, 135 MW (this is the power of a conventional heat engine, which, at a conversion efficiency of 33% would reject the 90 MW of thermal power that our laser rejects), and the reactor thermal power output, 184 MW (overall reactor energy multiplication is 1.37). Auxiliaries such as pumps can be neglected when compared to the laser power needs. Therefore, the effective thermal power (for purposes of calculating the cost of cooling system structures) is 319 MW in the reference case (laser efficiency of 10%). In the case of a 3% efficient laser, the effective thermal power is 669 MW.

-Hot cell building. This corresponds to the blanket replacement and storage building in the SOLASE design [1]. For lack of better data, the same cost is assumed as in the SOLASE case; the building volume is unknown. Using SOLASE as the cost basis is very conservative, because it is a much bigger system (3340 MWth).

-Laser hall. Again, the volume of this building is unknown, but the cost is assumed to be the same as in the case of SOLASE. However, this cost is already included in the scaling laws for the laser system cost. It is assumed that the necessary electrical equipment (transformers, power supplies, etc.) will be installed in this building, rather than having its own separate building.

-The rest. In this category, we have included the rest of the buildings from the SOLASE study (without change in size) that were deemed appropriate for the case of SIRIUS-M. This is a relatively small item, so the error introduced should not be large. The buildings included in this category are: security building, fire pump house, holding pond, control room emergency intake structure, makeup water pretreatment building and chlorination building. Excluded are nonessential switchgear building and auxiliary boiler house.

2.3 Reactor Equipment

Most of the reactor equipment is described in the SIRIUS-M preliminary report [5]. More detail is needed in the tritium treatment system and the various cooling circuits. The most important parameters of the reactor equipment are presented in Table 2.3.

-Reactor vessel. The reactor vessel is presented in Fig. 2.3 [5]. It consists of the first wall, Pb reflector, steel reflector and laser beam ports. The first wall consists of water cooled (removing 33.5 MW of heat) graphite tiles (20 in number). These are 1 cm thick and made of pyrolytic graphite. The tiles are triangular spherical elements. The laser beams come through the vertices and centers of these triangular elements. Therefore, there are 32 laser beams. The last mirrors are 20 m away from the target, which determines the size of the reactor building. Following the tiles and associated cooling channels is the Pb reflector. The liquid lead circulates through 20 m long pipes to a heat exchanger for cooling. The amount of lead in the heat exchanger is assumed to be the same as that in the pipes. The volume of lead in the pipes is 7.85 m^3 and in the reactor 24.4 m^3. The liquid lead reflector has an energy multiplication of 1.5, such that 105.5 MW of heat is produced there, and carried away to the heat exchanger. This gives the total energy multiplication of the reactor of 1.37. Following the lead reflector is the PCA reflector (30cm thick) and associated water cooling (PCA is a type of stainless steel). 45.2 MW of heat is produced there. There is no shield around the reactor vessel, which means high radiation fields in the reactor building during operation and for some time after shutdown (only remote maintenance postulated inside the reactor building).

Table 2.3: Reactor parameters

Item	Value and unit
Fusion power	134 MW
Tritium consumption rate	3.4 kg/CY
Target yield	13.4 MJ
Target gain	13.4
Burnup fraction	24.6%
Repetition rate	10 Hz
Laser energy	1 MJ
Number of laser beams	32
Neutron wall loading	2 MW/m^2
Chamber inner radius	2 m
Cavity gas	Xenon
Gas pressure	1 torr
Xe inventory @ STP	57. m^3
Number of tiles	20
Tile area	2.5 m^2/tile
Face material	graphite
Tile thickness	1 cm
Back material	PCA
Coolant	water
Cooling water temperature rise	50 deg. C [15]
Cooling water power absorption	78.7 MW [16]
Cooling water pipe diameter	50 cm [15]
Cooling water pipe length to HX	20 m [15]
Liquid lead temperature rise	375-450 deg. C (75 deg C) [15]
Liquid lead power absorption	105.5 MW [16]
Liquid lead pipe diameter	50 cm [15]
Liquid lead pipe length to HX	20 m [15]
Liquid lead energy multiplication	1.5 [16]
Overall energy multiplication	1.37
Distance from target to last mirror	20 m

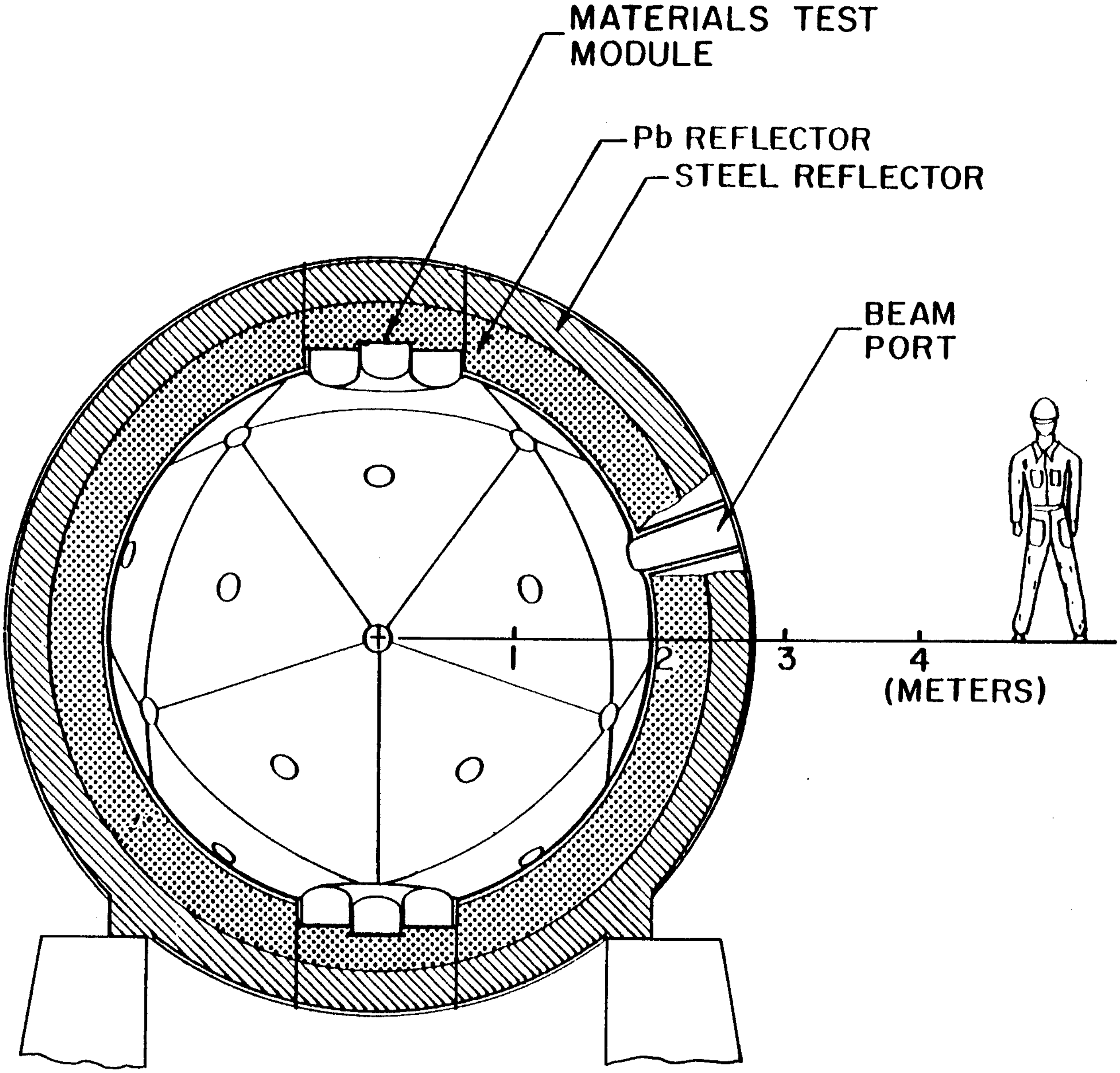


Figure 2.3: SIRIUS-M reactor vessel [5]

In the costing calculations of the reactor we have conservatively neglected the volume occupied by the laser beam tubes.

We have purposely omitted the radiation test modules (one at either pole of the reactor vessel) from this discussion, because these items are traditionally not included in the capital cost (but rather in the operating cost of the plant). In any case, the sum involved is small ($1.M for both modules).

-Pellet injector. We have included a spare pellet injector in the capital cost. The total number is 2 and they are assumed to be the same as in the SOLASE study, hence their cost will be the same.

-Last mirror shield. Not much is known about this item, but the cost should not be a major item, so the SOLASE cost was used.

-Reactor building and cavity vacuum system. This system is part of the vacuum, purification and hydrogen recovery system (see Figure 2.4 [5]). It consists of the Roots blowers and vacuum hose. Roots blowers can be used because of very mild vacuum requirements (1 torr pressure is needed). The capacity of Roots blowers for costing purposes is usually stated in l/sec. The maximum capacity Roots blower is rated at 3000 l/sec. The needed capacity is 3.E+05 l/sec. Therefore, 112 Roots blowers will be needed. A 25 m long, 75 cm diameter vacuum exhaust duct will also be needed.

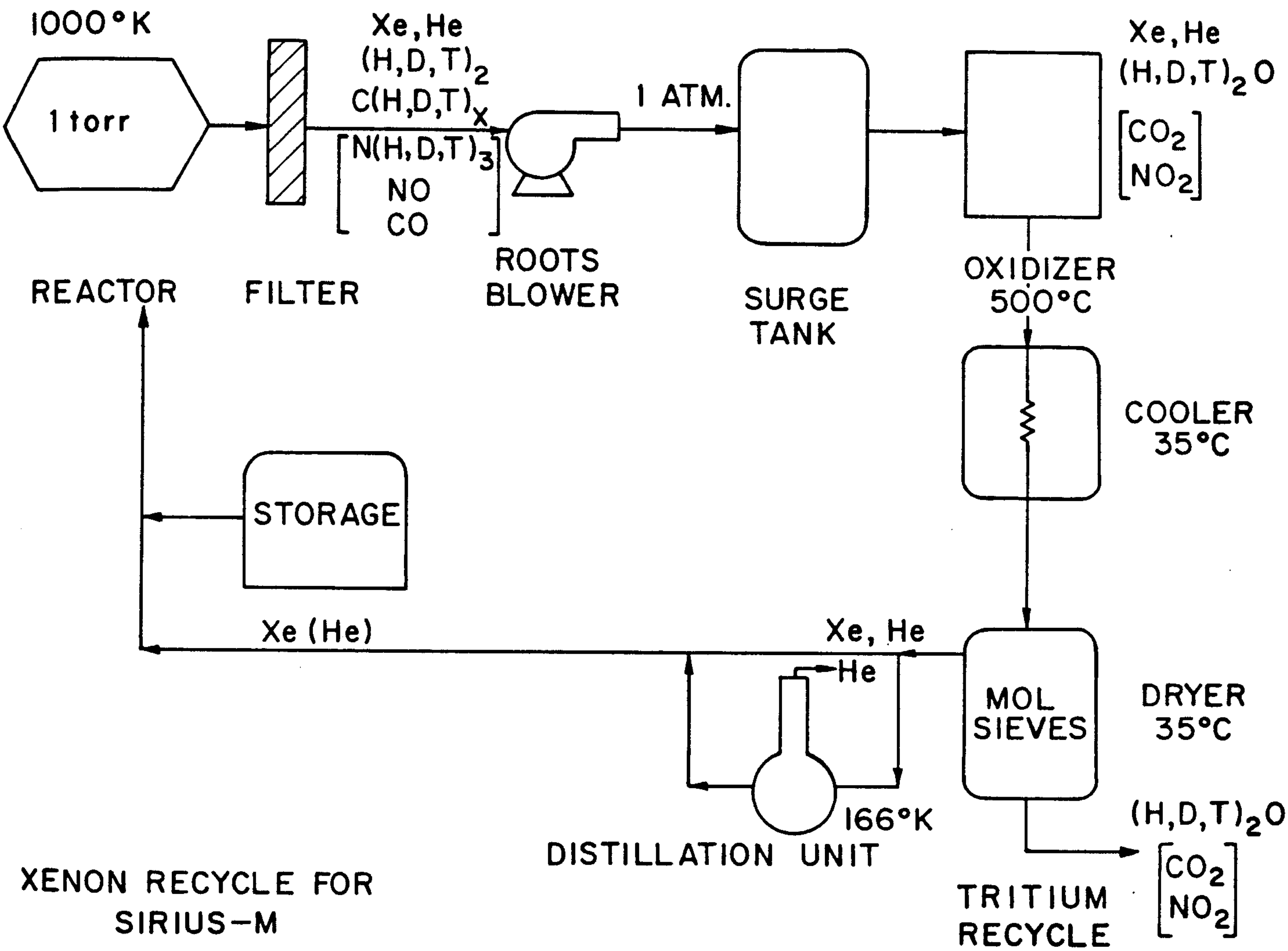


Figure 2.4: SIRIUS-M vacuum, purification and hydrogen recovery system [5]

-Hydrogen recovery system. This system will consist [12] of the following items: circulation pumps for the fuel mixture, fuel cleanup system, isotope separation system and uranium storage beds. These systems will be sized similarly to the corresponding systems at the TSTA (Tritium Systems Testing Assembly) at Los Alamos, with the exception of the isotope separation system. Although the TSTA system is much bigger than that of SIRIUS-M (processin g 1000 g of T_2 vs. 57 g per day), there is a certain minimum equipment size, and indications are that this size has been reached by the TSTA [6]. The exception is the isotope separation system. In our case we will use palladium based gas chromatography for hydrogen isotope separation, rather than the cryogenic distillation column used at the TSTA, with significant savings.

-Xe recycle. Cryogenic distillation will be used for separation of Xe (used for the first wall protection) and He. This distillation will take place at 166 K.

-Radwaste system. This system scales with thermal power of the facility. For SIRIUS-M, we include just the thermal power due to fusion, not the laser reject heat, thus 184 MWth.

-Fuel storage and cryogenic system. Assuming a one week supply of fuel and neglecting any heat transfer into the fuel box, we have to remove 564 W (max.) at 20 K due to the radioactive decay of tritium atoms. The best reference we have has costed a 3 kW, 4.2 K system, so we use this figure to be on the conservative side. As for the fuel tank, it will be small (< 1 m^3), see the reactor building section. It will contain a maximum of 530 g of T_2 and a like amount of D_2. Our reference has costed a fuel tank that can accommodate 20 kg of each of the species (for magnetic fusion), and again we'll use this equipment to be conservative.

Now, a short discussion about the amount of fuel in storage may be in order. For radiological protection, and for sizing of the cryogenic system, we obviously want to have frequent transport of fuel to (and of unburnt tritium from) our facility. Also, one may want to minimize the amount of fuel loss due to radioactive decay of tritium. This last item is not too large, however (about $700,000 per year for a month's fuel supply storage). To see this, let us suppose that the number of tritium atoms in storage is N_0 at time 0 (beginning of storage of this batch), while T is the total time of storage of the batch (T=2 weeks for a 1 week supply, or T = 2 mo for a month's supply due to 50% availability of the facility). Then the number of atoms available for decay at time t, $N_0'(t)$ is given by:

$$N_0'(t) = N_0 - (N_0 * t/T) - N_d(t) \tag{2.1}$$

$$N_d(t) = N_0 * (1 - t/T) * (1. - exp(-\lambda * t)) \tag{2.2}$$

The second term in equation 2.1 is the number of atoms consumed in the thermonuclear reaction (includes the atoms that had decayed prior to consumption). The average consumption rate is N_0/T. N_d is the number of atoms from the rest of the targets that have decayed away (and have not been consumed). Therefore, the rate of decay of tritium atoms is:

$$dN_d/dt = \lambda * N_0'(t) = \lambda * N_0 * (1. - t/T) * exp(-\lambda * t) \tag{2.3}$$

Integrating between 0 and T:

$$N_{d,tot}/N_0 = 1. - (1. - exp(-\lambda * T))/(\lambda * T) \tag{2.4}$$

For T=2 wk, this gives a fractional loss of 0.0011 and a yearly loss of 14.8 g (or roughly $150,000). For T= 2 mo, the fractional loss is 0.0047 and the yearly loss is 64.5 g (or $700,000).

-Cooling circuits. All the information necessary for costing the Pb and water cooling circuits (coolant mass, mass flow rate, piping size and length) is included in the discussion of the reactor vessel (see above). The items to be costed are the pumps, piping, heat exchanger, cleanup system and storage tanks (a 400 m^3 tank assumed for each of these two cooling circuits). Auxiliary cooling includes last mirror cooling, last mirror shield cooling, primary component cooling and we assume these systems will be similar to the ones used in SOLASE [1] but with the heat load proportional to the fusion power of the machine. A separate item is the laser power supply cooling, where we'll have to reject about 90 MWth in the base case (10% efficient laser) and 323 MWth in the case of an inefficient laser (3% efficiency).

-Instrumentation and control. This scales with thermal power output. In this case we'll include the laser reject heat in the calculation of the thermal power. The total power is then 274 MWth in the base case and 484 MWth in the case of a 3% efficient laser.

-Maintenance equipment. This item also scales with thermal power, so the comment above applies here as well.

2.4 Heat Rejection

This item scales with the effective thermal power. The effective thermal power is calculated as shown in the discussion of the cooling system structures (buildings).

2.5 Electrical Plant

This account consists of two items: the laser power supplies and associated equipment and the rest of the electrical plant. The laser equipment supply is assumed to be equal to that described in SOLASE [1]. We assume the important parameter in costing the laser power supply is the laser input power which is 100 MW in case of a 10% efficient laser and 333 MW in case of a 3% efficient laser. The rest of the electrical plant scales with the auxiliary power load (except for the protective equipment, which scales with the building size). Since we don't know the auxiliary power load we have assumed it to be proportional to the total thermal (fusion derived) power and have scaled the proper SOLASE items using this. Some of these items may include subitems specifically related to the power conversion part of the plant and therefore not applicable here, but this reasoning leads to a conservative estimate. These items include the switchgear (including station service which may include some inappropriate items, but excluding generator circuits), station service and startup transformers (again some parts may be inappropriate), low voltage and lighting transformers, battery system and inverters, diesel generators, switchboards, electrical structures and wiring containers, power and control wiring (which also includes containment penetrations). The protective equipment includes the general station grounding system and cathodic protection and its cost is proportional to the total floor area of the buildings [14]. This we have conservatively assumed to be the same as in the SOLASE design (the SOLASE reactor building is 3-4 times bigger than the SIRIUS-M reactor building. Also absent is the turbine hall. However, the laser hall and other buildings should be of comparable size).

2.6 Miscellaneous Plant Equipment

This account is a catch-all that includes such items as transportation and lifting equipment, air and water service systems (including fire protection), communications equipment and furnishings and fixtures. It scales with the gross electric power of the facility. Our facility does not produce any electric power; however, in order to calculate the gross electric power, we calculate how much electricity would be produced if we did have power conversion equipment and add that amount to the gross laser input power, 100 MWe for the case of a 10% efficient laser and 333 MWe for the case of a 3% efficient laser. Therefore, the effective gross electric power is 161 MWe in the former case, 394 MWe in the latter.

2.7 Laser Equipment

The SIRIUS-M design will be using a KrF laser, although it is possible that a free electron laser might be used instead. The free electron laser will achieve the needed efficiency with higher confidence (efficiency of 40-50% may be envisaged); however, its capital cost might be higher, too, and there are problems with focusing. In connection with the KrF laser, recent literature confidently predicts overall system efficiency of 8% [17], 9.1% [18] and 11% [19]. There are some hints (informal [20] and paper presentation [21]) which point to a much lower efficiency (around 3%), at least for the near term. The KrF laser should be easy to upgrade for repetitive operation, because it is a gas laser, and cooling equipment can be easily incorporated by circulating the lasing medium. There are also several known techniques to achieve the required 8-30 ns target illumination (10 ns assumed here). The main amplifier is most efficient when the pulse length is 300-400 ns. To compress this pulse in time, we assume that the optical angular multiplexing method is used in this design, whereby the path length of a packet of light (i.e. its angle of incidence upon a certain surface) depends upon its time of generation within the pulse (i.e. time of arrival at the surface). This method seems to be the most straightforward [19]. The other important parameters of our laser are the energy on target (1 MJ) and repetition rate (10 Hz). At this repetition rate, the efficiency (when compared to a single pulse laser) should not be compromised greatly; see Figure 2.5 [18]. Now we will turn to the subject of efficiency in greater detail.

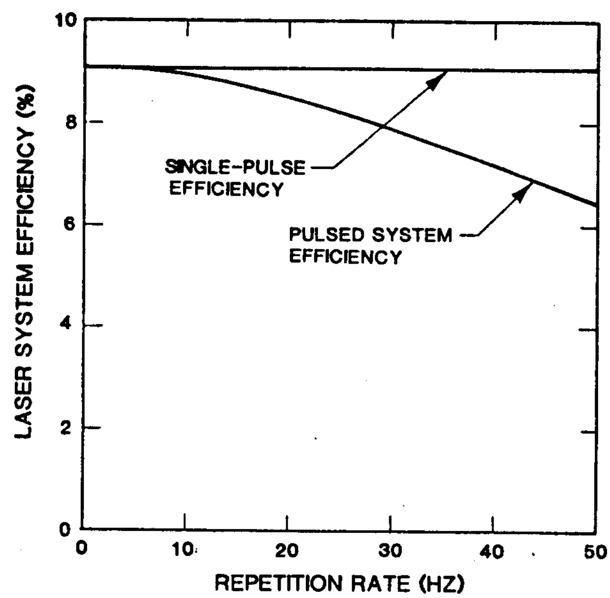


Figure 2.5: KrF laser efficiency vs. repetition rate [18]

Table 2.4: Efficiency improvements for KrF laser systems

Efficiency type	Conventional System, %	LANL System
Formation efficiency, η_f	24	28
Extraction efficiency, η_e	46	57
Intrinsic efficiency, η_i, $(\eta_f * \eta_e)$	11	16
El. energy dep. efficiency, η_{eede}	55	68
System efficiency , η_s, $(\eta_{eede} * \eta_i)$	6	11

One Los Alamos paper [19] cites improvements in electron optics and gas kinetics to arrive at an overall efficiency of 11%. The improvement in electron optics is that higher efficiency results if only those areas of the cathode that map into a clear transmission window are allowed to emit. The gas kinetics improvement is achieved by increasing the concentration of Kr vs. that of Ar, thus eliminating the self-absorption in Ar_2+. While it is true that a Kr rich mix forms more Kr_2F^*, the absorption of this species is subject to optical saturation. Table 2.4 is reproduced from the report.

The various efficiencies are defined below:

Formation efficiency = Energy in the upper laser level/energy deposited in laser gas

Extraction efficiency = Energy in laser beam/energy in the upper laser level

Intrinsic efficiency = Energy in laser beam/energy deposited in the laser gas

Electrical energy deposition efficiency = Energy deposited in laser gas/total energy delivered to the laser system

System or wall plug efficiency = Energy in laser beam/total energy delivered to the laser system

Another LANL team arrives at a somewhat different figure, and includes losses after the laser beam is formed [17]. They give the following set of figures to arrive at an overall efficiency of 8% for a laser utilizing a mixture of 99.5% Kr and 0.5% F_2:

Pulsed power efficiency = 59%

Amplifier fill factor = 98%

Laser intrinsic efficiency = 15%

Beam transmission efficiency (amplifier to target) = 95%

Transmission efficiency through the amplifier window = 98%

Transmission through unpumped regions containing fluorine = 97%

The optics surfaces today can handle 1.5 J/cm^2 of laser illumination. We would like to be able to achieve 5 J/cm^2 [17].

2.8 Target Factory

It has been decided that SIRIUS-M will incorporate a target factory in its design. While ICF power plants may buy targets from an offsite facility serving multiple plants (thus avoiding the direct cost of a target factory), SIRIUS-M is an experimental test reactor, thus a dedicated facility is needed for target manufacture due to lack of demand elsewhere (i.e. no ICF power plants exist at the time). This approach will substantially increase the direct cost of SIRIUS-M, however significant savings in annual fuel costs result, because there is no charge for return on investment on a private target factory (saving 15 to 25 ¢/target according to some scoping studies we have done and also refs. [38],[39]). On the other hand, we have to pay for tritium in each target, due to unavailability of breeding in this design. We assume that unburnt tritium is given the credit equal to its purchasing price.

There are no firm data on the design of the target factory, but there are rough estimates of its cost based on comparisons with the semiconductor industry[33]. Our target factory will produce about 158 million targets per year.

Chapter 3

The Economic Model

This chapter will explain the basic facts about our economic model. The model has been described in greater detail elsewhere [22], [23], [24], [26], [27]. The model has been implemented on the IBM-PC computer, employing user friendly, menu-driven input [27]. In short, the model takes plant parameters from the user, applies the scaling laws (see the next chapter) 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.

3.1 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 were 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 the 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, is 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 [28]. 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 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.

3.2 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 ¢/kWhr), tritium cost (down to \$7100/g), salvage fraction (up to 20%), general inflation rate (3%-12%), cost escalation rate (3%-12%), construction time (2 yr-10 yr), plant life (up to 20 yr) 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 3.1 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.
- 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 yr or 15 yr), 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

Table 3.1: Default values of economic parameters

Description	Default value
Cost of purchased electricity, ¢/kWhr	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

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 [24] 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.

Chapter 4

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. Tables 4.1 and 4.2 represent the scaling laws used in this study. These laws were drawn from several sources, because as of this writing there is no source for 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 [23]. The CPI has risen at the following rates in the period 1976-1986 [25]: 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

Table 4.1: Scaling laws for direct costs

Account item	Scaling law
LAND	
Land and land rights [14], [1], [29]	$5600/acre
BUILDINGS AND SITE	
Site improvements [29], [30]	$10M
Reactor building (1.5 m wall) [31]	$0.0038M * $V^{0.8}$
Concrete work [14]	$523/$m^3$
Tritium treatment building [31]	$0.00496M * $V^{0.8}$
Control building [31]	$0.00182M*$V^{0.85}$
Maintenance building [31]	$0.0018M*$V^{0.7}$
Radwaste building [31]	$0.00496M*$V^{0.8}$
Administration building [13]	$1.5M
Diesel generator building [13]	$0.5M
Cooling system structures [32]	$9.05M*$(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 [30], [14]	$145K*$P_g^{0.8}$
ELECTRICAL PLANT	
Elec. plant, ground and cathodic protec. [14]	$C_{ref} * A/A_{ref}$
Elec. plant, rest w/o laser pwr. supp. [14]	$C_{ref} * P_{aux}/P_{ref,aux}$
Laser power supply [1]	$31.7M*$P_{in}$/100.
MISCELLANEOUS PLANT	
Miscellaneous plant equipment [30]	$5.05M*$P_g^{0.3}$
LASER EQUIPMENT	
KrF laser [33], [34], [18]	$100.M*$E_d^{0.7}$
TARGET FACTORY	
Target factory equipment [33]	$100.M

Table 4.2: Scaling laws for direct costs, continued

Account item	Scaling law
REACTOR EQUIPMENT	
1st wall graphite [14]	\$4520./kg
Lead reflector [14]	\$4.5/kg
PCA reflector [14]	\$50./kg
Pellet injector [1]	\$0.75M
Last mirror shield [1]	\$2.11M
Reactor vacuum Roots blower (3000 l/s) [14]	\$13.5K/unit
Vacuum exhaust duct [14]	\$15.1K/m
Exhaust circulation, 1 atm [12]	\$316K
Fuel cleanup [12]	\$2.01M
Hydrogen isotope separation [6]	\$250.K
Uranium storage beds [12]	\$107.K
Xe recycle (cryogenic separation from He) [12]	\$3.14M
Xe inventory [5]	\$10.20/l
Radwaste (gas, solid, liq.) system [32]	\$1951.*P_{th}
Fuel storage cryogenics [14], 3 kW @ 4.2 K	\$2.71M
Fuel storage tank, 40 kg DT capacity [14]	\$121.K
Pb cooling, pumps and motor dr. [15]	\$27.45M*$\dot{m}$/3.2E+8 kg/h
Pb cooling, SS piping (50 cm) + insulation [14]	\$339.K/m
Pb cooling, heat exchangers [15]	\$81.2M*$P_{th,Pb}$/2081 MW
Pb cooling, cleanup system (Na system) [14]	\$7.5/kg coolant
Pb cooling, dump,makeup, hot storage tanks, 400 m^3 [14]	\$1433/m^3
Water cooling, pumps and motor drives, 1E+05 kg/hr [14]	\$264.K/unit
Water cooling, SS piping (50 cm) + insulation [14]	\$12.1K/m
Water cooling, heat exchangers [15]	\$31.8M*$P_{th,w}$/730 MW
Water cooling, tanks, 400 m^3 capacity [14]	\$173./m^3
Auxiliary cooling [14]	$C_{ref} * P_{aux}/P_{aux,ref}$
Laser power supply cooling [14]	\$4.5/kWth
Instrumentation and control [30]	\$2.52M*$P_{th}^{0.3}$
Maintenance equipment [30]	\$4.1M*$P_{th}^{0.3}$

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 [13]. 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 Chapter 2
- P_g is the effective gross electric power, again explained in Chapter 2.
- P_{th} is the facility's total thermal power (see Chapter 2)
- $P_{th,Pb}$ 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 in this case). See the comment in Chapter 2.

- 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 [29], [30], [31]. 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 [31]. For the "rest of the buildings" we used the costs from SOLASE directly [1], escalated to 1986 and including the buildings described in Chapter 2. 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 [14]. For the Xe recycle, we used the cost of the cryogenic distillation column from the TSTA [12], 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 [35], and scaled according to the mass flow rate (pumps and motor drives) or the thermal power removed by the coolant (heat exchangers) [14]. The exception is the item SS piping and insulation (which includes associated valves) where the scaling law was taken directly from Ref. [14] 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 [33] 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 4.1 [18] 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 [17] 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. 4.2 shows, anything much shorter than 5 ns results in significant cost increase of the laser [18]. Figure 4.3 shows the increase in cost with repetition rate (Fig. 4.1 refers to a single-pulse laser) [18]. Another source [17] 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.

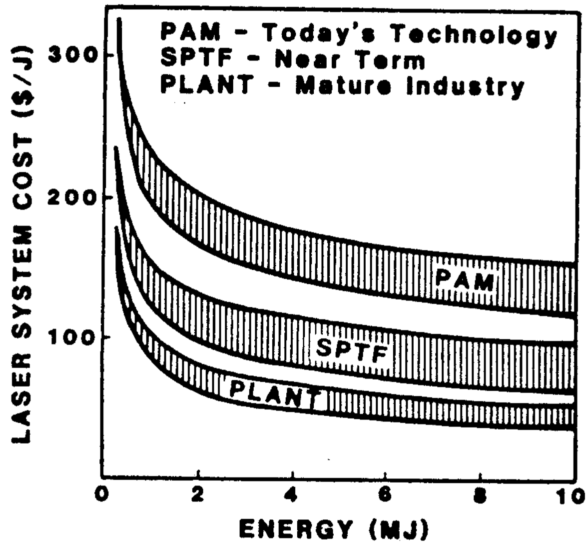


Figure 4.1: Single-pulse KrF laser system cost [18]

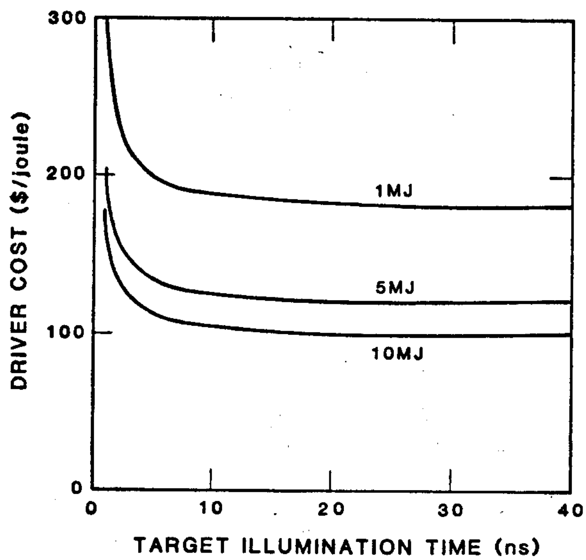


Figure 4.2: 10 Hz KrF laser system cost scaling vs. illumination time [18]

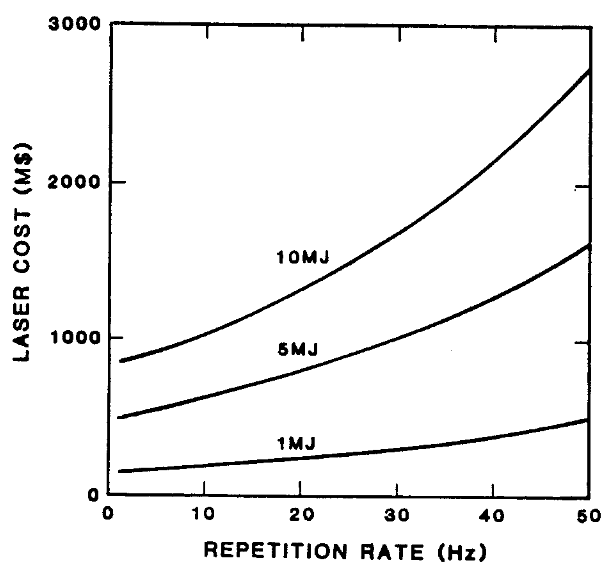


Figure 4.3: KrF laser cost scaling vs. repetition rate for a 10-ns system [18]

For the target factory cost, flat direct costs of $100.M [33], $200.M [38] 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 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.

Chapter 5

Facility Costs

This chapter will present the itemized direct cost of the facility and its overnight and capital costs. The base case driver is a \$100M, 10% efficient laser. A case was also run for a \$250M, 10% efficient laser, \$100M, 3% efficient laser and a \$100M, 50% efficient (free electron) laser. The capital cost was parametrized with respect to construction time and inflation rate. Private financing was also considered with little impact on the total capital cost (TCC) because of the short construction time postulated. All costs are given in 1986 dollars except for the current dollar estimates.

The annual costs of owning and operating the facility are presented in Chapter 6.

5.1 Itemized Direct Cost, Base Case

Tables 5.1 and 5.2 present the base case itemized direct costs of SIRIUS-M. Figure 5.1 shows pictorially the major cost drivers within each account. The case of the free electron laser (50% efficiency and no change in direct cost) and the 3% efficient laser are shown next in Table 5.3.

Table 5.1: Itemized direct costs of SIRIUS-M equipment

Equipment	Bare direct cost, $M
LAND	**0.0**
Land and land rights	0.0
BUILDINGS AND SITE	**82.9**
Site improvements	10.0
Reactor building	49.0
Tritium treatment building	1.7
Control building	2.3
Maintenance building	1.4
Radwaste building	1.4
Administration building	1.5
Diesel generator building	0.5
Cooling system structures	4.6
Hot cell building	7.1
Laser hall, in "Laser equipment"	NA
Rest of buildings	3.4
HEAT REJECTION PLANT	**6.0**
Heat rejection equipment	6.0
ELECTRICAL PLANT	**37.8**
Ground and cathodic protection	2.1
Rest, excl. laser power supply	3.9
Laser power supply	31.7
MISCELLANEOUS PLANT	**23.2**
Miscellaneous plant equipment	23.2
LASER EQUIPMENT	**100.0**
KrF laser, incl. laser hall	100.0
TARGET FACTORY	**100.0**
Target factory equipment	100.0

Table 5.2: Itemized direct costs, continued

Equipment	Bare direct cost, $M
REACTOR EQUIPMENT	**102.0**
1st wall	4.1
Lead reflector	1.9
PCA reflector	11.8
Pellet injector	1.5
Last mirror shield	2.1
Reactor vacuum	1.5
Vacuum exhaust duct	0.4
Exhaust circulation	0.3
Fuel cleanup	2.0
Hydrogen isotope separation	0.3
Uranium storage beds	0.1
Xe recycle	3.1
Xe inventory	0.6
Radwaste system	0.4
Fuel storage cryogenics	2.7
Fuel storage tank	0.1
Pb cooling, pumps and motor drives	2.7
Pb cooling, SS piping and insulation	13.8
Pb cooling, heat exchangers	4.2
Pb cooling, cleanup system	3.3
Pb cooling, tanks	0.6
Water cooling, pumps and motor drives	3.6
Water cooling, SS piping and insulation	0.5
Water cooling, heat exchangers	3.3
Water cooling, tanks	0.1
Auxiliary cooling	0.9
Laser power supply cooling	0.4
Instrumentation and control	13.6
Maintenance equipment	22.1

Table 5.3: Impact of laser efficiency on select direct costs, $M

Equipment affected	ΔC, 3% laser	ΔC, 50% laser
Cooling system structures	+1.2	-0.5
Laser power supply cooling	+1.1	-0.3
Instrumentation and control	+2.5	-1.4
Reactor maintenance equipment	+4.1	-2.2
Heat rejection equipment	+4.9	-1.6
Laser power supply	+73.8	-25.3
Miscellaneous plant equipment	+7.1	-4.3
TOTAL	**+94.7**	**-35.6**

Table 5.4: Total cost of facility for various laser scenarios, $M

Cost type	10%, $100M	3%, $100M	10%,$250M	50%,$100M
BDC	452.	547.	602.	416.
TDC	519.	629.	692.	479.
TOC	855.	1040.	1144.	791.
TCC, const.	1016.	1235.	1361.	941.
TCC, curr.	1281.	1559.	1716.	1187.

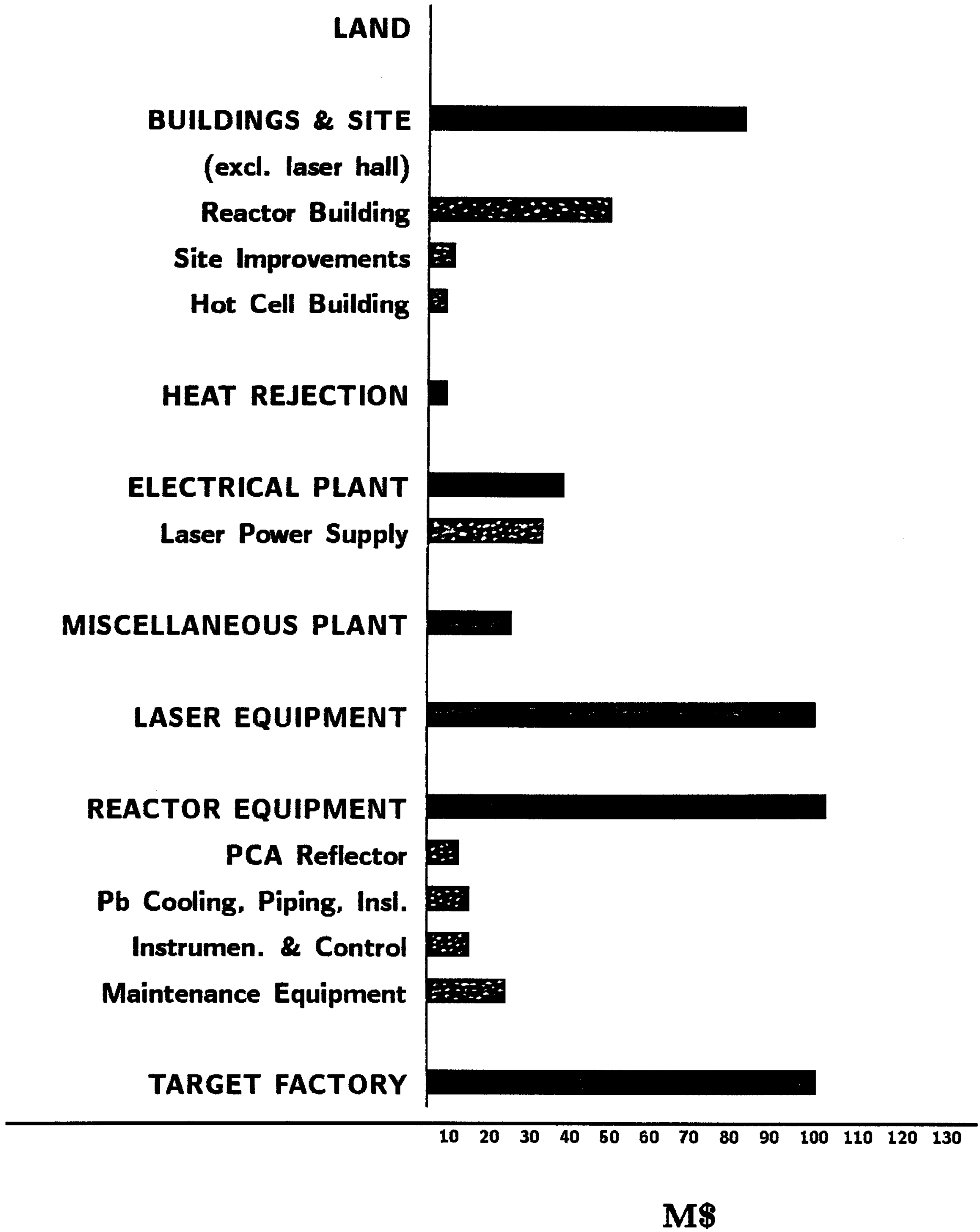


Figure 5.1: Major accounts and cost drivers within accounts for SIRIUS-M

5.2 Total Costs of the Facility

Table 5.4 presents the total costs of the facility for the four driver cases: 10% efficient, $100M (direct cost) laser; 3% efficient, $100M laser; 10% efficient, $250M laser; 50% efficient, $100M (free electron) laser. The first case (10%, $100M) is the base case.

The total direct cost of the facility (TDC) is obtained by adding a 5% spare allowance and a 10% design allowance to the bare direct cost (BDC) of the facility. The total overnight cost (TOC) is the sum of the TDC and the TIC (total indirect cost). The total capital cost (TCC) takes into account the cost of money and escalation during construction (4 year construction is the base case). Abbreviation const. denotes constant dollar mode, while curr. is for the current dollar mode.

5.3 Parametric Analyses

Parametric studies have been run on the SIRIUS-M capital costs, with the most important parameters being the construction time and the inflation rate during construction. Figures 5.2 and 5.3 present the results of these runs. When a parameter is varied, other parameters are at the default value (see Chapter 3). A case was also run for accelerated construction (most money spent early in the construction schedule), but with little difference in the results (a few million dollars) because of the short construction time for the base case.

5.4 Comparison with TASKA-M

We can compare the total costs of SIRIUS-M and TASKA-M, since these two facilities have a similar purpose (materials testing), but employ two different fusion confinement concepts. The comparison can be misleading since two different sets of scaling laws were used for cost estimation of these two facilities, and as stated earlier, there is still uncertainty in scaling

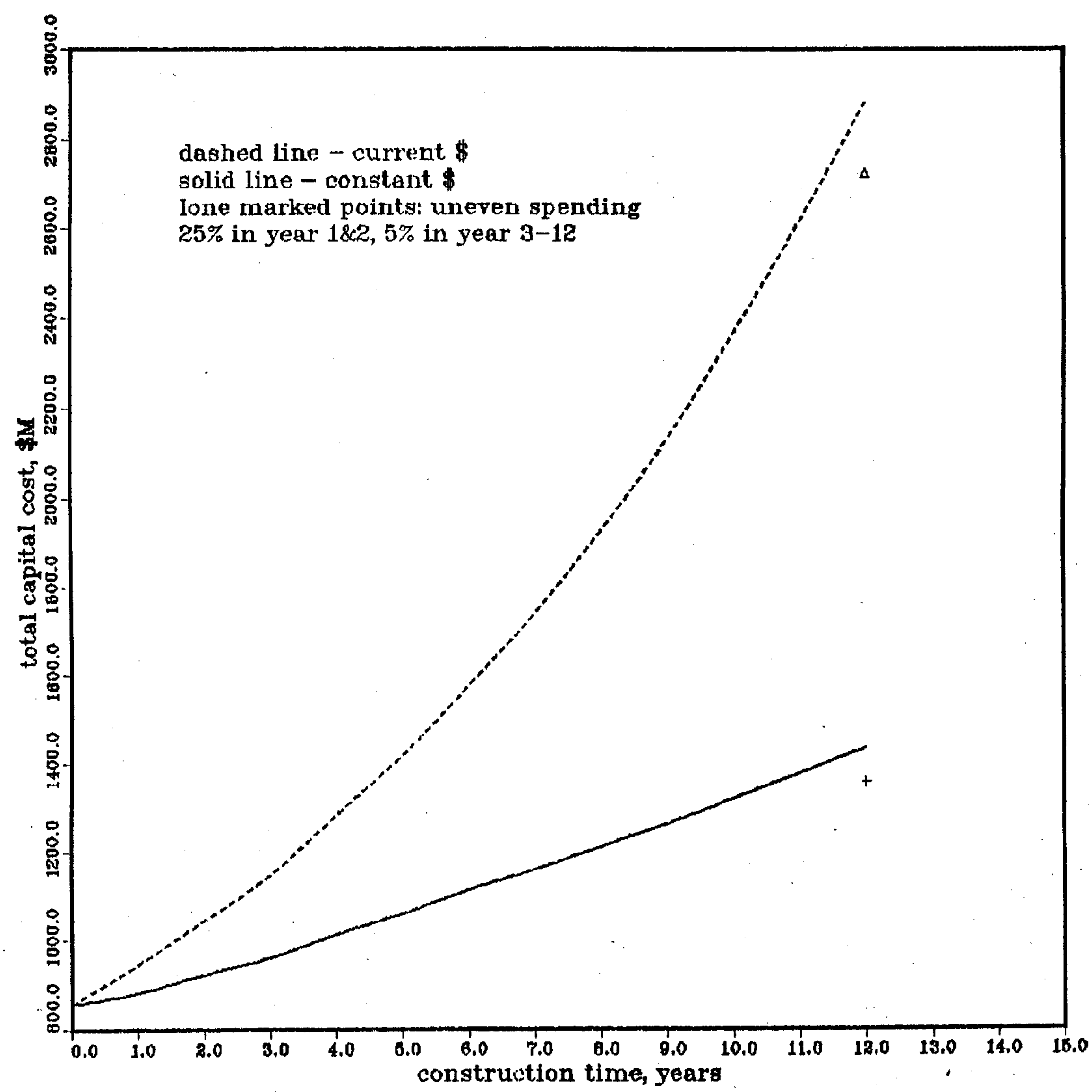


Figure 5.2: Capital cost as a function of construction time

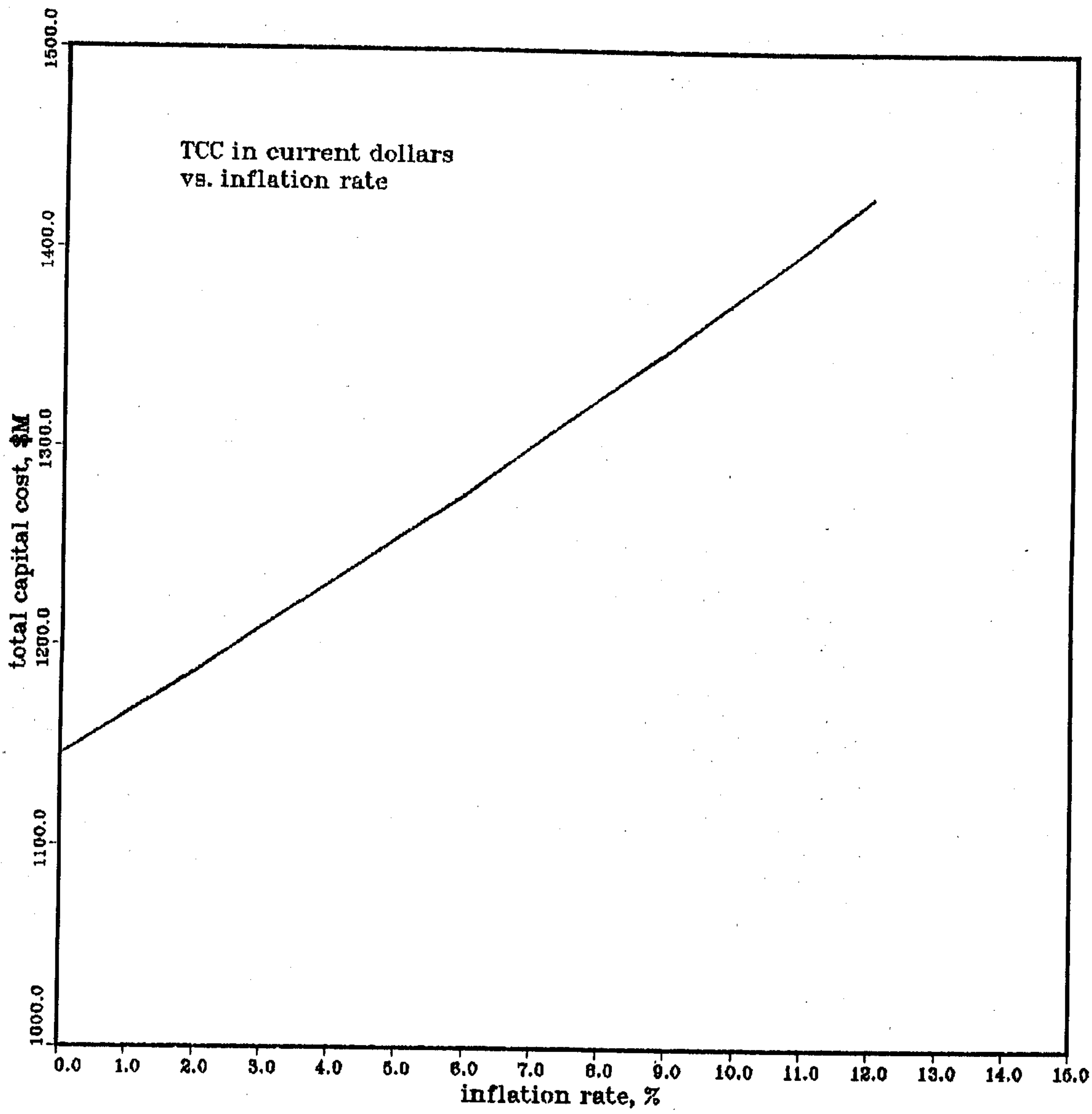


Figure 5.3: Capital cost as a function of inflation in current dollars

laws with different sources giving different scaling laws. If one looks at the TASKA-M direct cost, one notices that the major cost drivers are the magnets ($59M), neutral beam heating ($57M), RF heating ($91M), cryogenic system ($14M) and vacuum system ($16M), besides some of the systems (e.g. instrumentation and control) that might be similar to SIRIUS-M. All costs for TASKA-M given above are in 1983 dollars. In order to remove the economic assumptions (e.g. inflation rate, construction time, cost of money, etc.), we will look at the direct costs of these two facilities. We compare the TASKA-M total direct cost to the TDC of SIRIUS-M, adjusted to 1983 levels (see Chapter 3). Figure 5.4 shows this comparison with TASKA-M and other proposed facilities. The figure was taken from the TASKA-M report [13], with the SIRIUS-M cost (in 1983 dollars) added in. It can be seen that the direct cost of SIRIUS-M is only slightly greater than that of TASKA-M, but the fusion power is substantially greater.

Figures 5.5 and 5.6 show the comparison of major cost drivers between SIRIUS-M and TASKA-M, as percentages of the total direct cost of each facility.

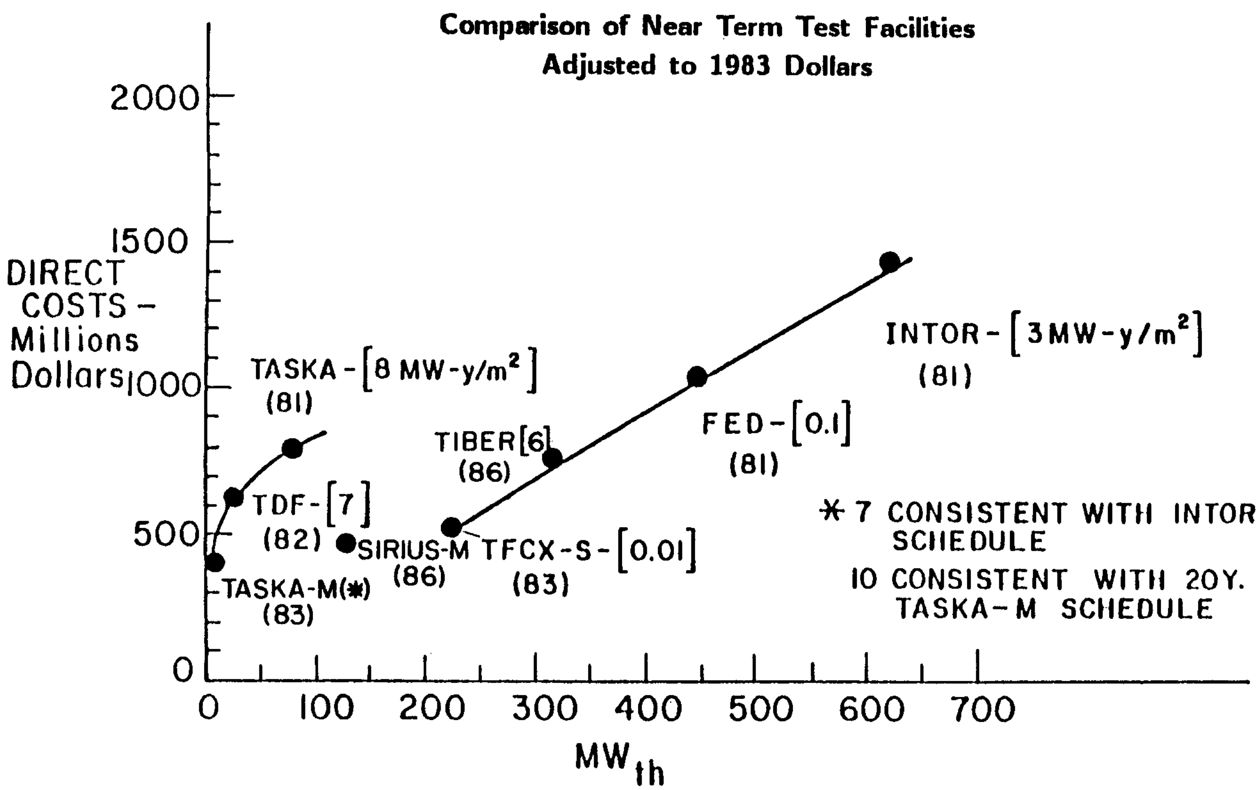


Figure 5.4: Comparison of near term test facilities [13]

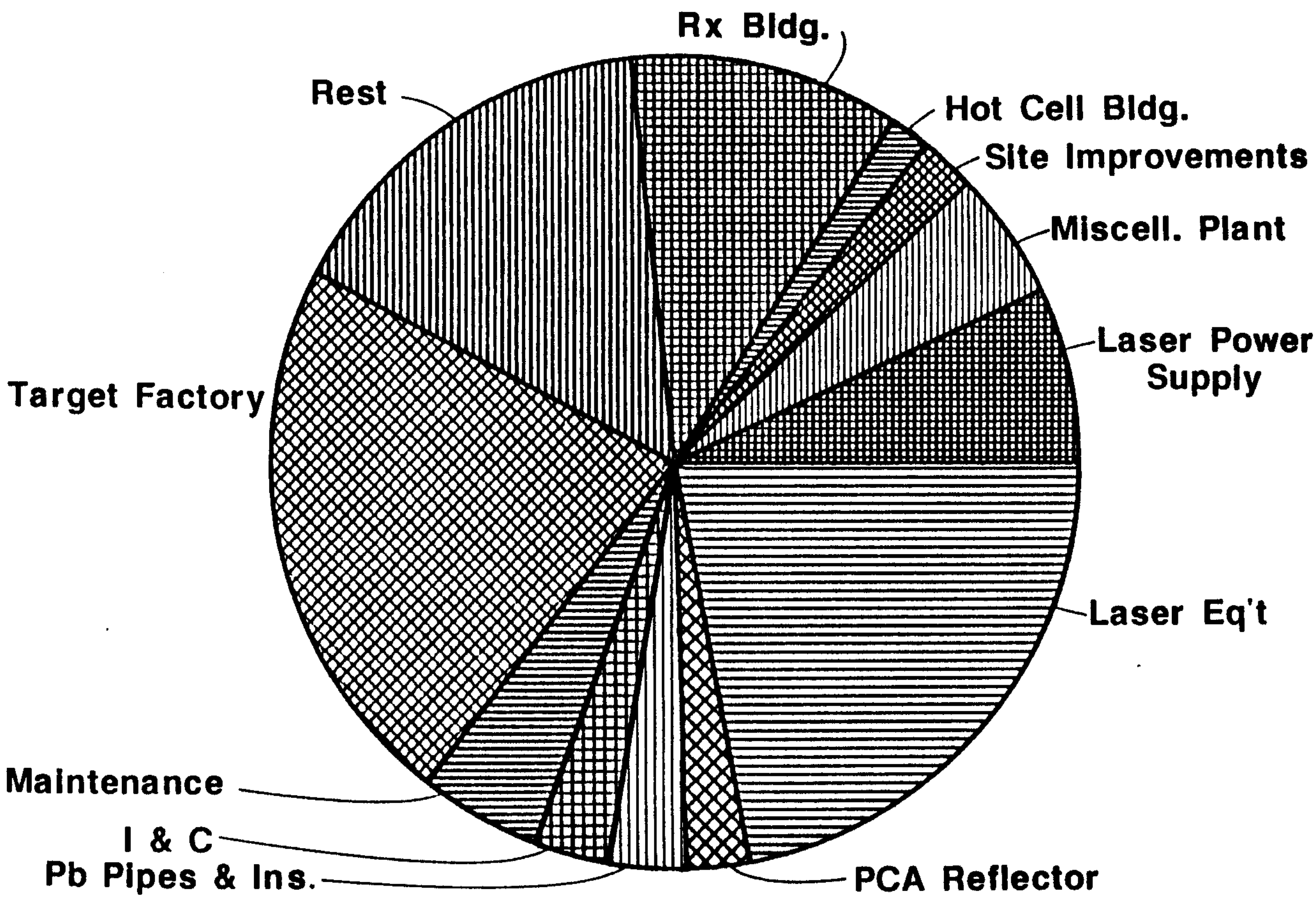


Figure 5.5: SIRIUS-M major cost drivers as fractions of total direct cost

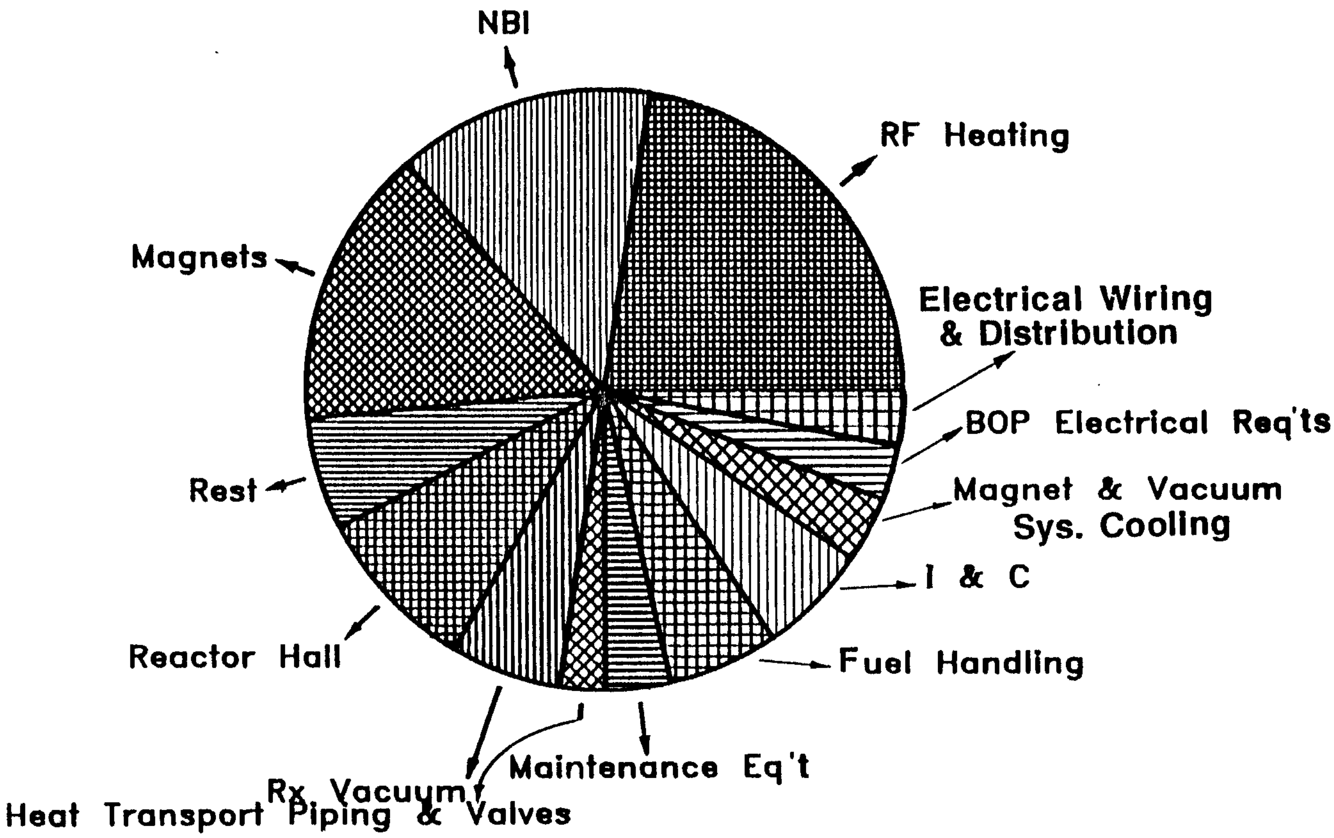


Figure 5.6: TASKA-M major cost drivers as fractions of total direct cost

5.5 Siting Considerations

It is possible to minimize the cost of the facility by carefully selecting a site. For instance, the direct cost for the same piece of installed equipment will vary across the United States, for many reasons (e.g. labor cost). The scaling laws used here are representative of an average direct cost for the U.S. and approximately equal to that in the Chicago area. It is possible to save about 9% of the direct cost by siting the facility in the Atlanta area [36]. Presumably, the same direct cost will be valid in the Tennessee area. By placing the facility at the site of the abandoned Clinch River Breeder Reactor project, further savings can be realized because extensive site characterization has already been done, with probable limited site preparation and land acquisition. Furthermore, the earthquake potential at the site is minimal [9], which means savings on the reactor building and any other Class 1 seismic structures. The strongest earthquake at the site (Fig. 5.7) has been Mercalli intensity VI (which may cause slight damage on regular buildings - falling of plaster, chimney damage [37]). The design basis ground acceleration of CRBR (0.25 g) is half that of the San Onofre reactors in California. While it is not possible to quantify these observations into cost figures at this time, we may take a significant credit on capital costs with proper site choice, with some sites also offering a low cost of electricity of 3 ¢/kWhr (see Chapter 6). Therefore, for this example, a 9% credit may be taken, which reduces our base case TDC by $47M, and the constant dollar TCC by $92M. These savings have not been incorporated in our cost figures, however.

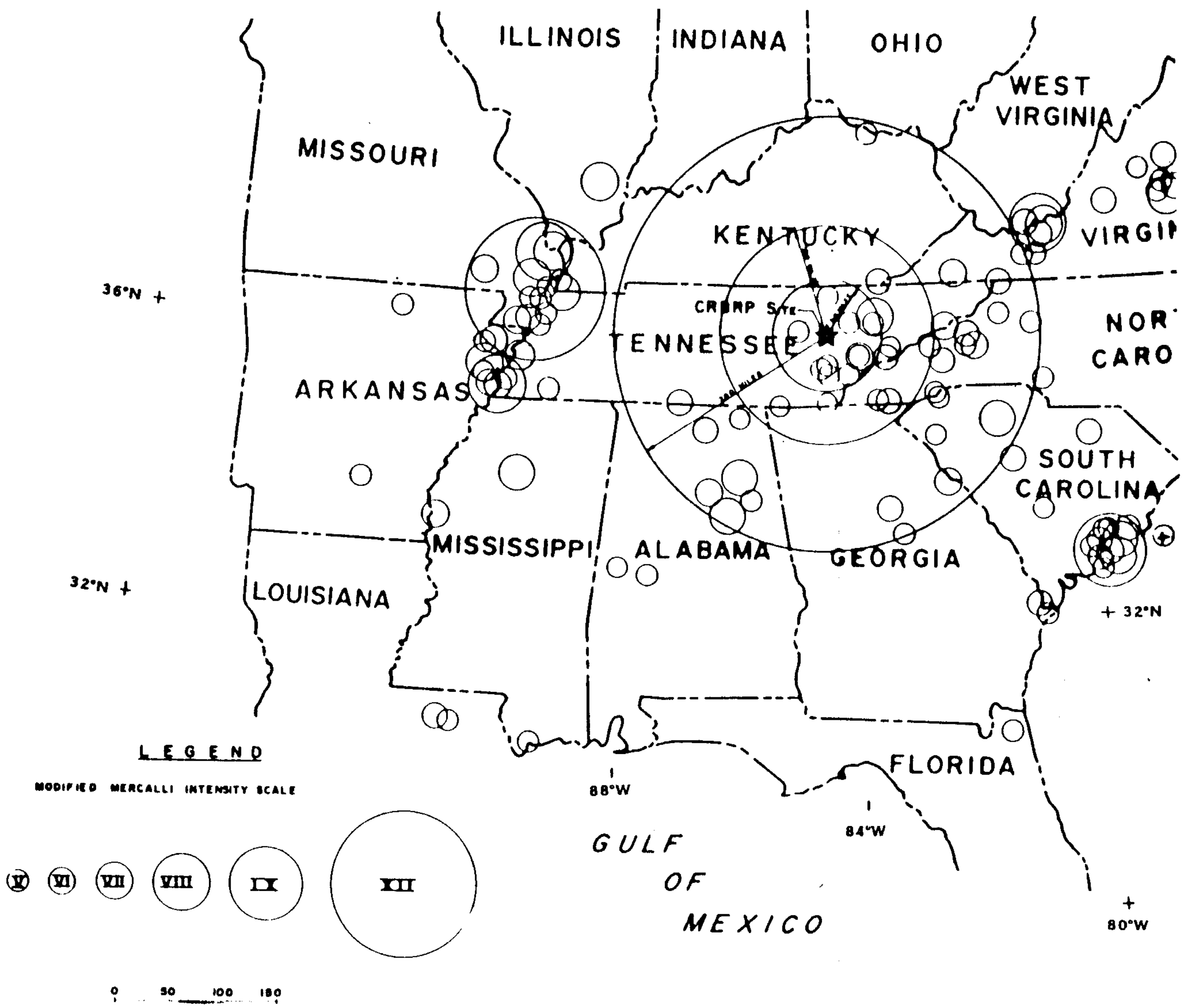


Figure 5.7: Earthquake history of the CRBR site [9]

Chapter 6

Annual Costs of the Facility

The annual costs of the facility will have several components. Since the government would build and own the facility, the annual cost of paying off the investment would not be charged to the facility, as has been argued before. Therefore, the remaining annual costs of operating SIRIUS-M will include the cost of fuel, electricity, regular operations and maintenance (O&M) costs and the cost of replacement test modules. The latter will not be considered here, partly because it should be a small cost item (the direct cost of the two modules is about $1.M) and partly because no replacement schedule has been derived yet (it could be irregular). As mentioned in Chapter 3, we assume a 50% facility availability. Current dollars are 1990 dollars (4 year construction) in the base case.

6.1 Fuel Cost

The annual fuel cost will consist only of the cost of tritium (the O&M cost of the target factory is included in the O&M cost of the whole facility). The cost of deuterium and of other target materials are assumed to be negligible in comparison.

Estimates for the price of tritium vary, depending on the source of information and the source of tritium. Reference [40] quotes a price of $4500-$7000/g in 1978 dollars. Another report [14] cites $5000/g in 1979 dollars. The SIRIUS-M preliminary report quotes \$10,000/g [5]. Most of these prices are for tritium produced in the DOE production reactors. According to private conversation [41], the current market price is US\$1.1/Ci (our target will have about 0.85 Ci of tritium) or about \$10,600/g. A speculative source of tritium might be an ICF reactor designed specifically for production of tritium [21] from which the design-basis price is \$8100/g. A more secure source (and possibly less expensive than DOE T_2 due to lack of reprocessing) would be the tritium produced in (pressurized) heavy water nuclear reactors, specifically Canadian CANDUs. Most of these reactors are in multiple-reactor plants, each reactor with a capacity of 500-800 MWe typically [42]. The tritium production rate is 6.3 Ci/MWe-day in the moderator and 90 mCi/MWe-day in the coolant (both are heavy water) [40]. This translates into 95 g T_2/year/500 MWe reactor, assuming an 80% capacity factor [40]. This assumption is actually conservative due to on-line refueling of these reactors, and capacity factors have been higher in practice [40]. Right now, the capacity of the CANDU reactors in Canada is 15,422 MWe [42]. Most of these reactors are installed and operating, some are in a very advanced stage of construction (80-99% complete) and three units at Darlington are in earlier stages (5-40% complete). Past projections of Canadian capacity in the year 2000 run as high as 100,000-131,000 MWe [40]. While this is probably optimistic, some new capacity might be added before the year 2000. The present capacity (if all the reactors were finished and operating) yields a yearly production rate of 2.9 kg of T_2. This is a little short of the SIRIUS-M requirements of 3.4 kg/year.

The tritium content in the CANDU reactors has to be kept as low as possible in order to limit radiation doses to operating personnel and tritium releases into the environment after a spill or an accident. The tritium content in the CANDU D_2O is between 2 and 30 Ci/kg [41]. Up until very recently there has been no capability in Canada to extract that tritium. The Sulzer Company of Switzerland has built a small extraction facility (capacity of 160,000 Ci/year, or 17 g/year) at the high flux heavy water reactor in Grenoble, France [43], operating since 1972 [44]. Since then, a much bigger facility has been built in Canada, which is being brought into operation at this time. The plant uses a similar process to that of the Grenoble plant (catalytic exchange for converting DTO into DT in combination with a converter for splitting the DT into D_2 and T_2 and a

Table 6.1: Tritium cost per target for DOE and CANDU tritium

	DOE tritium	CANDU tritium
Cost per target, ¢ const.	23.	16.
Cost per target, ¢ curr.	37.	26.

Table 6.2: Total annual fuel cost of SIRIUS-M

Source of tritium	U.S. DOE	CANDU
Fuel cost, $M const.	36.3	25.2
Fuel cost, $M curr.	58.4	41.0

cryogenic separation column [43], [44]). It will be capable of processing 350 kg of D_2O per hour. Its capacity is 8 million Ci of T_2 per year (about 830. g/year)[41]. Its projected cost was $58M in 1982 dollars [44], and the informal quoted price of tritium could be as low as CAN$1./Ci [41], or US$7100/g.

In order to arrive at the price of tritium per target, we assume that only the burnt tritium will be charged, with the unburnt tritium receiving credit equal to its purchasing price. Table 6.1 presents the price per target for the DOE tritium ($10,600/g) and the CANDU tritium ($7100/g).

Table 6.2 presents the annual fuel cost of SIRIUS-M for the cases of the two different sources of tritium: U.S. DOE tritium and Canadian CANDU tritium.

Table 6.3: Annual cost of electricity at 3 ¢/kWhr

Cost type	10% laser	3% laser	50% laser
Elec. cost, $M const.	13.2	43.9	2.6
Elec. cost, $M curr.	22.2	74.1	4.4

6.2 Cost of Electricity

In this study, a cost of electricity of 3 ¢/kWhr was assumed [21]. This low cost might exist in the Pacific Northwest and perhaps some other areas. In Madison, WI, the rate is about 6 ¢/kWhr. Tables 6.3 and 6.4 show the annual cost of purchased electricity for SIRIUS-M for the cases of 3 ¢/kWhr and 6 ¢/kWhr electricity, and for the case of a 10% efficient, 3% efficient and 50% efficient laser. As has been stated earlier, the electricity

Table 6.4: Annual cost of electricity at 6 ¢/kWhr

Cost type	10% laser	3% laser	50% laser
Elec. cost, $M const.	26.3	87.7	5.3
Elec. cost, $M curr.	44.5	148.2	8.9

consumption takes into account only the laser requirements, and neglects any auxiliaries such as pumps, instrumentation etc.

6.3 O&M Costs

The O&M costs include traditional costs of running a plant, including the cost of personnel on site. The usual procedure is to compute the annual O&M costs as a fraction of TOC (see Chapter 3 for default value). The

Table 6.5: Annual O&M cost of SIRIUS-M for various driver cases, $M

Cost type	10%,$100M	3%,$100M	10%,$250M	50%,$100M
Const. $	25.5	31.2	34.3	23.7
Curr. $	43.1	52.8	58.0	40.1

Table 6.6: Total yearly cost of running SIRIUS-M

Type cost	Best case	Worst case	Base case	Base case w/o fuel
O&M+fuel+el., $M const.	51.5	155.2	75.	39.
O&M+fuel+el., $M curr.	85.5	259.4	123.7	65.3

fraction that we used is representative of a power plant, and therefore might not be entirely applicable in this case. Table 6.5 shows the annual O&M costs for the same cases used in Table 5.4.

6.4 Total Facility Annual Costs

This section will present the total annual cost of operating SIRIUS-M, by assuming a few scenarios. The worst case assumes a 3%, $100.M laser driver for our facility. The targets will be made with DOE tritium. The cost of electricity is 6 ¢/kWhr. The best case is for a 50%, $100.M laser driver, the cost of electricity is 3 ¢/kWhr and the targets are made from the lower priced Canadian tritium. The representative case is for a 10%, $100.M laser driver, burning DOE tritium and the electricity is bought at 3 ¢/kWhr. One can also imagine the case in which no charge is assessed for DOE tritium (SIRIUS-M being a government facility). This is the base case without fuel charge. Table 6.6 gives the total annual costs for these four cases.

Chapter 7

Total Lifetime Cost vs. Performance

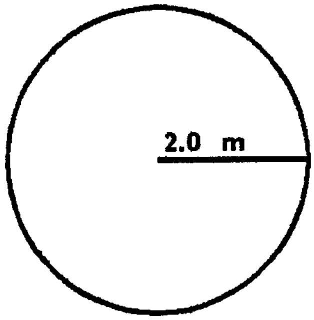
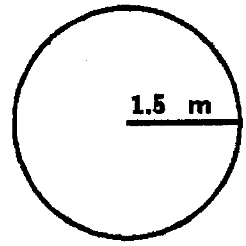
This chapter discusses the total lifetime cost and cost per dpa-l for several scenarios. Dpa-l is the unit for cumulative damage in the test modules. Cumulative damage is in this case synonymous with cumulative performance, because testing of cumulative damage levels in the test modules is the mission of SIRIUS-M. The scenarios that were analyzed are the base case, which is the case of the 2 m cavity (reflected light limited design) and that of the 1.5 m cavity (target debris limited design). The parameters for the two designs and the corresponding cost figures are given in Fig. 7.1 through 7.4. The parameters of interest are the wall loading, the target yield, the chamber repetition rate, the total operation time (lifetime) of the facility, the cumulative performance over that time period and the facility availability.

For the 1.5 m cavity design, we can have several cases, depending which parameters are varied from the base case (2 m cavity design). Case I preserves the fusion power and the cumulative performance (Fig. 7.1), therefore the facility life is shortened to compensate for the higher wall loading of the 1.5 m cavity. There is a slight decrease in the TDC and TOC of the 1.5 m cavity design (due to a decrease in the amount of reactor materials for the smaller reaction chamber), whereas the annual cost stays the same. Multiplying the annual cost by the lifetime in years and adding the TOC yields the total lifetime cost (TLC), which is now significantly reduced due to the shortened facility lifetime.

Case II (Fig. 7.2) preserves the wall loading and cumulative performance. This is accomplished by decreasing the rep-rate (to compensate for smaller surface area of the 1.5 m cavity), while all the other parameters are the same as in the base case. Due to a decrease in the fusion and thermal power of the facility, there is now a more pronounced decrease in the TDC and the TOC. The operating cost goes down substantially due to the lower consumtpion of electricity and fuel. However, the TLC and the cost per dpa-l don't decrease as much as in case I.

Case III (Fig. 7.3) preserves the fusion power and the facility lifetime. Therefore, due to the higher wall loading of the 1.5 m cavity, the cumulative performance goes up substantially over that for the 2 m cavity design. Consequently, the cost per dpa-l is the smallest of all the cases examined.

Case IV preserves the fusion power, cumulative performance and operating time (Fig. 7.4) by decreasing the availability for the 1.5 m cavity design. This availability may, in any case, be more realistic than the 50% availability assumed for the base case design. While the operating cost decreases substantially, the total lifetime cost and the cost per dpa-l is highest of all the 1.5 m cavity design scenarios.

Reflected Light Limit	Target Debris Limit
	

- **Case I: Constant Fusion Power and Cumulative Performance**

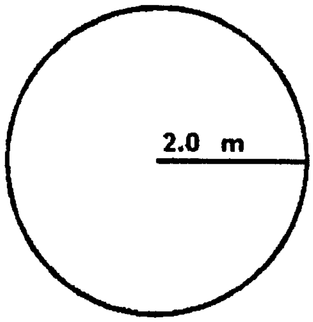
2.0 MW/m^2	Wall Loading	3.6 MW/m^2
13.4 MJ	Yield	13.4 MJ
10 Hz	Rep. Rate	10 Hz
10 years	Operation Time	5.6 years
14,200 dpa-ℓ	Cum. Performance	14,200 dpa-ℓ

Economic Impact

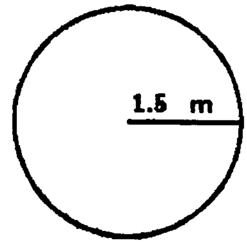
519 M$	Total Direct Cost	510 M$
855 M$	Total Overnight Cost	841 M$
74 M$/y	Operating Cost	74 M$/y
1595 M$	Total Lifetime Cost	1255 M$
112 k$/dpa-$\ell$	Cost per dpa-ℓ	88 k$/dpa-$\ell$

Figure 7.1: Cavity design optimization, case I

Reflected Light Limit



Target Debris Limit



•Case II: Constant Wall Loading and Cum. Performance

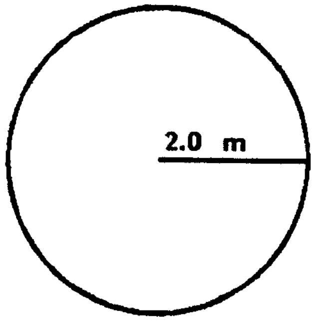
2.0 MW/m^2	Wall Loading	2.0 MW/m^2
13.4 MJ	Yield	13.4 MJ
10 Hz	Rep. Rate	5.6 Hz
10 years	Operation Time	10 years
14,200 dpa-ℓ	Cum. Performance	14,200 dpa-ℓ

Economic Impact

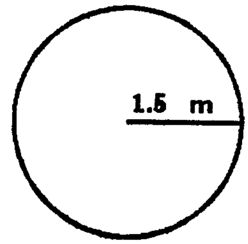
519 M$	Total Direct Cost	490 M$
855 M$	Total Overnight Cost	807 M$
74 M$/y	Operating Cost	52 M$/y
1595 M$	Total Lifetime Cost	1323 M$
112 k$/dpa-$\ell$	Cost per dpa-ℓ	93 k$/dpa-$\ell$

Figure 7.2: Cavity design optimization, case II

Reflected Light Limit



Target Debris Limit



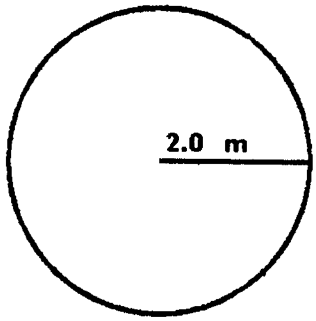
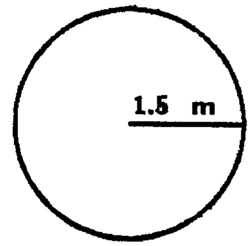
•Case III: Constant Fusion Power and Op. Time

2.0 MW/m^2	Wall Loading	3.6 MW/m^2
13.4 MJ	Yield	13.4 MJ
10 Hz	Rep. Rate	10 Hz
10 years	Operation Time	10 years
14,200 dpa-ℓ	Cum. Performance	25,245 dpa-ℓ

Economic Impact

519 M$	Total Direct Cost	510 M$
855 M$	Total Overnight Cost	841 M$
74 M$/y	Operating Cost	74 M$/y
1595 M$	Total Lifetime Cost	1581 M$
112 k$/dpa-$\ell$	Cost per dpa-ℓ	63 k$/dpa-$\ell$

Figure 7.3: Cavity design optimization, case III

Reflected Light Limit	Target Debris Limit
	

•Case IV: Constant Fusion Power, Cumulative Performance and Operating Time

2.0 MW/m^2	Wall Loading	3.6 MW/m^2
13.4 MJ	Yield	13.4 MJ
10 Hz	Rep. Rate	10 Hz
10 years	Operation Time	10 years
14,200 dpa-ℓ	Cum. Performance	14,200 dpa-ℓ
50%	Availability	28%

Economic Impact

519 M$	Total Direct Cost	510 M$
855 M$	Total Overnight Cost	841 M$
74 M$/y	Operating Cost	52 M$/y
1595 M$	Total Lifetime Cost	1357 M$
112 k$/dpa-$\ell$	Cost per dpa-ℓ	96 k$/dpa-$\ell$

Figure 7.4: Cavity design optimization, case IV

Chapter 8

Conclusions and Recommendations

The most important drivers of capital cost (Chapter 5) are the reactor building, the laser power supply, the laser itself and the target factory. In addition, the laser and the target factory (and to a smaller extent the reactor building) have large uncertainties associated with their cost estimates. Therefore, in order to minimize the total capital cost and pinpoint it with high accuracy, one should strive to minimize the costs of these drivers and to learn more about their true cost.

In terms of the annual operating cost (Chapter 6), the most important factors are the laser efficiency, the cost of electricity at the site and the cost of purchased tritium. Since the O&M cost depends on the total overnight cost, then limiting the direct cost will also help in limiting this component of the annual operating cost.

One can claim significant savings in both the capital and annual costs if the site of the facility is carefully chosen. A site in the low cost area of the country (see Chapter 5), in a low earthquake risk zone and on partially developed federal land will give us a considerable credit on the direct cost. Similarly, a low cost of electricity (3 ¢/kWhr) is important for limiting the annual cost of operating SIRIUS-M.

If it's possible to base the design on a 1.5 m target chamber (as opposed to the 2 m chamber), then certain savings in the total overnight cost, operating cost and total lifetime cost per dpa-l may be realized (Chapter 7). The 1.5 m target chamber is limited by the target debris damage considerations, and would be possible if the reflected light limit for the 2 m chamber can be relaxed. The scenario offering the most savings of 1.5 m cavity over the 2 m cavity design would be to conserve the fusion power (thus accepting the higher wall loading) and the total facility operating time.

It is recommended that particular attention be paid to the scaling laws for the laser drivers and the target factories. Furthermore, there should be uniformity in scaling laws between the MFE and the ICF part of the fusion community and also within either of these parts. These laws should be updated often (perhaps every two years) because escalation and inflation rates will vary for each piece of equipment. Some guidance is needed (both in the area of the scaling laws and the area of economic factors) as to how experimental test reactors such as SIRIUS-M should be treated.

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