CONTENTS

8.0 ECONOMIC ASSESSMENT

8.1 INTRODUCTION

At the beginning of the IFE Reactor Design Studies, we performed preliminary parameter studies to help us select a set of reference design parameters, which were used to develop the detailed point designs discussed in the previous sections of this report. These preliminary parametric studies used costs and cost scaling relationships from earlier IFE reactor and driver designs documented in the SAFIRE code.[8.1] These cost scaling relationships were coupled with the new target gain curves supplied with the study guidelines.[8.2] This procedure provided us with our best guess of parameters to use for the point designs.

After completing the conceptual designs of Osiris, SOMBRERO, and the two drivers, cost estimates were made for the point designs, and new cost scaling relationships were developed and incorporated into systems economic codes for Osiris and SOMBRERO power plant. (The codes were written using MathCAD™). These codes were then used to do parametric studies of the two designs to determine the cost of electricity (COE) as a function of design and operating parameters. Not surprisingly, the optimum operating points (minimum COE) for Osiris and SOMBRERO do not coincide with the reference point parameters selected at the beginning of the study.

In this chapter, we report the costs for the reference point design, describe the cost scaling algorithms used in the modeling, and present results of the parametric studies using the new economic models. The costs are given in 1991 dollars and represent costs for a fully commercial system. Studies such as ARIES have applied learning curve factors to calculate the 10th-of-a-kind plant cost. We have not applied any learning curve credits to our costs for several reasons.

1) The results can be misleading if learning curve effects are improperly applied. For example, learning curves should not be applied to the cost of concrete or to construction labor since it is unlikely that the same crew will be building all ten plants. Multi-unit plants might benefit, but that scenario is not part of our baseline configuration.

2) Many of the large cost items are already costed assuming large quantity purchases where the costs are dominated by the cost of materials and not manufacturing costs. For example, the metglas for the induction cores is costed on a $/kg basis assuming orders greater than 1000 tonne. We have not further reduced this cost assumption for the 10th-of-a-kind plant. Likewise, the costs of conventional plant equipment (i.e., buildings, turbines, electric plant equipment, etc.) are already based on commercialized systems.

3) Since the cost estimates are uncertain to begin with, applying imprecise learning curve effects will only lead to greater uncertainly.

The costs presented here are most useful for 1) relative comparisons to other fusion designs costed on the same basis and 2) for determining an attractive operating point in the plant design space. More detailed design work and costing are needed before any meaningful comparisons can be made to future fission or coal power plants. The accuracy of the costs on an absolute basis is clearly questionable. It is interesting to note that a construction firm such as Bechtel will spend on the order of 1% of the project cost in developing detailed cost estimates for the project (i.e., \$10 M for a \$1 B plant). Even with that level of effort and even for a conventional, Nth-of-a-kind coal plant, a project contingency of 20% is included to account for items that can not be precisely estimated or events that can not be anticipated during construction.

8.2 COST OF ELECTRICITY

The figure of merit used in our economic assessment is the constant dollar cost of electricity (¢/kWh) which is given by

$$COE = \frac{FCR \cdot TCC + OM + F}{0.0876 \cdot \alpha \cdot Pn} + D$$

where

FCR	=	constant dollar fixed charge rate, yr^{-1}
TCC	=	total capital cost, \$M
OM	=	annual O&M cost, \$M/yr
F	=	annual fuel cost, \$M/yr
α	=	availability factor
Pn	=	net electric power, MWe
D	=	allowance for decommissioning, ¢/kWh

The economic parameters used in these studies are summarized in Table 8.1. The values presented here were agreed on with the Technical Oversight Committee for the Reactor Design Studies and the McDonnell Douglas design team.

The total capital cost (TCC) is the sum of the direct capital cost, indirect capital costs, and time related costs. It is calculated from the following equation using the factors given in Table 8.1.

$$TCC = (1 + f91 + f92 + f93) \cdot (1 + f94) \cdot (1 + f96) \cdot (1 + f97 + f98) \cdot TDC$$

Table 8.1. Economic Parameters Used in This Study

Plant Operating Lifetime, yrs		30				
Plant Construction Lead Time, yrs		6				
Contingency Factor, Project and Progress		See below				
Spare Parts Multiplier		1.0 (no spares)				
Constant Year Dollars		1991				
Nominal Year Dollars		1997				
Inflation Rate, %/yr		5.0				
Escalation Rate, %/yr		5.0				
		Average		Tax-Adjusted		
Effective Cost of Money, Nominal Dollars		0.1135		0.0957		
Effective Cost of Money, Constant Dollars		0.0605		0.0435		
Fixed Charge Rate, Nominal Dollars		0.1638				
Fixed Charge Rate, Constant Dollars		0.0966				
Indirect Cost Factors		LSA 1	LSA 2	LSA 3	LSA 4	
f91 Construction Services and Equip.	(× TDC)	0.113	0.120	0.128	0.151	
f92 Home Office Engr. and Services	(× TDC)	0.052	0.052	0.052	0.052	
f93 Field Office Engr. and Services	(× TDC)	0.052	0.060	0.064	0.087	
f94 Owners Cost	(× TDC+91+92+93)	0.150	0.150	0.150	0.150	
f95 Process Contingency	(× TDC+91+92+93+94)	0.000	0.000	0.000	0.000	
f96 Project Contingency	(× TDC+91+92+93+94)	0.1465	0.173	0.184	0.195	
		Constant $		Nominal $		
f97 IDC Factor		0.1652		0.3178		
f98 EDC Factor		0		0.2436		

where TDC = total direct capital cost. Note that f91, f93, and f96 depend on the level of safety assurance (LSA). For LSA = 2, the total capital cost is

$$TCC = 1.936 \cdot TDC$$

This overall multiplier varies from 1.870 for LSA = 1 to 2.066 for LSA = 4.

The TDC for the major subsystems are expressed as functions of the plant operating parameters. These cost scaling relationships are given in Section 8.4 for Osiris and Section 8.5 for SOMBRERO.

8.3 CALCULATING PLANT OPERATING PARAMETERS

The costs of the major subsystems of the power plants are scaled as a function of various system design parameters such as the driver energy, pulse repetition rate, thermal power, and gross electric power. These key design parameters can all be related to the driver energy, which then serves as the independent variable in our analysis.

8.3.1 Thermal Power

The total thermal power (MWt) of the plant is given by

$$Pt = \frac{Pn}{\eta t \cdot \left(1 - fa - \frac{1}{\eta d \cdot G \cdot M \cdot \eta t}\right)}$$

where

Pn	=	net electric power, MWe,
ηt	=	thermal conversion efficiency,
fa	=	auxiliary power fraction (for pumping and other in-plant power requirements),
M	=	total energy multiplication factor (ratio of total energy deposited in target and blanket to fusion yield per pulse),
G	=	target gain, and
ηd	=	driver efficiency.

The thermal power is a function of driver energy because the target gain and driver efficiencies are function of E. The net electric power, thermal conversion efficiency, auxiliary power fraction, and energy multiplication factor are fixed parameters for both designs. The base case values for these fixed parameters are given in Table 8.2. The guidelines for the study specified that the base case net electric power of the plant should be 1000 MWe.

Table 8.2. Base Case Fixed Parameters for Calculating Thermal Power

	Osiris	SOMBRERO
Pn (MWe)	1000	1000
ηt (%)	45	47
fa (%)	4	4
M	1.26	1.08

8.3.2 Target Gain and Yield

For the HIB driver, the target gain is a function of the driver energy, the beam spot size on target, and the ion range. In our modeling of the driver, the ion energy (GeV) varies with driver energy, and the focusing half angle is selected to give the smallest spot size and, thus, highest gain for a given E. The resulting base case gain curve is shown in Fig. 8.1 for our reference driver design with 12 beams, A = 131 and q = +1. In the parametric analysis, we examined the effects of more optimistic and more conservative target gain relationships. For the optimistic case, the base case gain is increased by a factor of 2, and for the conservative case, the base case gain is decreased by 30%. These curves are also shown in Fig. 8.1.

The target gain curves for direct drive laser targets are shown in Figure 8.2. The optimistic and conservative curves were provided as an supplement[8.3] to the original study guidelines.[8.2] The base case gain is the average of the optimistic and conservative gain.

The target yield (MJ) is the product of the driver energy and target gain, Y = E·G. The target yield as a function of driver energy is shown in Fig. 8.3 for the base case laser and HIB gain curves.

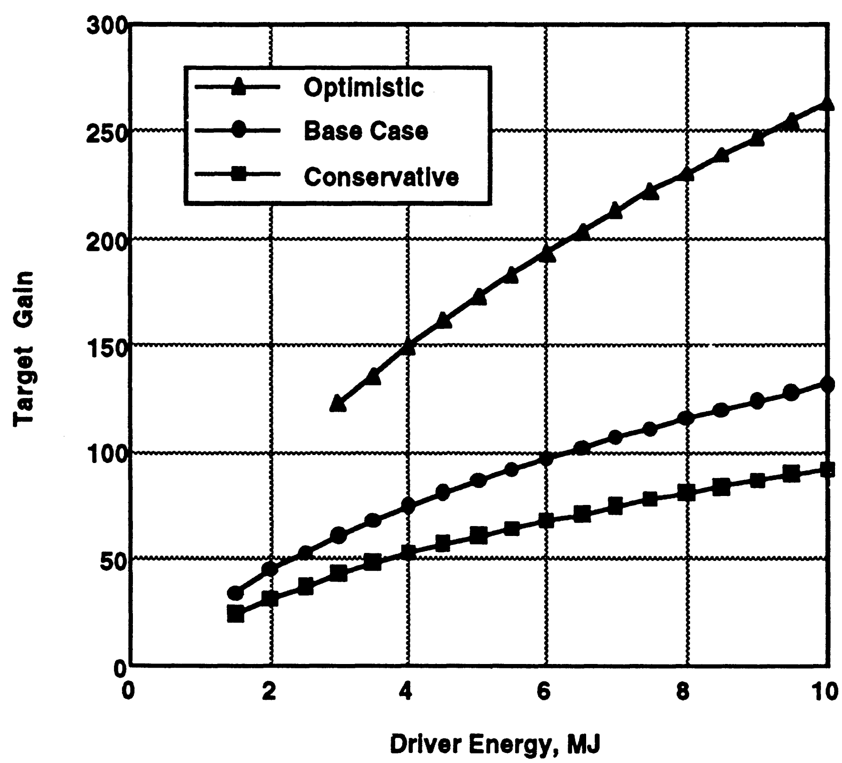

Fig. 8.1. Target gain curves for the base case HIB driver (12 beams, A = 131, q = +1) using indirect drive targets. The optimistic curve is only valid for E > 3.2 MJ, at which point the yield is ~ 400 MJ.

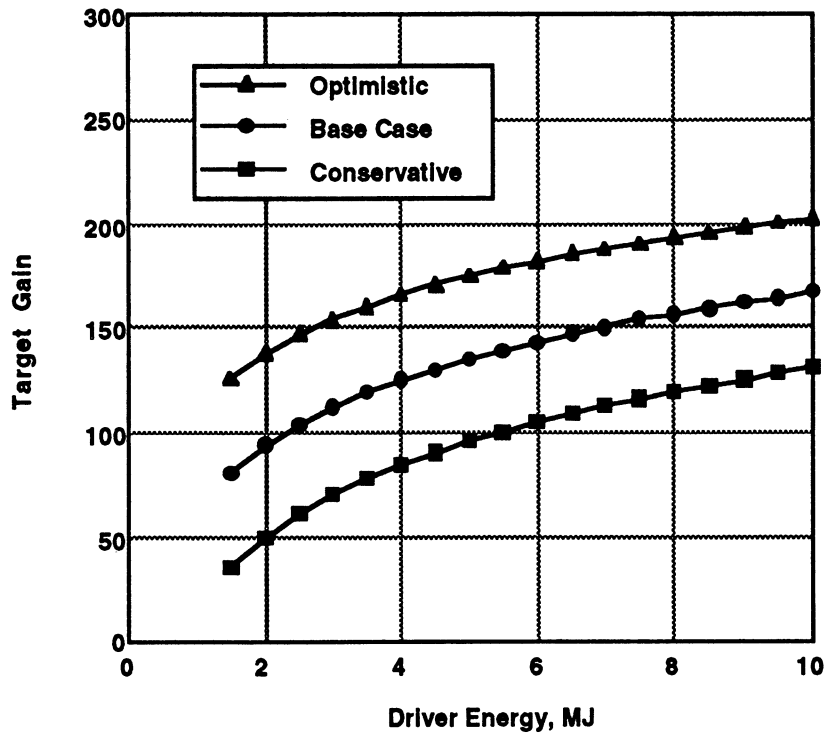

Fig. 8.2. Target gain curves for the KrF Driver. The base case curve is the average of the optimistic and conservative curves.

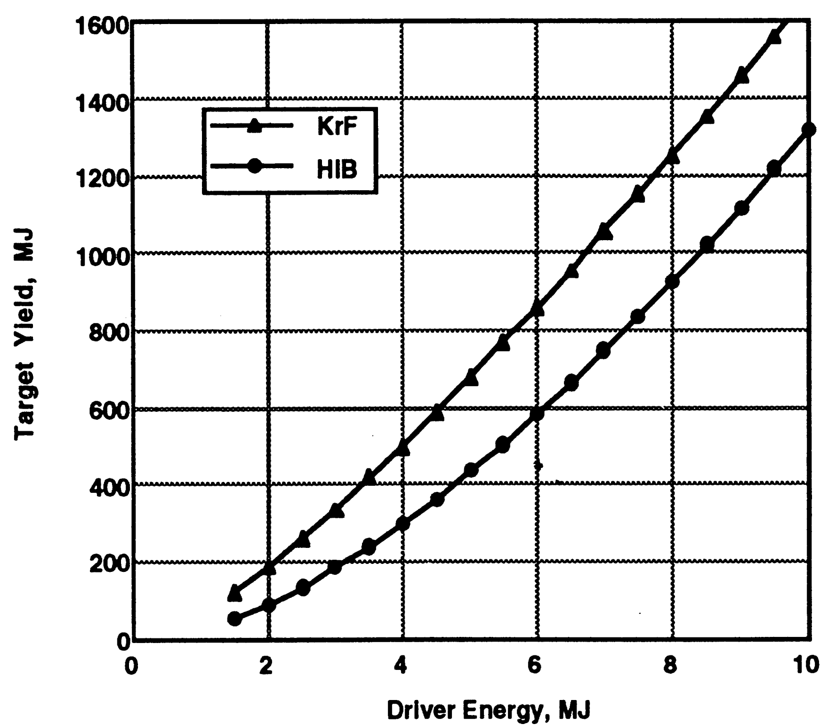

Fig. 8.3. Target yield as a function of driver energy for the two drivers. For a given driver energy, the yield is higher for the KrF laser.

8.3.3 Driver Efficiency

The final parameter required to calculate the thermal power is the driver efficiency, ηd. The HIB driver efficiency is a function of the driver energy (E) and the pulse repetition rate (RR), as described in Section 2.4. As shown below, the rep-rate is calculated from the thermal power. Therefore, we must iterate to find self consistent values for Pt, ηd, and RR. For a given energy, the thermal power is first determined using an estimate for the driver efficiency. The rep-rate is calculated from the thermal power and then used to find a new value for efficiency. This procedure converges rather rapidly. The HIB driver efficiency as a function of energy for the 1000 MWe plant is shown in Fig. 8.4.

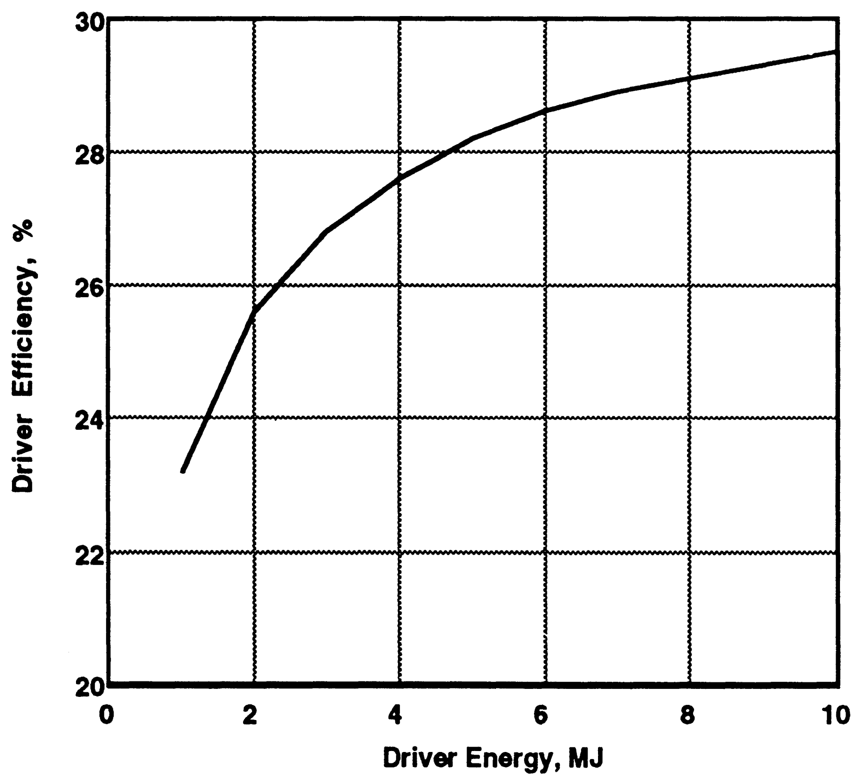

Fig. 8.4. HIB driver efficiency as a function of energy for a 1000 MWe plant.

The KrF driver efficiency is a function of the driver energy and pulse rep-rate. The dependence on rep-rate is very weak (e.g., at E = 3.6 MJ, ηd only decreases from 7.6% at 1 Hz to 7.5% at 10 Hz) and is therefore ignored in these system studies. The dependence on energy is the most important factor. The KrF driver efficiency as a function of driver energy is shown in Fig. 8.5. In the laser model, the amplifier dimensions increase with increasing driver energy while the number of amplifiers remains constant. As discussed in Section 3.4, increasing the length of the amplifier reduces the efficiency as seen in Fig. 8.5. We consider this scaling to be valid from ~1.8 to 5.4 MJ (i.e., ± 50% from the 3.6 MJ design point). (Note that the laser design was done at 3.6 MJ and then scaled to the final base case energy of 3.4 MJ.)

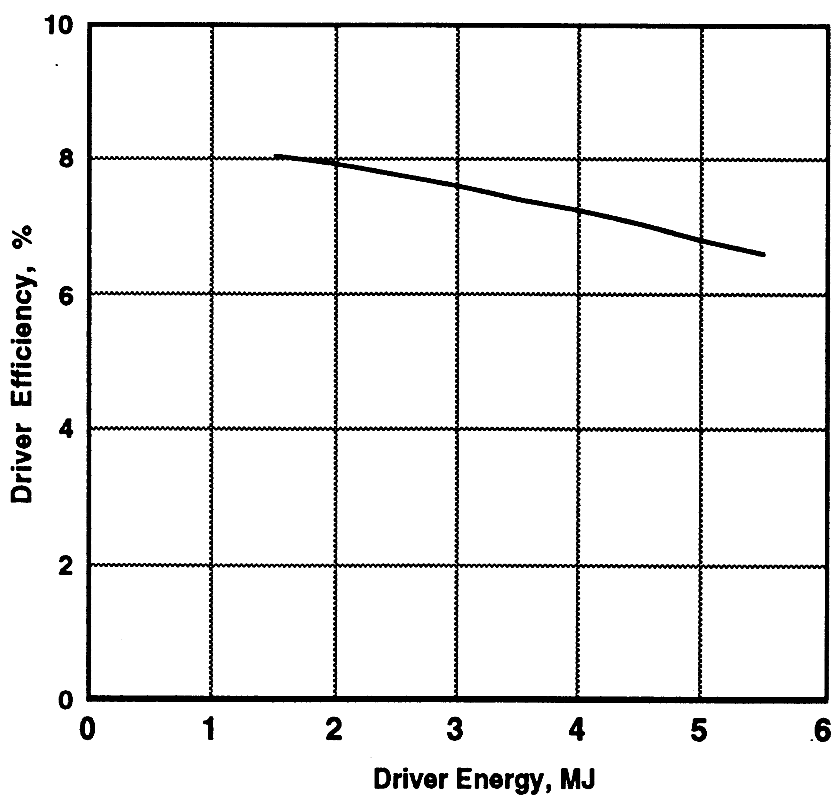

Fig. 8.5. KrF driver efficiency as a function of energy.

8.3.3 Pulse Repetition Rate

The rep-rate (Hz) required for a 1000 MWe plant is given by

$$RR = \frac{Pt}{E \cdot G \cdot M}$$

The rep-rate as a function of driver energy (using the base case gain curves) is shown in Fig. 8.6 for the laser and HIB drivers. The HIB driver operates at a higher rep-rate for a given energy since the target gain is lower.

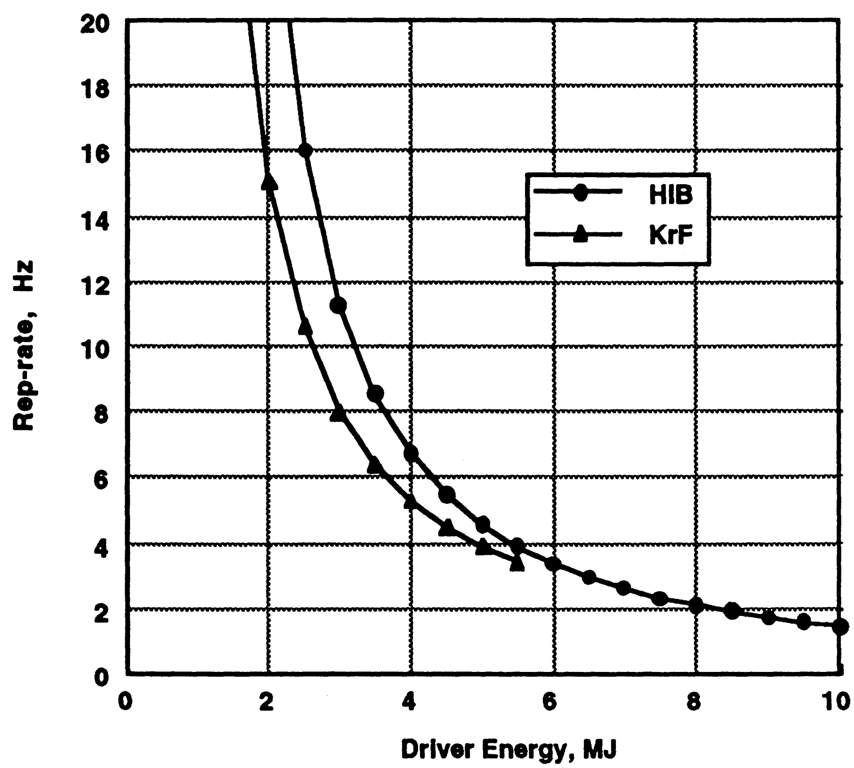

Fig. 8.6. Pulse repetition rate required for a 1000 MWe (net) power plant.

8.3.4 Gross Electric Power, Driver Power, and Auxiliary Power

The gross electric power (MWe) is

$$Pg = \eta t \cdot Pt$$

The power needed to operate the driver (MWe) is given by

$$Pd = \frac{E \cdot RR}{\eta d}$$

The auxiliary power (MWe) is

$$Pa = fa \cdot Pg$$

Figures 8.7 and 8.8 show the gross electric power and driver power as a function of driver energy for the HIB and KrF drivers. The key operating parameters for the Osiris and SOMBRERO base case designs are given in Table 8.3.

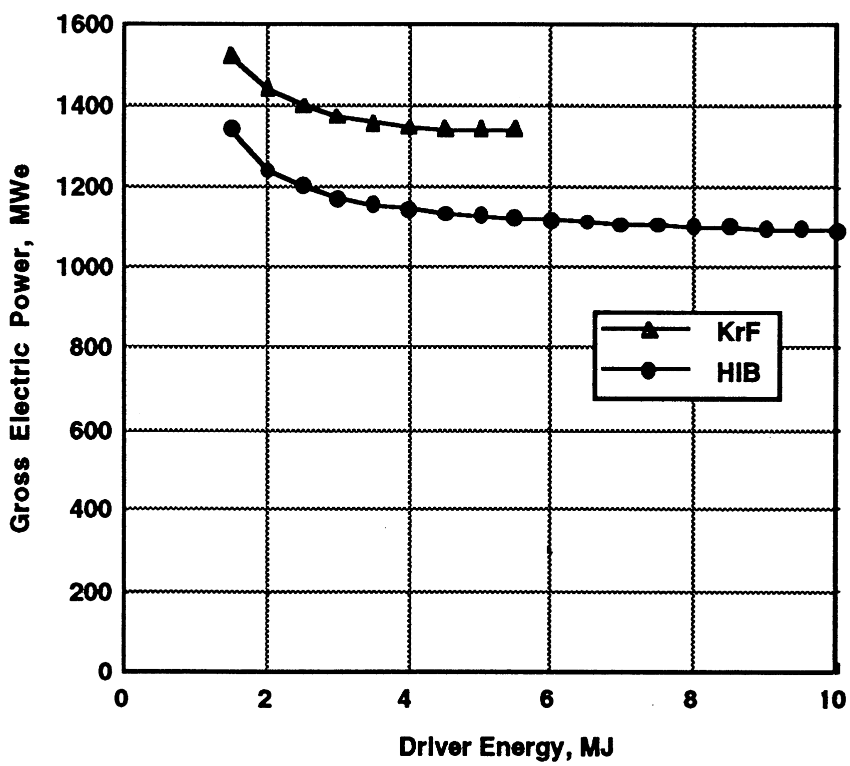

Fig. 8.7. Gross electric power as a function of driver energy. Pg is higher for the laser driven plant due to the larger driver power consumption.

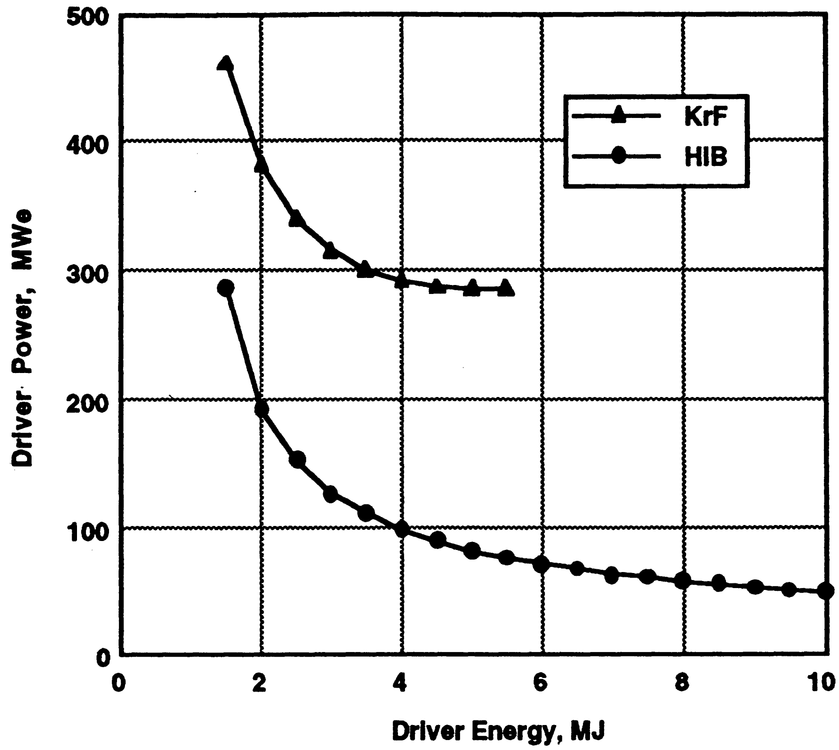

Fig. 8.8. Recirculating power required to run the driver.

Table 8.3. Base Case Operating Parameters

	Osiris	SOMBRERO
Driver energy (MJ)	5.0	3.4
Gain	86.5	118
Yield (MJ)	432	400
Rep-rate (Hz)	4.6	6.7
Driver Efficiency (%)	28.2	7.5
Thermal Power (MWt)	2504	2891
Gross Electric (MWe)	1127	1359
Driver Power (MWe)	82	304
Auxiliary Power (MWe)	45	55
Net Electric Power (MWe)	1000	1000

8.4 COST MODELING FOR OSIRIS

8.4.1 Introduction

Direct capital costs and cost scaling relationships have been developed for the HIB driver, the reactor, balance of plant systems, and the target systems. Through the use of the above expressions, all of these costs can be related to the driver energy.

8.4.2 Direct Capital Cost for the Reference Design

Table 8.4 gives the base case direct capital cost for the Osiris power plant. All costs are presented in 1991 dollars. Note that this base case design is not the minimum COE design. Lower capital cost can be achieved by lowering the driver energy. The basis for these costs and cost scaling relationships is discussed in the next section. Figure 8.9 shows the breakdown of the total direct capital cost for the reference design. The total direct cost is ~$1.6 B with the Reactor Plant Equipment and Driver Equipment making up the largest portions. Figure 8.10 shows the components that contribute to the Reactor Plant Equipment. This account is dominated by the Heat Transfer Equipment, but the breeder and remote maintenance equipment are also large cost items. Figure 8.11 shows the major components of the HI driver cost. Here we see that the inductors, pulsed power, and superconducting quads are the major cost items.

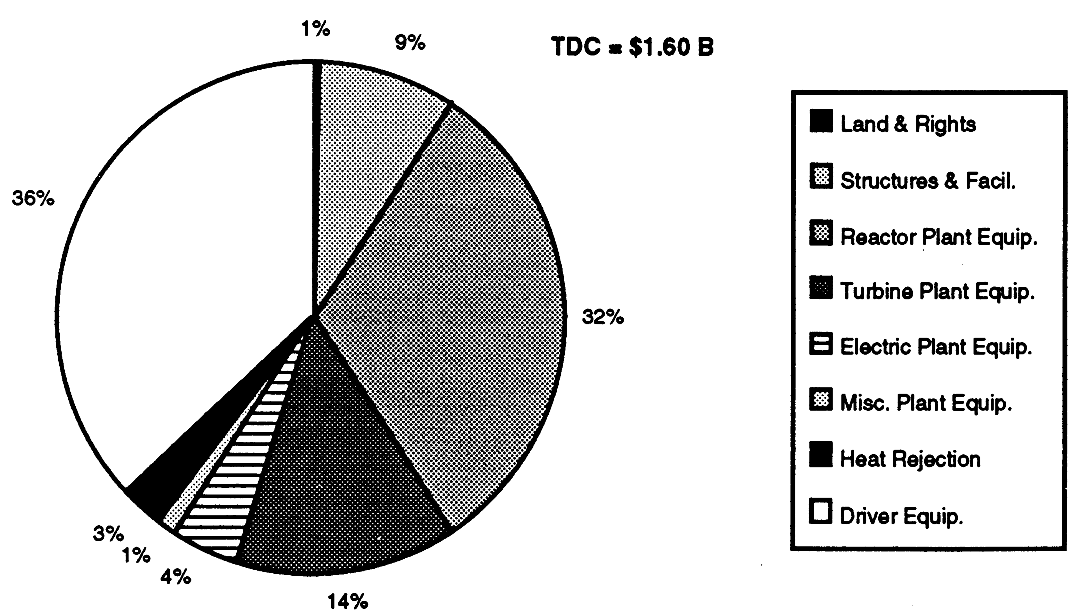

Fig. 8.9. Breakdown of total direct capital cost (TDC) for the Osiris power plant (Base Case, 1000 MWe).

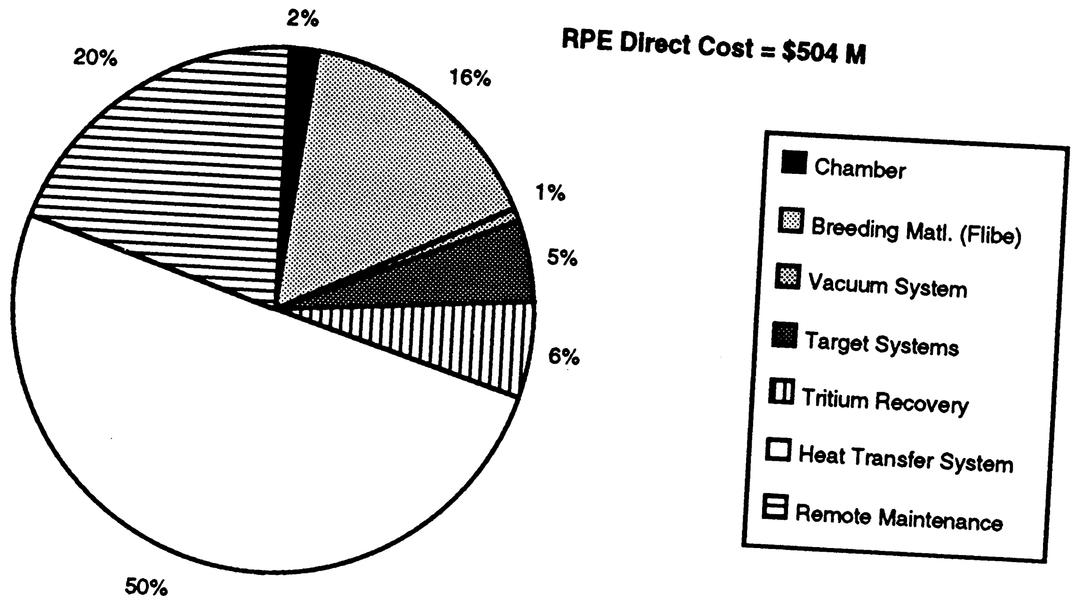

Fig. 8.10. Breakdown of Account 22 - Reactor Plant Equipment Direct Cost (Osiris Base Case, 1000 MWe).

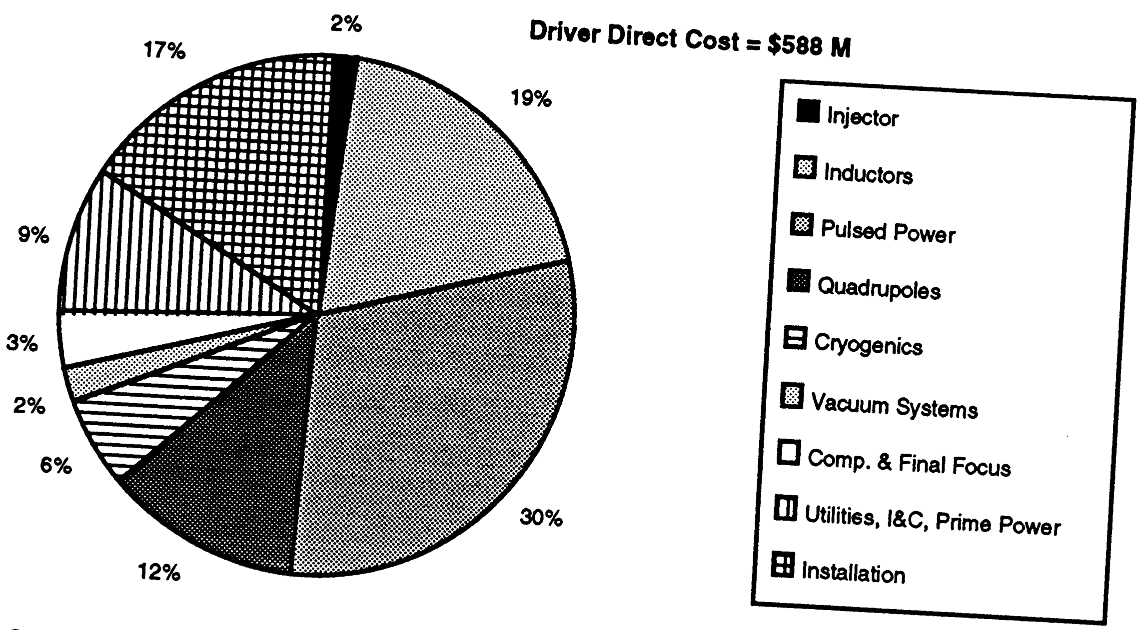

Fig. 8.11. Breakdown of Account 27 - Driver Equipment Direct Cost (Osiris Base Case, 1000 MWe).

Table 8.4. Direct Capital Cost for the Osiris Base Case Design

Account	Title		$M (1991 Dollars)	
20	**Land and Land Rights**			**11.6**
21	**Structures and Site Facilities**			**137.6**
21.1	Site Improvements and Facilities		13.8	
21.2	Reactor Building		32.9	
21.3	Turbine and Control Buildings		29.4	
21.4	Cooling System Structures		5.2	
21.5	Driver Buildings		29.2	
21.6	Miscellaneous Buildings		27.2	
	Reactor Aux. Building	4.0		
	Steam Generator Building	9.8		
	Target Fabrication Building	7.0		
	Control Room Building (w/ 21.3)			
	Admin. and Service Building	5.6		
	Hot Cell Building (w/ 21.2)			
	Misc. Structures and Bldg. Work	0.8		
22	**Reactor Plant Equipment**			**504.3**
22.1	First Wall and Vacuum Vessel		10.1	
	First Wall	0.8		
	Vacuum Vessel	9.3		
22.2	Breeding Material (Flibe)		79.8	
22.3	Vacuum System		5.0	
22.4	Target Systems		24.9	
	Production Equipment	19.9		
	Injection and Tracking	5.0		
22.5	Tritium Recovery		31.1	
22.6	Shielding (w/ 21.2)			
22.7	Heat Transport System		253.3	
	Primary Coolant Piping	27.3		
	Primary Pumps and Motors	22.5		
	Intermediate Heat Exchangers	99.9		
	Intermediate Coolant Piping	14.8		
	Intermediate Pumps and Motors	25.6		
	Intermediate Coolant Clean-up	4.2		
	Steam Generator Set	59.1		
	Remote Maintenance Equipment		100.0	

Table 8.4. Direct Capital Cost for the Osiris Base Case Design (continued)

23	**Turbine Plant Equipment**			**225.8**
23.1	Turbine-Generators		115.5	
23.2	Main Steam System (w/23.6)			
23.4	Condensing Systems		19.0	
23.5	Feed Heating System		23.1	
23.6	Other Turbine Plant Equipment		67.9	
23.7	Instrumentation and Control		0.3	
24	**Electric Plant Equipment**			**66.2**
24.1	Switch gear		12.8	
24.2	Station Service Equipment		9.3	
24.3	Switchboards		1.9	
24.4	Protective Equipment		5.0	
24.5	Electrical Structures		20.5	
24.6	Power and Control Wiring		16.7	
24.7	Electrical Lighting (w/ 21.)			
25	**Miscellaneous Plant Equipment**			**18.5**
25.1	Transportation and Lifting Equipment		6.0	
25.2	Air and Water Service Systems		8.3	
25.3	Communications Equipment		2.6	
25.4	Furnishings and Fixtures		1.6	
26	**Heat Rejection Systems**			**44.7**
27	**Heavy Ion Driver (5 MJ, 4.6 Hz)**			**587.5**
	Injector		10.0	
	Inductors		112.4	
	Metglas	71.7		
	Structure	31.2		
	Insulation	9.6		
	Pulsed Power		177.3	
	Quadrupoles		70.8	
	Cryogenics		33.0	
	Vacuum Systems		13.6	
	Compression and Final Focus		20.0	
	Special Utilities		8.7	
	Instrumentation and Control		21.9	
	Prime Power		21.9	
	Installation		97.9	
	Total Direct Cost			**1596.3**

Table 8.5 gives the total capital cost, unit capital cost, and COE for the base case design. As previously noted, the total capital cost is nearly two times the direct capital cost. The constant dollar cost of electricity is 5.61 ¢/kWh.

Table 8.5. Total Capital Cost, Unit Costs, and Cost of Electricity for Osiris Base Case Design

Total Direct Cost (M$)		**1596**
Indirect Capital Costs (M$)		
Construction Services and Equipment	192	
Home Office Engineering and Services	83	
Field Office Engineering and Services	96	
Owners Cost	295	
Project Contingency	391	
Total		**1057**
Time Related Costs (M$)		
Interest During Construction	438	
Escalation During Construction	0	
Total		**438**
Total Capital Cost (M$)		**3091**
Unit Capital Cost ($/kWe-gross)		**2743**
Unit Capital Cost ($/kWe-net)		**3091**
Constant Dollar Cost of Electricity (¢/kWh)		
Return on Capital	4.54	
Operation and Maintenance	1.00	
Fuel	0.02	
Decommissioning	0.05	
Total		**5.61**

8.4.3 Cost Scaling Relationships

The cost scaling relationships for the Osiris power plant are summarized in Table 8.6.

8.4.3.1 Balance of Plant

A rough capital cost estimate for the balance-of-plant systems and components was prepared by Bechtel. These include all structures and site facilities, steam generators and steam supply systems, turbine plant equipment, electric plant equipment (except equipment integral with the HIB), remote maintenance equipment, and miscellaneous plant equipment. The cost estimate was developed utilizing the Energy Economic Data Base[8.4] estimates for fossil-fired plants and adjusting for plant size and scoping differences. Using non-nuclear construction costs is consistent with the safety features of Osiris as discussed in Section 5. Estimates were prepared for the conceptual-designed components and structures based on past experiences where applicable and based on judgment where no previous experience existed. A specific allowance of $100 million is made for remote operated maintenance equipment. The estimates for BOP include direct labor and materials costs only. Field indirect costs for construction facilities, equipment and services, and engineering and construction management are accounted for with the indirect cost multipliers discussed above.

The scaling of the various accounts is based on the scaling given in the Nuclear Energy Cost Data Base.[8.5] Note that the driver buildings (tunnel and pulsed power building) and the target factory building are included in the Account 21 – Structures and Site Facilities.

8.4.3.2 Reactor Plant Equipment

Reactor plant equipment costs were derived from a variety of sources. The chamber and vessel costs were estimated by GA. Most of the other reactor plant equipment costs were taken from the SAFIRE Code.[8.1] The costs for primary loop piping, the IHX, and the tritium recovery system, however, were scaled from Hoffman's work[8.6] on the molten-salt cooled HYLIFE-II reactor.[8.7] The costs of the steam generator set, vacuum systems, and remote maintenance equipment were provided by Bechtel.

The first wall scales with the fusion power since we assume that the wall radius will be made large enough to last one year. The cost of the wall goes as Rw^2, which is proportional to Pt for a fixed annual fluence. The same scaling holds for the vessel wall since its location is determined by the first wall radius. The Osiris chamber design is insensitive to the yield per pulse. A higher yield simply results in more liquid Flibe being vaporized on each shot, which has to be recondensed between shots in the spray region at the bottom of the chamber. Since the fraction of energy in x rays and debris does not vary significantly with yield, the required spray flow rate is simply proportional to the chamber power.

Table 8.6. Cost Scaling Relationships for Osiris Power Plant

Account		Cost Scaling (M$ unless noted)
20	Land and Land Rights	11.6
21	Structures & Site Improvements	
21.1	Site Improvements & Facilities	$13.6\ (Pg/1100)^{0.5}$
21.2	Reactor Building	32.1 (Pg/1100)
21.3	Turbine and Controls Buildings	$29.0\ (Pg/1100)^{0.5}$
21.4	Cooling System Structure	$5.1\ (Pg/1100)^{0.5}$
21.5	Driver Building	29.2 (L/4.8)
21.6	Miscellaneous Buildings	$26.9\ (Pg/1100)^{0.5}$
22	Reactor Plant Equipment	
22.1	First Wall and Vacuum Vessel	10.1 (Pt/2500)
22.2	Breeding Material (Flibe)	79.8 (Pt/2500)
22.3	Vacuum System	5.0
22.4	Target Systems	
	Production Equipment	$24.0\ (RR/6)^{0.7}$
	Injection and Tracking	5.0
22.5	Tritium Recovery	41.0 (Pt/3300)
22.6	Shielding (w/ 21.2)	
22.7	Heat Transport System	
	Primary Coolant Piping	$27.0\ (Pt/2450)^{0.5}$
	Primary Pumps and Motors	$22.1\ (Pt/2450)^{0.74}$
	Intermediate Heat Exchanger	97.8 (Pt/2450)
	Intermediate Coolant Piping	$14.6\ (Pt/2450)^{0.5}$
	Intermediate Pumps and Motors	$25.2\ (Pt/2450)^{0.74}$
	Intermediate Coolant Clean-up	$4.0\ (Pt/2450)^{1.5}$
	Steam Generator Set	$58.0\ (Pt/2450)^{0.89}$
22.8	Remote Maintenance Equipment	100.0
23	Turbine Plant Equipment	$221.5\ (Pg/1100)^{0.8}$
24	Electrical Plant Equipment	$65.6\ (Pg/1100)^{0.4}$
25	Miscellaneous Plant Equipment	$18.4\ (Pg/1100)^{0.3}$
26	Heat Rejection Equipment	44.0 (Pt - Pg)/1350

Table 8.6. Cost Scaling Relationships for Osiris Power Plant (continued)

27	Driver Equipment	
	Injector	$10 M
	Inductors	
	Metglas	$5/kg
	Structure	$12.4 k / large core $ 3.1 k / small core
	Insulation	$1.25 k / core
	Pulsed Power	$10/J
	Quadrupoles	$35.8 k / quad array ($3 k / quad)
	Cryogenics	
	Fixed	$19 M
	Variable	$7.2 k / quad array ($600 / quad)
	Vacuum Systems	
	Roughing	$21 k / pump
	Number of pumps	116 (L/10.4)
	Cryopumps	$14 k / pump
	Number of pumps	1920 (L/10.4)
	Compression and Final Focus	$20 M
	Other Driver Costs	12% of above
	Special Utilities (2%)	
	Instrumentation and Control (5%)	
	Prime Power (5%)	
	Installation	20% of above including Other Driver Costs

The costs for the target factory are based on rough estimates of the equipment required for our baseline production approach. This approach uses microencapsulation to produce an empty CH shell, a cryogenic DT injection process, and rapid laser heating to produce a uniform DT layer. For the HIB targets, the fuel capsule is then loaded into a Ta hohlraum before being transported to the reactor building. The cost of the injection system ($5 M) is simply an allowance that we consider to be conservative for the gas gun injector and laser diode tracking system.

8.4.3.3 Driver

The driver cost modeling is largely based on cost information developed by Lawrence Berkeley Laboratory and present in Ref. 8.8. The metglas cost of $5/kg is a cost for large lot orders (>1000 tonne) quoted to LBL by Allied. Our driver design has a metglas requirement of 20,000 tonne. The cost of the quads was estimated from the amount of material (superconducting windings, copper stabilizer, steel structure), which is calculated for the quad model described in Section 2.4. The pulsed power cost of $10/J (electric energy into the pulse forming network) is somewhat lower than LBL's estimate for future commercial systems, but reasonable based on an analysis of pulsed power costs as a function of the output pulsewidth.[8.9] We have not done the design of the pulsed power system, but since pulsed power turns out to be one of the largest cost items, it warrants more detailed analysis in future studies.

8.4.3.4 Operating and Decommissioning Costs

Annual operations and maintenance costs are based on guidance given in the study guidelines.[8.2] For an LSA = 2, the annual O&M cost is $66.4 M and scales with the square root of the gross electric power. We add an annual cost of $2 M for replacing the fabric first wall and blanket.

$$OM = 66.4 \cdot \left(\frac{Pg}{1200}\right)^{0.5} + 2.0$$

Annual fuel costs include the cost of deuterium and materials to manufacture targets. They scale directly with the fusion power, which is proportional to the thermal power.

$$F = 1 \cdot \left(\frac{Pt}{2500}\right)$$

As specified in the guidelines, we have included an allowance of 0.05 ¢/kWh for decommissioning.

8.4.4 Results of Parametric Studies

In this section we examine the capital cost and cost of electricity as a function of driver energy. We also examine the effects of using more conservative and more optimistic gain curves and the effects of operating at different net electric power levels. In most cases, the driver energy is quoted to the nearest 0.5 MJ.

8.4.4.1 Direct Capital Cost vs. Driver Energy

Figure 8.12 shows the direct capital cost of the reactor (Accounts 20-26) and driver, as a function of the driver energy for a fixed net electric power of 1000 MWe. As the driver energy increases,

- target gain and yield increase,
- pulse rep-rate decreases,
- driver power decreases, and
- thermal power decreases.

As a result, the reactor costs decrease with increasing driver energy while the driver cost increases. The minimum direct capital cost is \$1.46 B at a driver energy of ~2 MJ. The TDC of the reference plant design with a 5 MJ driver is ~10% higher at \$1.60 B.

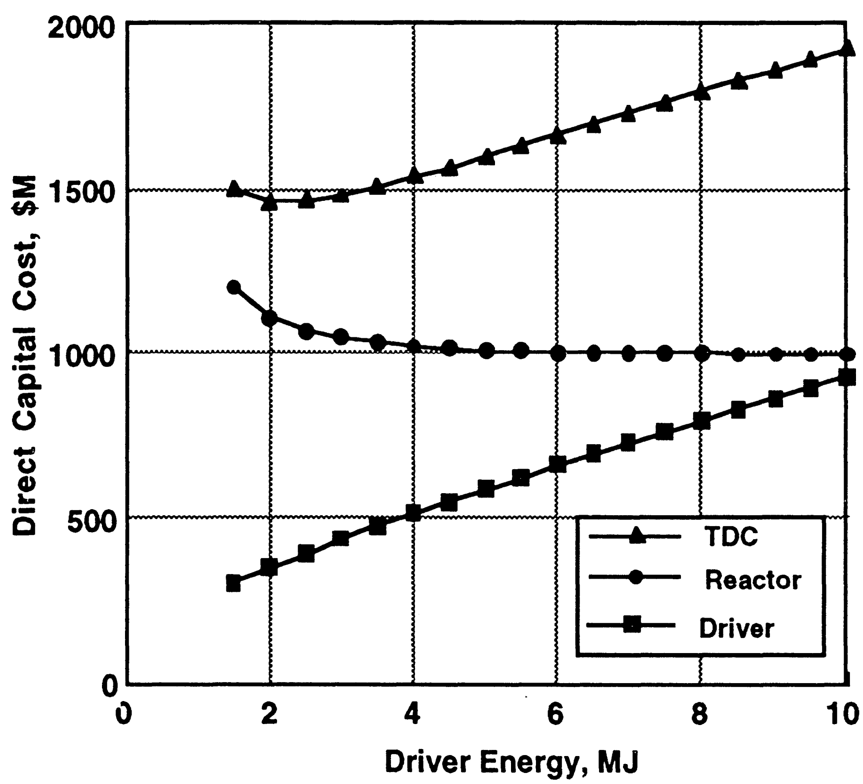

Fig. 8.12. Total direct cost (TDC) vs. driver energy for the Osiris power plant.

8.4.4.2 COE as a Function of Driver Energy

The COE as a function of driver energy is shown in Fig. 8.13. The shape of this curve is essentially the same as the direct capital cost curve. The minimum COE is 5.27 ¢/kWh, and it occurs at a driver energy of 2.5 MJ. The rep-rate at E = 2.5 MJ is 16 Hz, which is probably too high for operation of the Osiris chamber. Increasing the driver energy to 3.5 MJ reduces the rep-rate to a manageable 8.6 Hz. The COE at this point is 5.37 ¢/kWh, only 2% higher than the minimum COE. The COE of the reference point design at E = 5 MJ is 5.61 ¢/kWh, less than 5% higher than the minimum COE and 3% higher than the 3.5 MJ case.

Our original choice of a 5 MJ driver results in a COE that is about 5% higher than the minimum COE and about 3% higher than the practical minimum when we consider the rep-rate limits on the chamber. If we were to select a new point design at this time, we would lower the driver energy to 3.5 or 4 MJ to get a small reduction in COE without significantly increasing the pulse rep-rate. Table 8.7 compare the original point design with the results at 3.5 MJ.

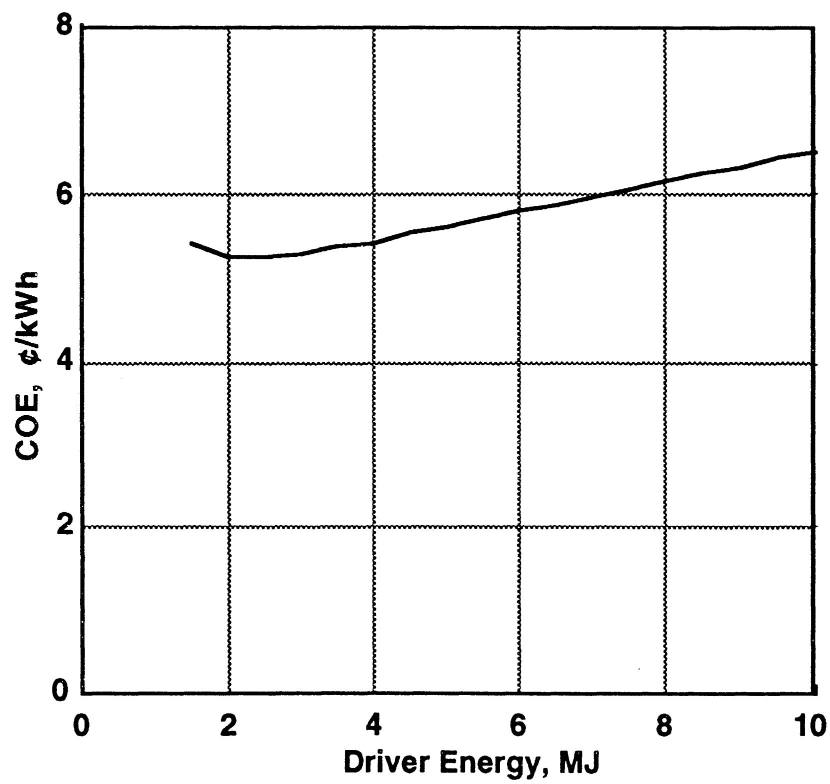

Fig. 8.13. COE for 1000 MWe Osiris power plant.

Table 8.7. Key Parameters for Two Osiris Designs

	Original Point Design	Lower COE Design
Driver Energy (MJ)	5.0	3.5
Gain	86.5	68
Rep-rate (Hz)	4.6	8.6
Gross Electric Power (MWe)	1127	1157
Driver Power (MWe)	82	110
Driver Direct Cost ($M)	587	475
Total Direct Cost ($M)	1596	1506
COE (¢/kWh)	5.61	5.37

8.4.4.3 COE with Different Target Gain Assumptions

Figure 8.14 shows the effect of increasing and decreasing the target gain. For the optimistic case, the base case gain is increased by a factor of 2. For the conservative case, the base case gain is multiplied by 0.7. Decreasing the base case gain curve by 30% shifts the point of minimum COE to E = 3.0 MJ. The rep-rate at this point (17 Hz), however, is too high. At E = 4.5 MJ the rep-rate is down to 8.2 Hz, and the COE is 5.64 ¢/kWh, or about 5% higher than the 5.37 ¢/kWh obtained with the base case gain curve. According to the revised target information supplied by the Oversight Committee,[8.3] the optimistic gain curve is only valid for yields greater than 400 MJ. Therefore, points below ~3.2 MJ on the optimistic curve are not valid. The COE at E = 3.2 MJ is 5.15 ¢/kWh, which is about 4% less than with the base case gain curve. The pulse rep-rate at E = 3.2 MJ is 4.7 Hz.

We see from Fig. 8.14 that the COE is not very sensitive to the target gain assumptions, at least over the range considered. The driver recirculating power fraction is less than 25% even with the conservative gain curve all the way down to 2 MJ. For the HIB driven system, higher driver energies (i.e., greater than 2 MJ) are needed to get higher yield per pulse so that the rep-rate can be low enough to reestablish the Osiris chamber conditions between pulses.

8.4.4.4 COE for Different Net Electric Powers

Finally, we examine the effect on the COE if the net power is increased or decreased by 50%. Figure 8.15 shows the effects of these changes. The penalty for operating at 500 MWe is significant. At 2.5 MJ, the rep-rate is 8.0 Hz, and the COE is 7.69 ¢/kWh, or 43% higher than with the base case gain curve. While the penalty for going to 500 MWe is significant, the resulting COE is in the range of results previously reported for 1000 MWe plants.[8.7,8.10] At 1500 MWe, we would operate at E = 4.5 MJ to give a rep-rate of 8.3 Hz. The COE at this point is 4.48 ¢/kWh, or 17% lower than the 5.37 ¢/kWh obtained at 1000 MWe. Both of these curves were generated using the base case gain curve.

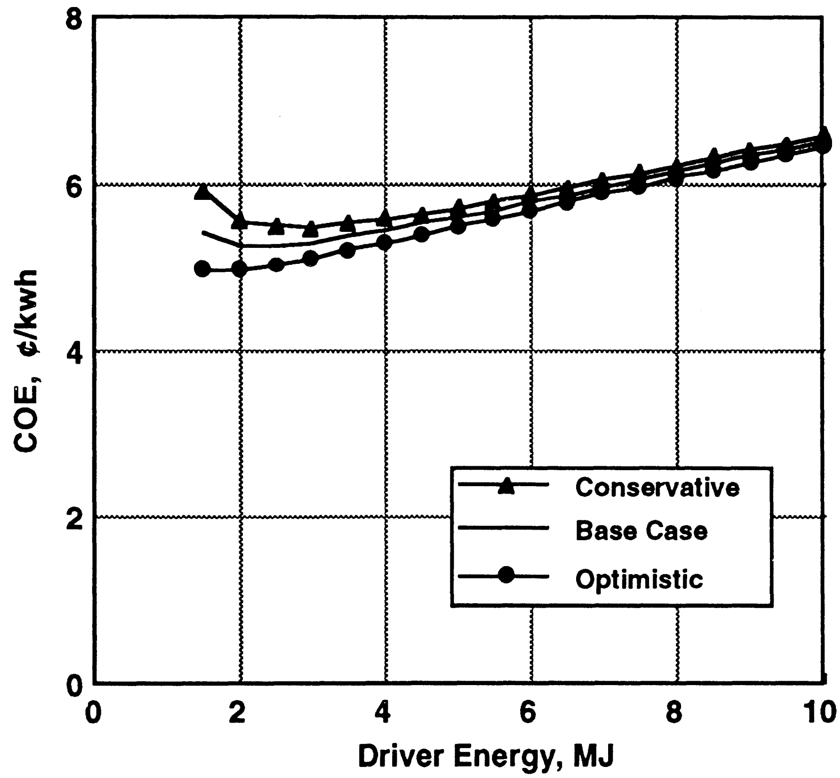

Fig. 8.14. COE for 1000 MWe Osiris power plant with different target gain assumptions. The different gain curves are shown in Fig. 8.1.

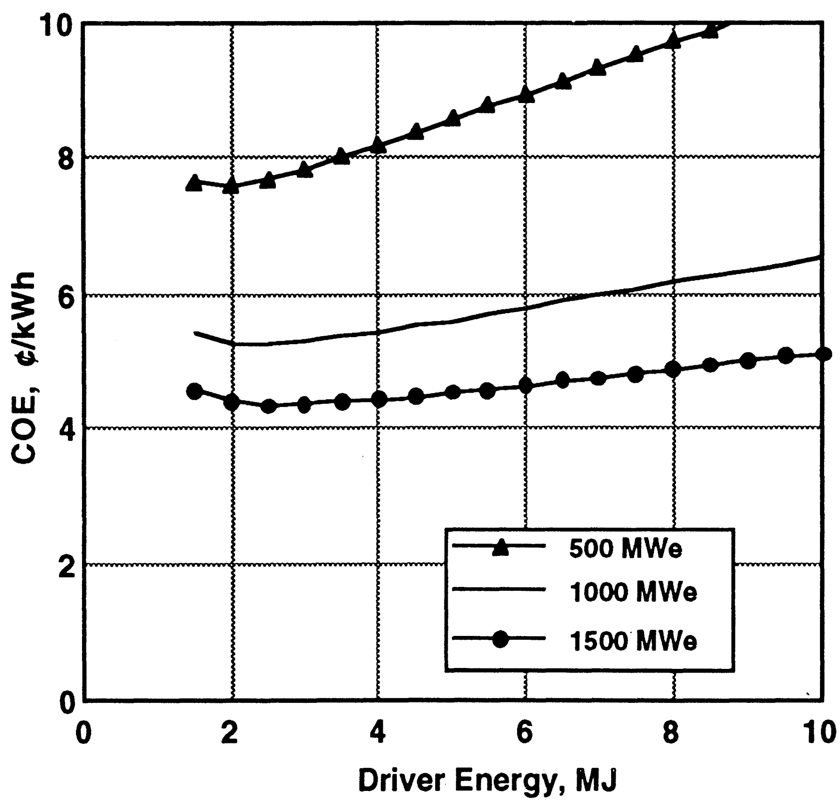

Fig. 8.15. COE for 500, 1000, and 1500 MWe Osiris power plants.

8.5 COST MODELING FOR SOMBRERO

8.5.1 Introduction

Direct capital costs and cost scaling relationships have been developed for the KrF laser, the SOMBRERO reactor, balance of plant systems, and the target systems. The costs are given in 1991 dollars and represent costs for a fully commercial system. As with Osiris, we have not applied any explicit learning curve savings in the cost estimates.

8.5.2 Direct Capital Cost for the Reference Design

Table 8.8 gives the base case direct capital cost for the SOMBRERO power plant. As with Osiris, this base case design is not the minimum COE design. Lower capital cost can be achieved by lowering the driver energy. The basis for these costs and cost scaling relationships is discussed in the next section. Figure 8.16 shows the breakdown of the total direct capital cost for the reference design. The total direct cost is ~$1.9 B with the Reactor Plant Equipment and Driver Equipment making up the largest portions. Figure 8.17 shows the components that contribute to the Reactor Plant Equipment. This account is dominated by the Heat Transfer Equipment, but the breeder and remote maintenance are also be large cost items. Figure 8.18 shows the major components of the KrF laser cost. Here we see that pulsed power and the flow systems are the major cost items.

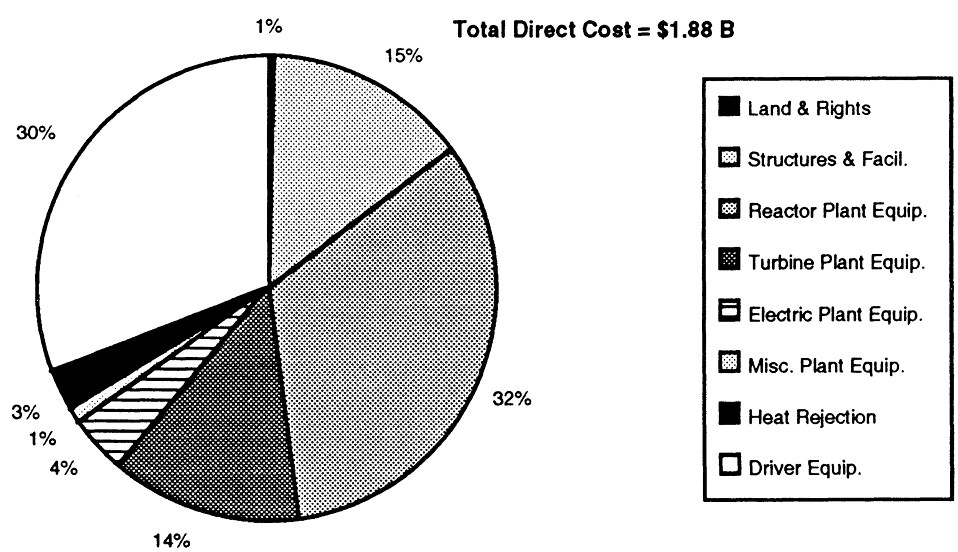

Fig. 8.16. Breakdown of total direct cost for the SOMBRERO power plant (Base Case, 1000 MWe).

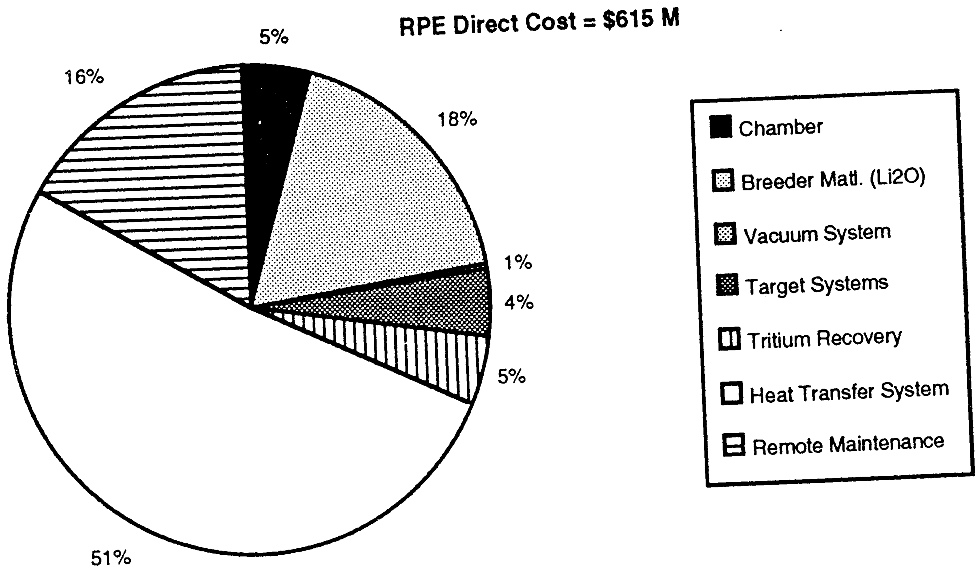

Fig. 8.17. Breakdown of Account 22 - Reactor Plant Equipment Direct Cost (SOMBRERO Base Case, 1000 MWe).

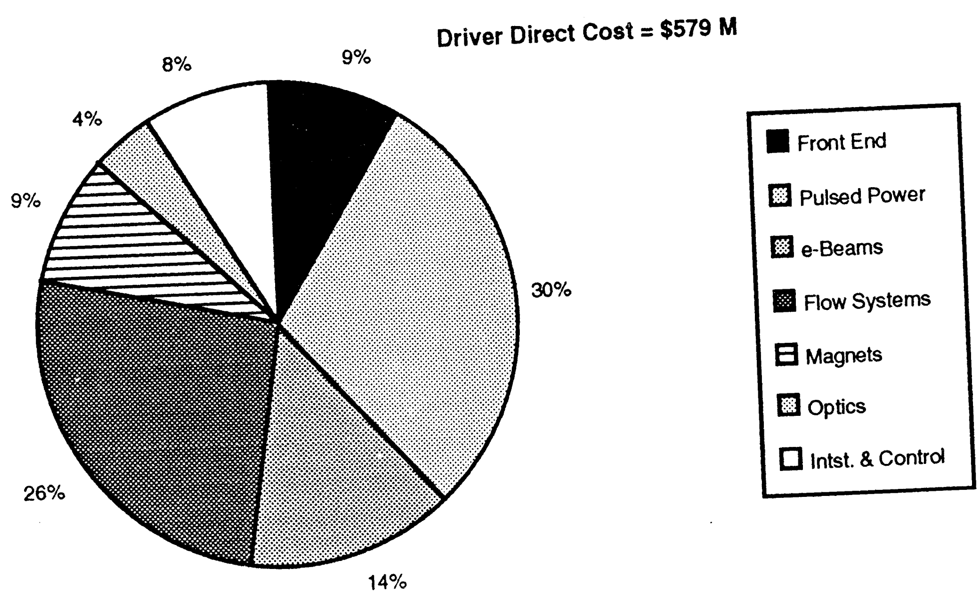

Fig. 8.18. Breakdown of Account 27 - Driver Equipment Direct Cost (SOMBRERO Base Case, 3.4 MJ).

Table 8.8. Direct Capital Cost for the SOMBRERO Base Case Design

Account	Title		$M (1991 Dollars)	
20.	**Land and Land Rights**			**10.5**
21.	**Structures and Site Facilities**			**276.1**
21.1	Site Improvements and Facilities		14.9	
21.2	Reactor Building		143.8	
21.3	Turbine Building		31.8	
21.4	Cooling System Structures		6.1	
21.5	Laser and Power Supply Buildings		31.3	
21.6	Miscellaneous Buildings		48.2	
	Reactor Aux. Building	4.6		
	Steam Generator Building	10.5		
	Target Fabrication Building	6.9		
	Control Room Building (w/ 21.3)			
	Admin. and Service Building	6.1		
	Hot Cell Building	19.2		
	Misc. Structure and Bldg. Work	0.9		
21.7	Ventilation Stack		0.0	
22.	**Reactor Plant Equipment**			**615.5**
22.1	First Wall and Vacuum Vessel		30.2	
	First Wall	9.0		
	Vacuum Vessel	21.2		
22.2	Breeding Material (Li2O)		108.4	
22.3	Vacuum System		5.0	
22.4	Target Systems (6.7 Hz)		26.6	
	Production Equipment	21.6		
	Injection and Tracking	5.0		
22.5	Tritium Recovery		28.0	
22.6	Shielding (w/ 21.2)			
22.7	Heat Transport System		317.3	
	Primary Coolant Piping	29.2		
	Primary Coolant Circulators	6.5		
	Intermediate Heat Exchangers	167.1		
	Intermediate Coolant Piping	15.9		
	Intermediate Pumps and Motors	28.4		
	Intermediate Coolant Clean-up	5.2		
	Steam Generator Set	65.0		
	Remote Maintenance Equipment		100.0	

Table 8.8. Direct Capital Cost for the SOMBRERO Base Case Design (continued)

23.	**Turbine Plant Equipment**			**256.3**
23.1	Turbine-Generators		131.2	
23.2	Main Steam System (w/23.6)			
23.4	Condensing Systems		21.5	
23.5	Feed Heating System		26.2	
23.6	Other Turbine Plant Equipment		77.1	
23.7	Intrumentation and Control		0.3	
24.	**Electric Plant Equipment**			**70.0**
24.1	Switchgear		13.6	
24.2	Station Service Equipment		9.8	
24.3	Switchboards		2.1	
24.4	Protective Equipment		5.3	
24.5	Electrical Structures		21.6	
24.6	Power and Control Wiring		17.6	
24.7	Electrical Lighting (w/ 21.)			
25.	**Miscellaneous Plant Equipment**			**19.9**
25.1	Transportation and Lifting Equipment		7.0	
25.2	Air and Water Service Systems		8.6	
25.3	Communications Equipment		2.7	
25.4	Furnishings and Fixtures		1.6	
26	**Heat Rejection Systems**			**52.0**
27	**KrF Laser (3.4 MJ, 60 beams)**			**579.1**
	Front End		52.6	
	Pulsed Power		170.5	
	DC Power	27.4		
	Modulator	24.6		
	Pulse Transformer	41.0		
	Cables	28.7		
	Switch	48.8		
	e-Beams		81.7	
	Bushing	6.5		
	Diode Box & Pumps	14.7		
	Cathode Surround	47.1		
	Foil Support	3.2		
	Foil Cooling	7.6		
	Foils	2.7		
	Flow Systems		151.3	
	Magnets		50.1	
	Optics		23.8	
	Mirrors	12.5		
	Transmissive	3.7		
	Gracing Incidence	7.7		
	Controls		49.0	
	Total Direct Cost			**1879.4**

Table 8.9 gives the total capital cost, unit capital costs and COE for the base case design. As previously noted, the total capital cost is nearly two times the direct capital cost. The constant dollar cost of electricity is 6.67 ¢/kWh.

Table 8.9. Total Capital Cost, Unit Cost, and Cost of Electricity for the SOMBRERO Base Case Design

Total Direct Cost ($M)		**1879**
Indirect Capital Costs ($M)		
Construction Services and Equipment	225	
Home Office Engineering and Services	98	
Field Office Engineering and Services	113	
Owners Cost	347	
Project Contingency	461	
Total		**1244**
Time Related Costs ($M)		
Interest During Construction	516	
Escalation During Construction	0	
Total		**516**
Total Capital Cost ($M)		**3639**
Unit Capital Cost ($/kWe-gross)		**2678**
Unit Capital Cost ($/kWe-net)		**3639**
Constant Dollar Cost of Electricity (¢/kWh)		
Return on Capital	5.35	
Operation and Maintenance	1.25	
Fuel	0.02	
Decommissioning	0.05	
Total		**6.67**

8.5.3 Cost Scaling Relationships

The cost scaling relationships for the SOMBRERO power plant are given in Table 8.10.

8.5.3.1 Balance of Plant

The balance of plant costs were done by Bechtel using the same assumptions and resources as for Osiris.[8.4] Bechtel used non-nuclear (i.e., coal-fired power plant) data base for their cost estimates. This is consistent with the safety feature of SOMBRERO as discussed in Section 5. The scaling of the various accounts is based on the scaling given in the Nuclear Energy Cost Data Base. Note that the laser buildings and the target factory building are included in the Account 21, Structures and Site Facilities.

8.5.3.2 Reactor Plant Equipment

Reactor plant equipment costs were derived from a variety of sources. The chamber cost, cost of piping, and helium recirculator in the primary coolant loop were estimated by GA. Intermediate loop pumps, piping, and clean-up systems were scaled in the same way as for Osiris. The core mass of SOMBRERO's four IHXs is about 50% greater than the total core mass in the two Osiris IHXs; therefore, the cost/kWt is increased by a factor of 1.5. The tritium recovery system cost is scaled from the Cascade reactor study.[8.5]

The first wall radius (Rw) of SOMBRERO was set large enough to avoid vaporization by x-rays and debris. By scaling Rw with the square root of the yield per pulse, the J/cm^2 is kept constant. The first wall radius is also constrained by heat transfer considerations through the first wall (i.e., a limit on W/cm^2 that can be handled). We assume that the reference case design with a radius of 6.5 m for a fusion power of 2680 MW is near the heat transfer limit. The mass of graphite structure in the SOMBRERO first wall and blanket is then found as a function of Rw as shown in Table 8.10. The total mass of Li_2O breeder is three times the mass of breeder in the breeding blanket.

The target production equipment is the same as for Osiris except the fuel capsules do not have to be loaded into hohlraums. The cost of target production for Osiris is 20% higher to account for the manufacture and loading into Ta hohlraums. The cost of the injection and tracking systems is the same as for Osiris.

Table 8.10. Cost Scaling Relationships for SOMBRERO Power Plant

Component		Cost Scaling ($M unless noted)
20	Land and Land Rights	10.5
21	Structures and Site Improvements	
21.1	Site Improvements and Facilities	$17.0\ (Pg/1360)^{0.5}$
21.2	Reactor Building	$143.8\ (Pg/1360)$
21.3	Turbine & Controls Building	$31.8\ (Pg/1360)^{0.5}$
21.4	Cooling System Structure	$6.1\ (Pg/1360)^{0.5}$
21.5	Driver Building	$32.2\ (E/3.6)^{0.5}$
21.6	Miscellaneous Buildings	$48.2\ (Pg/1360)^{0.5}$
22	Reactor Plant Equipment	
22.1	First Wall & Vessel	$27.3\ (3Rw^2 + 3Rw + 1)/147$
22.2	Breeding Material (Li_2O)	
	Chamber	$30.0\ (3Rw^2 + 3Rw + 1)/147$
	Flow loops	$60.0\ (Pt/2900)$
22.3	Vacuum System	5.0
22.4	Target Systems	
	Delivery, Tracking, Alignment	5.0
	Target Factory Equipment	$20.0\ (RR/6)^{0.7}$
22.5	Tritium Recovery	$28.0\ (Pt/2900)$
22.6	Shielding (Included in 21.2)	
22.7	Heat Transport System	
	IHX	$166.6\ (Pt/2900)$
	Primary Coolant Piping	$29.2\ (Pt/2900)^{0.5}$
	Primary Coolant Circulators	$6.5\ (Pt/2900)^{0.74}$
	Secondary Coolant Piping	$15.9\ (Pt/2900)^{0.5}$
	Secondary Pumps and Motors	$28.4\ (Pt/2900)^{0.74}$
	Secondary Loop Clean-up	$5.2\ (Pt/2900)^{1.5}$
	Steam Generator Set	$65.0\ (Pt/2900)^{0.89}$
22.8	Remote Maintenance Equip.	100.0
23	Turbine Plant Equipment	$256.3\ (Pg/1360)^{0.8}$
24	Electrical Plant Equipment	$70.0\ (Pg/1360)^{0.4}$
25	Miscellaneous Plant Equipment	$19.9\ (Pg/1360)^{0.3}$
26	Heat Rejection Equipment	$52.0\ (Pt - Pg)/1540$

Table 8.10. Cost Scaling Relationships for SOMBRERO Power Plant (continued)

27	Driver Equipment (KrF Laser)	**($K unless noted)**
	Pulsed Power (per e-Beam)	
	DC Power Supply	245 (Es/365) (RR/6.7)
	Modulator	219 (Es/365)
	Pulsed Transformer	365 (Es/365)
	Cables	256 (Es/365)
	Switch	$300 + 113\ (\mathrm{Acat}/2)^{1.5}$
	e-Beams (per e-beam)	
	Bushing	56 (Acat/2)
	Diode B & Pumps	$16\ (\mathrm{Acat}/2) + 113\ (\mathrm{Acat}/2)^{1.5}$
	Cathode Surround	200 + 200 (Acat/2)
	Foil Support	28 (Acat/2)
	Foil Coiling	$69\ (\mathrm{Es}/365)\ (\mathrm{RR}/6.7)\ (\mathrm{Acat}/2)^{0.5}$
	Foils	23 (Acat/2)
	Flow System (per amp)	$2640\ (\mathrm{Eamp}/60)^{0.8}$
	Magnets (per amp)	3600 (Bself/7.5) (Acoil/8)
	Optics	
	Mirrors	
	Cost, k$/$m^2$	$11.0 + 7.2\ [(E/3.6)\ (5/F)]^{0.5}$
	Area, m^2	734 (E/3.6) (5/F) (Nm/8)
	Transmissive Optics	
	Cost, k$/$m^2$	$10.2 + 33.2\ [(E/3.6)\ (5/F)]^{0.5}$
	Area, m^2	91.7 (E/3.6) (5/F) (Nt/1)
	Grazing Incidence Mirrors	
	Cost, k$/$m^2$	$11.0 + 19.1\ (E/3.6)^{0.5}$
	Area, m^2	276 (E/3.6) (Nb/60)
	Controls	49,000
	Front End	10% of all the above

Note: There are 2 e-beams per amplifier

Es = Energy stored per e-beam, kJ
RR = Rep-rate, Hz
Acat = Cathode area, m^2
Eamp = Energy per final amplifier, kJ
Bself = Self magnetic field, kG
Acoil = Magnetic field-coil area (per coil), m^2
E = Total driver energy, MJ
F = Optical fluence, J/cm^2
Nm = Number of mirrors per beam
Nt = Number of transmissive optics per beam
Nb = Number of beam lines

8.5.3.3 KrF Laser

The cost estimates and scaling algorithms for the KrF laser are given in Table 8.10. The reference point from which the costs are scaled is a laser that delivers 3.6 MJ on target. This is slightly higher than the 3.4 MJ we used as our reference point design for the SOMBRERO power plant. To scale the design to the lower energy, the volume of the final amplifiers would be reduced in proportion to the laser energy (i.e., by 5.6%). The cost scaling relationships were developed by Textron and are given in thousands of dollars. The following categories are used for costing:

1) Pulse Power
2) e-Beams
3) Flow Loop
4) Magnets
5) Optics
6) Instrumentation & Controls
7) Front End.

Pulse Power

As indicated in Table 8.10, pulse power is subdivided by the following categories which correspond to the sequential flow of energy through the system: D.C. supply, modulator, pulse transformer, cables, and switch. In these equations, Es is the energy stored per e-beam (kJ), RR is the rep-rate (Hz), and Acat is the cathode area (m^2). There are two e-beams per amplifier, and the energy stored per e-beam (kJ) is calculated from

$$Es = \frac{E_{Amp}}{\eta_{LS}} \cdot \frac{\eta_{wps}}{2 \text{ e-beams/Amp}}$$

where

E_{Amp} = energy on target per amplifier, kJ,
η_{LS} = laser system efficiency, and
η_{wps} = wall plug to stored energy efficiency.

For the 3.6 MJ design that was used as the reference point for costing,

E_{Amp} = 60 kJ,
η_{LS} = 7.4%, and
η_{wps} = 90%,

which gives a stored energy of 365 kJ per e-beam.

The cathode area per e-beam (m^2) is

$$Acat = L \cdot H$$

where

L = cavity pumped length in optical direction, m, and
H = cavity height in the flow direction, m.

The 3.6 MJ design has L = 1.0 and H = 2.0, which give Acat = 2 m^2. These dimensions scale as the cube root of the amplifier energy.

$$L = 1.0 \cdot \left[\frac{E_{Amp}}{60}\right]^{\frac{1}{3}}$$

$$H = 2.0 \cdot \left[\frac{E_{Amp}}{60}\right]^{\frac{1}{3}}$$

The width of the cavity, W, is 1.0 m for the reference design and also scales as the cube root of E_{Amp}. Therefore, the volume of the cavity is proportional to the laser energy as previously stated.

For 60 cavities at 60 kJ per cavity (3.6 MJ total), the pulse power cost is $1.48 M per e-beam or about $4 per stored joule ($3.6 per joule input to pulse power system).

e-Beam

The e-beam system is subdivided by the following categories, which correspond to the sequential flow of energy from the pulse power, via the e-beam system, to the laser gas: bushing, diode box and pumps, cathode and surround, foil support "hibachi", foil cooling, and foils. The total direct cost per e-beam for the 3.6 MJ design is $0.7 M.

For the e-beam voltage (kV) we use:

$$V_{eB} = \left[\frac{P_{atm} \cdot W}{8.8 \cdot 10^{-4} \cdot (1+\psi_{Ar})}\right]^{\frac{4}{7}}$$

where

P_{atm} = laser gas mixture pressure, atmospheres
ψ_{Ar} = fraction of argon in Ar + Kr of the mixture.

Flow Loop

Flow cost was calculated for relevant point designs using a Textron code for high average power excimer lasers from which a scaling algorithm was generated. As indicated in Table 8.10, the cost per laser amplifier cavity scales as the amplifier energy raised to the 0.8 power.

Magnets

The magnet cost given in Table 8.10 is the cost per amplifier for two cryogenic coils and associated power supply. The cost is proportional to the self field and area of the coil. The self field (kGauss) is calculated from

$$B_{self} = \frac{2\pi}{100} \cdot \frac{J_c \cdot H \cdot L}{(H + L)}$$

where J_c is the cathode current density (A/cm^2) and is given by

$$J_c = \frac{100 \cdot Es \cdot \eta_{wps}}{L \cdot H \cdot V_{eB} \cdot \tau_p}$$

with L and H in meters, V_{eB} in kV, and the pulse time (τ_p) in μsec. The coil dimensions are twice the cathode dimensions, therefore, the coil area (A_{Coil}) equals 2H·2L. We assumed NbTi superconductor at 6.2 K, superconductor costs of $100/kg, and copper stabilizer at $20/kg.

Optics

The cost of optics (excluding grazing incidence mirrors) is

$$C_o = \left[U_M \cdot N_M + U_T \cdot N_T\right] \cdot A_o$$

where

U_M	=	unit cost of mirrors, k$/m^2,
N_M	=	number of mirror stages from ultimate amplifiers to target,
U_T	=	unit cost of transmissive optics, k$/m^2,
N_T	=	number of transmissive optics in route, and
A_o	=	total optics area, m^2.

For the reference design, N_M is 8, and N_T is 2. The total area of optics per stage (m^2) is

$$A_o = \frac{E}{F} \cdot \frac{4}{\pi} \cdot 10^2$$

where

E = energy on target, MJ, and

F = design average fluence per pulse, J/cm^2.

For the reference design, F = 5 J/cm^2. The $4/\pi$ factor allows a cushion in the cost by assuming that one may need to pay for an enclosing round optic for square shapes. Rectangular shapes (H/W = 2) may be paired in cutting from a round blank.

For optics cost we mainly examined the LMF cost algorithms and the BDM study done for Los Alamos.[8.10] In Figure 8.19 we show a summary graph of the BDM results for 95 cm round plane mirrors, when done in a 900 unit order. The mirrors are coated for 248 nm, figured to $\lambda/10$ with 20 Angstrom RMS roughness.

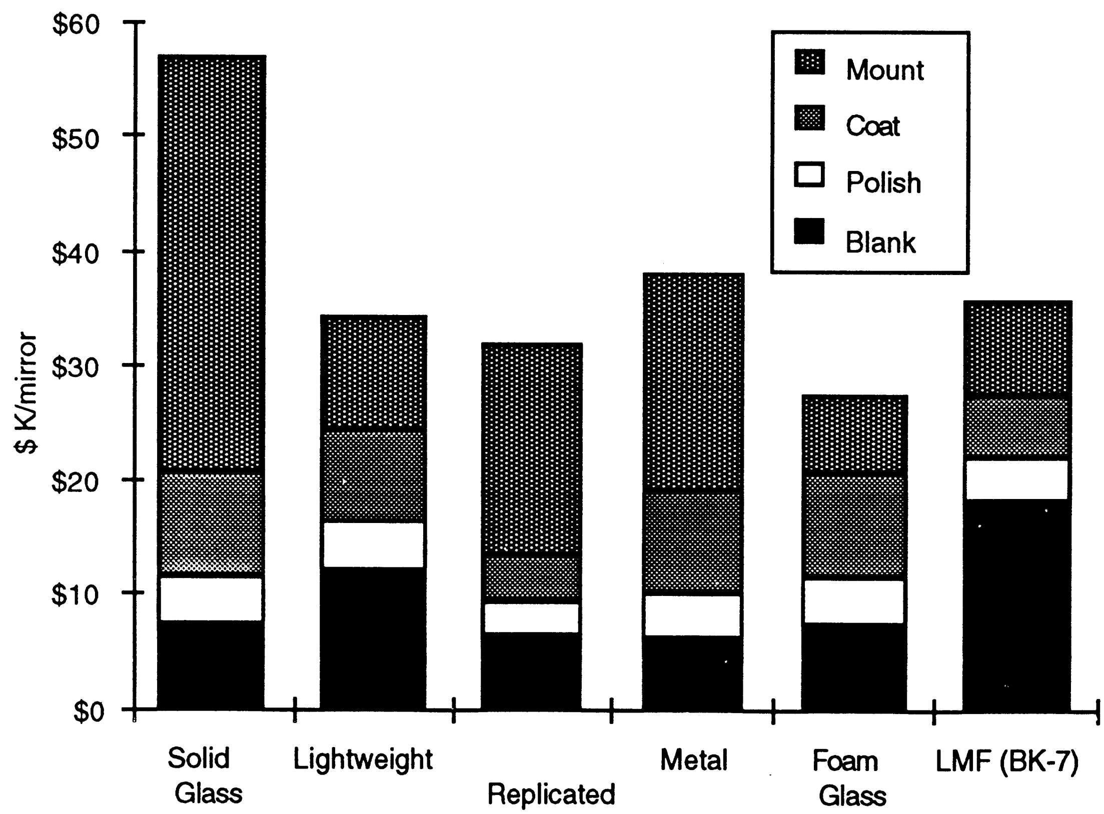

Fig. 8.19. Optics cost comparison for 900 coated 248 nm mirrors, $\lambda/10$ figure, and 20 A finish (information from Ref. 8.10).

The unit costs equations given in Table 8.10 were derived from

$$U_M = 11.0 + 0.47 \cdot \sqrt{\frac{\pi}{4}} \cdot d$$

$$U_T = 10.2 + 2.16 \cdot \sqrt{\frac{\pi}{4}} \cdot d$$

where d is the mirror or transmissive optic diagonal dimension in cm, and U_M and U_T are in $k/m^2. The diagonal dimension is given by

$$d = \sqrt{\left[\frac{H}{W} + \frac{W}{H}\right] \cdot \frac{E \cdot 10^6}{F \cdot N_A \cdot N_B}}$$

where N_A is the number of amplifier cavities (e.g., 60 at 60 kJ each), and N_B is the number of beamlets per amplifier (600 ns / 6 ns = 100). In our design, we fixed H/W = 2, N_A = 60, and N_B = 100. This gives d = 17.3 cm for E = 3.6 MJ and F = 5 J/cm^2.

The cost scaling for the grazing incidence metal mirrors (GIMMs) is the same as for the mirrors with an appropriate adjustment for the diagonal dimension. It is assumed that the GIMM is made up of 100 individual segments instead of a single large optic. Thus the characteristic dimensions of about 10 by 46 cm are not unreasonably large. Each GIMM has an optical area of 4.6 m^2, giving a total area of 783 m^2 for the 60 beam directions.

Instrumentation and Controls

With reference to the description in Section 4.6, the cost for the KrF driver system instrumentation and controls is estimated at ~$49 M, or $13.60 per joule on target.

8.5.3.4 Operating and Decommissioning Costs

Annual operations and maintenance costs are the same as for Osiris except the annual blanket replacement cost is higher. We allow twice (to account for labor) the original cost every five years, or about $11M/yr.

$$OM = 66.4 \cdot \left(\frac{Pg}{1200}\right)^{0.5} + 11.0$$

The annual fuel cost scales the same as for Osiris

$$F = 1 \cdot \left(\frac{Pt}{2500}\right)$$

As specified in the guidelines, we have included an allowance of 0.05 ¢/kWh for decommissioning.

8.5.4 Results of Parametric Studies

8.5.4.1 Direct Capital Cost vs. Driver Energy

Figure 8.20 shows the direct capital cost of the reactor (Accounts 20-26) and driver, as a function of the driver energy for a fixed net electric power of 1000 MWe. As indicated, the reactor cost decreases with increasing driver energy, while the driver cost increases. The minimum direct capital cost is $1.79 B at a driver energy of ~2 MJ. The TDC of the reference plant design with a 3.4 MJ driver is 5% higher at $1.88 B.

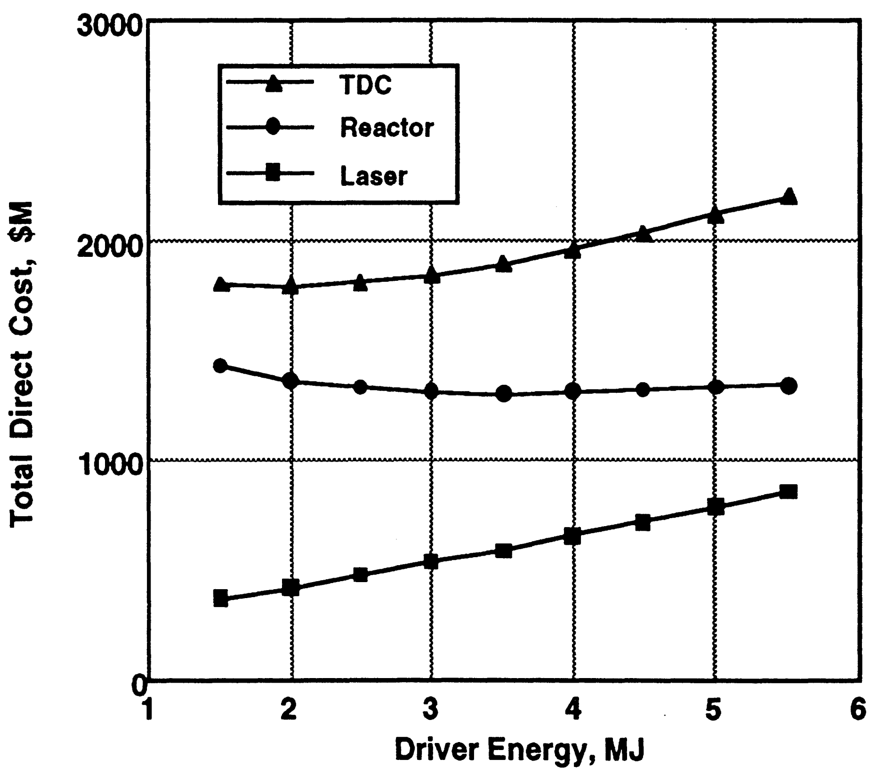

Fig. 8.20. Total direct capital cost vs. driver energy for the SOMBRERO power plant.

8.5.4.2 COE as a Function of Driver Energy

The COE as a function driver energy is shown in Fig. 8.21. The minimum COE is 6.45 ¢/kWh, and it occurs at a driver energy of 2.0 MJ. The rep-rate at E = 2 MJ is 15 Hz. We believe that the SOMBRERO chamber conditions could be reestablished at this frequency, although operating at this rep-rate puts additional stress on the target injection and tracking system.

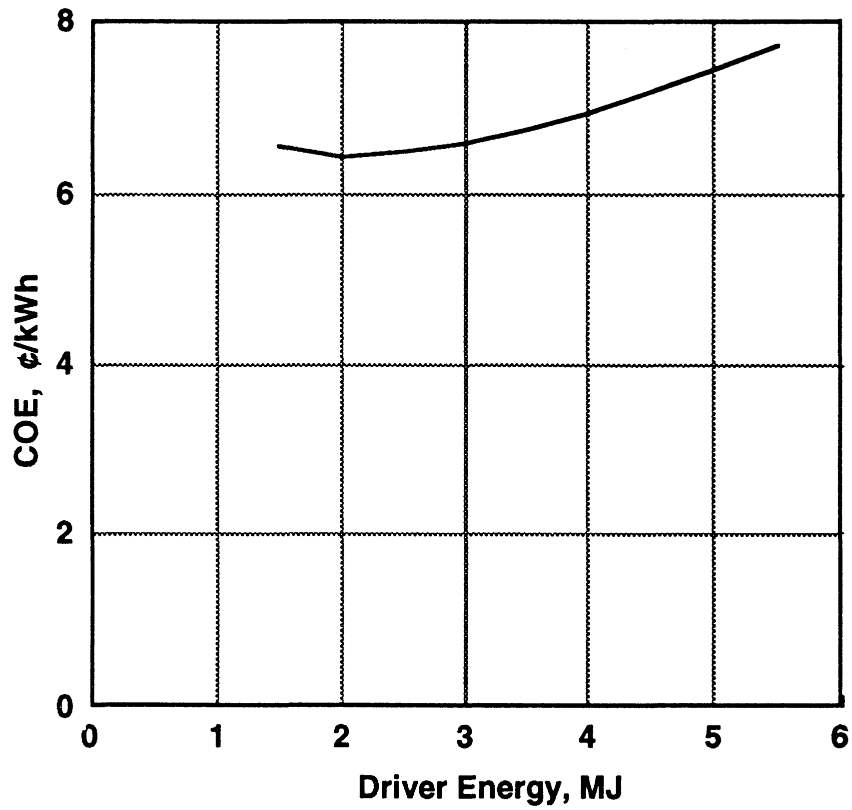

Fig. 8.21. COE for 1000 MWe SOMBRERO power plant.

The COE of the reference point design at E = 3.4 MJ is 6.67 ¢/kWh, about 3% higher than the minimum COE. Table 8.11 compares the original point design with the results at 2.0 MJ. It is interesting to note that lower COE design has a higher recirculating power fraction than the original design. The product of driver efficiency and target gain (ηG) is often used as a measure of attractiveness for IFE systems. This can be a misleading figure of merit, as we see in this example, where the lower COE design has an ηG of 7.4 compared to 8.9 for the reference point design. This occurs because the target gain curves used in this study do not fall off dramatically at low driver energy, while the cost of the laser scales strongly with energy in this range of energies. Therefore, the benefit of higher gain does not offset the cost of a larger driver.

Table 8.11. Comparison of Two SOMBRERO Design Points

	Original Point Design	Lower COE Design
Driver Energy (MJ)	3.5	2.0
Gain	118	93.9
Rep-rate (Hz)	6.7	15.1
Gross Electric (MWe)	1360	1440
Driver Power (MWe)	304	382
Driver Direct Cost ($M)	579	420
Total Direct Cost ($M)	1879	1785
COE (¢/kWh)	6.67	6.45

8.5.4.3 COE with Different Target Gain Assumptions

Figure 8.22 shows the effect of using more conservative and more optimistic target gain curves, which were supplied by DOE with the study guidelines.[8.2] The base case gain curve is the average of the optimistic and conservative curves. Using the conservative gain curve increases the COE by 15% (to 7.44 ¢/kWh) and shifts the point of minimum COE to E = 3.5 MJ. Using the optimistic gain curve lowers the COE by 7% (to 5.98 ¢/kWh) and shifts the optimum driver energy to 2 MJ.

The direct drive laser gain can be improved if the spot size of the beams at the target is zoomed to a smaller size as the pellet implodes. We examined the effect of using the gain curves with zooming. As with the curves without zooming, we have three curves with zooming: conservative (G_{cz}), base (G_{bz}), and optimistic (G_{oz}). At a fixed energy, G_{bz} is about 20 - 30% higher than G_b, the base case target gain without zooming (e.g., G_{bz} = 142 compared to G_b = 118 at E = 3.4 MJ). The minimum COE with G_{bz} is 6.00 ¢/kWh (E = 1.5 MJ, RR = 15.6 Hz, G = 113) or 7% lower than the 6.45 ¢/kWh achieved with the base case curve without zooming and about the same as the 5.98 ¢/kWh obtained with the optimistic curve without zooming. Using the highest curve of all, the optimistic curve with zooming G_{oz}, gives a COE of 5.65 ¢/kWh, or 6% lower than the optimistic curve without zooming. From these results, it does not appear that there is great incentive for zooming the laser spot size as the target implodes.

8.5.4.4 COE for Different Net Electric Powers

We also examined the effect on the COE if the net power is increased or decreased by 50%. Figure 8.23 shows the effects of these changes. (Both of these curves were generated using the base case gain curve.) At 500 MWe, the minimum COE is 8.88 ¢/kWh (E = 1.5 MJ, and RR = 12.4 Hz). This is about 38% higher the 1000 MWe case. At 1500 MWe, the minimum COE is 5.49 ¢/kWh (E = 2.5 MJ, RR = 15.9 Hz), which is 15% less than the 1000 MWe case.

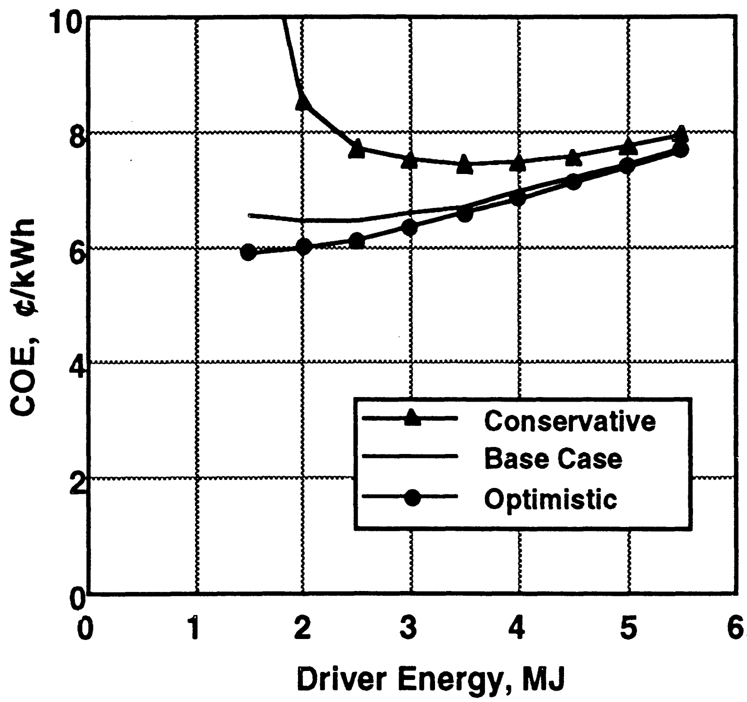

Fig. 8.22. COE for 1000 MWe SOMBRERO power plant with different target gain assumptions. The different gain curves are shown in Fig. 8.2.

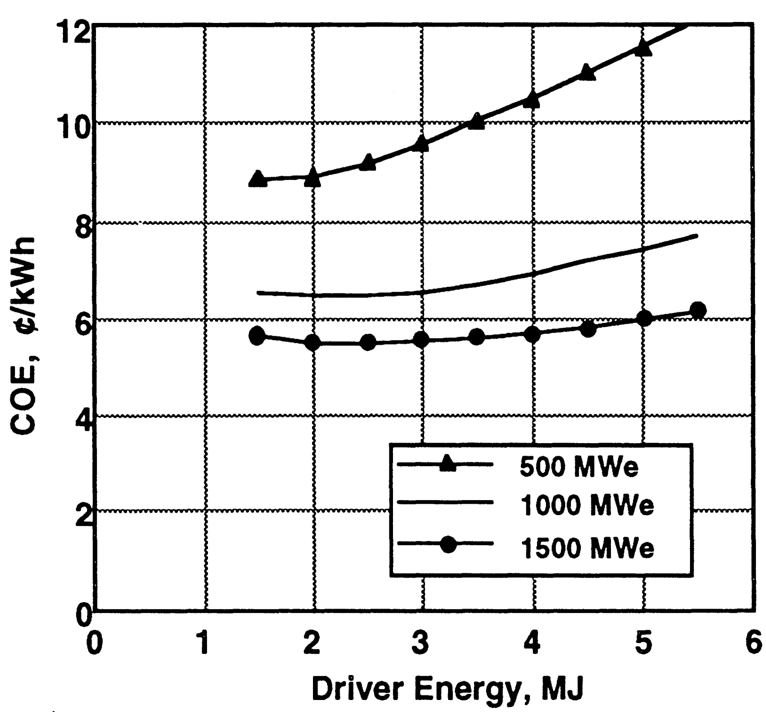

Fig. 8.23. COE for 500, 1000, and 1500 MWe SOMBRERO power plants.

8.6 COMPARISON OF OSIRIS AND SOMBRERO

The following tables compare some key operating parameters for Osiris and SOMBRERO designs that give minimum COE for various assumptions. The rep-rate for the Osiris design has been limited to <10 Hz, and the rep-rate for the SOMBRERO design has been limited to <20 Hz.

The original base case designs are compared in Table 8.12. The recirculating power for SOMBRERO is higher due to a lower efficiency driver (7.5% vs. 28.2%) and a lower energy multiplication factor (1.08 vs. 1.26). These disadvantages are partially offset by a higher gain (118 vs. 86.5) and a higher plant conversion efficiency (47% vs. 45%). As a result, SOMBRERO requires 35% more fusion power and 21% more gross electric power to produce the same 1000 MWe net power. This is reflected in the bottom line COE, which is 19% higher for SOMBRERO.

Table 8.12. Comparison of Reference Point Designs

	Osiris	SOMBRERO
Net Electric Power (MWe)	1000	1000
Gain Curve	Base	Base
Driver Energy (MJ)	5.0	3.4
Gain	86.5	118
Rep-rate (Hz)	4.6	6.7
Fusion Power (MW)	1987	2677
Gross Electric (MWe)	1127	1360
Driver Power (MWe)	82	304
Driver Direct Cost ($M)	587	579
TDC ($M)	1596	1879
COE (¢/kWh)	5.61	6.67

In both cases, the COE can be lowered by reducing the driver energy. The lower COE designs are compared in Table 8.13. The same trends as discussed for Table 8.12 are true for this comparison. In this case, the COE for SOMBRERO is 20% higher than Osiris.

Table 8.14 compares the designs when different target gain curves are used. SOMBRERO is much more sensitive to a reduction in target performance. Comparing the first two columns shows that with conservative target gain assumptions, the COE for SOMBRERO is 32% higher. SOMBRERO also benefits more from better target performance. If the optimistic gain curves are realized, the COE from SOMBRERO is only 14% higher than Osiris.

Table 8.13. Comparison of Lower COE Designs

	Osiris	**SOMBRERO**
Net Electric Power (MWe)	1000	1000
Gain Curve	Base	Base
Driver Energy (MJ)	3.5	2.0
Gain	68	93.9
Rep-rate (Hz)	8.6	15.1
Gross Electric (MWe)	1157	1440
Driver Power (MWe)	110	382
Driver Direct Cost ($M)	475	420
TDC ($M)	1506	1785
COE (¢/kWh)	5.37	6.45

Table 8.14. Comparison of Results with Conservative and Optimistic Gain Curves

	Osiris	**SOMBRERO**	**Osiris**	**SOMBRERO**
Net Electric Power (MWe)	1000	1000	1000	1000
Gain Curve	Conservative	Conservative	Optimistic	Optimistic
Driver Energy (MJ)	4.5	3.5	3.2	1.5
Gain	56.4	78.1	128	127
Rep-rate (Hz)	8.2	11.6	4.7	13.6
Gross Electric (MWe)	1179	1612	1100	1305
Driver Power (MWe)	132	547	56	253
Driver Direct Cost ($M)	551	622	451	345
TDC ($M)	1598	2103	1438	1612
COE (¢/kWh)	5.64	7.44	5.15	5.89

Results for 500 and 1500 MWe plants are compared in Table 8.15. At 500 MWe SOMBRERO's COE is 15% higher than the COE for Osiris. At 1500 MWe, the difference is 23%.

Table 8.15. Comparison of Results at 500 and 1500 MWe

	Osiris	SOMBRERO	Osiris	SOMBRERO
Net Electric Power (MWe)	500	500	1500	1500
Gain Curve	Base	Base	Base	Base
Driver Energy (MJ)	2.5	1.5	4.5	2.5
Gain	52.8	80.9	80.6	104
Rep-rate (Hz)	8.0	12.4	8.3	15.9
Gross Electric (MWe)	601	761	1701	2096
Driver Power (MWe)	76.5	231	133	512
Driver Direct Cost ($M)	394	342	551	496
TDC ($M)	1080	1224	1891	2295
COE (¢/kWh)	7.69	8.88	4.48	5.49

8.7 SUMMARY

We have developed economic models of the Osiris and SOMBRERO power plants and examined the COE as a function of the driver energy for several different sets of assumptions. For the base case assumptions, the minimum COE is 5.37 ¢/kWh for Osiris and 6.45 ¢/kWh for SOMBRERO. The difference is largely attributable to the larger fusion power and gross electric power required by SOMBRERO to generate the same 1000 MWe output. In addition, the cost of the SOMBRERO reactor building is significantly larger than the Osiris reactor building due to locating the final optics 50 m from the target. The difference in the cost of reactor buildings is ~$110 M, which is about half of the total difference in the direct capital costs of the two plants.

In the context of the level of accuracy of our cost estimates, the 20% difference in the COE is not important enough to eliminate the KrF-driven design from further development. In fact, we note that the COEs for these designs are both quite competitive with cost estimates made for ARIES-I and ARIES-II magnetic fusion energy designs, which reported constant (1988$) dollar COEs of 8.11 ¢/kWh and 6.69 ¢/kWh, respectively.[8.12] While we have not done a careful comparison of the IFE designs with the MFE designs, it is interesting to note that the cost of the drivers (at ~$600 M) is on the same order as the $500 M sum of costs for the magnets ($339 M), current heating ($108 M), and energy storage ($51 M) for ARIES-I (ARIES costs in 1988$). The COEs for Osiris and SOMBRERO are higher than the projected COEs for the 1200 MWe Improved PWR (4.3 ¢/kWh) and 1200 MWe Advanced PWR (4.5 ¢/kWh), but they are competitive with the projected COE from future coal plants (5.8 ¢/kWh) and best experience present day PWRs (5.4 ¢/kWh).[8.13]

The sensitivity of the results to different levels of target performance and net electric output was examined. With optimistic target gain assumptions, the minimum COE is about 4-9% lower (Osiris result given first), and with conservative target gain assumptions, the COE is about 5-15% higher than the base case. Increasing the net power to 1500 MWe reduces the COE by 17-15%, and reducing the net electric power to 500 MWe increases the COE by 43-38%. The cost comparisons are most useful for identifying the most attractive operating space.

8.8 REFERENCES FOR CHAPTER 8

8.1 T.J. McCarville, W. R. Meier, C. F. Carson, and B. B. Glasgow, " SAFIRE - A Systems Analysis Code for ICF Reactor Economics," LLNL Report UCRL-15872 Vol. 1 (Jan. 1987).

8.2 R.C. Davidson et al., "Inertial Confinement Fusion Reactor Design Studies Recommended Guidelines," (Sept. 1990).

8.3 "Revised Target Information for ICF Reactor Studies," Memo prepared by Target Working Group of IFE Reactor Studies Oversight Committee (Feb. 1991).

8.4 "Energy Economic Data Base (EEDB) Program-1X, Phase 9," United Engineers & Constructors/Oak Ridge National Laboratory, Report No. DOE/NE-0091 (July 1988).

8.5 "Nuclear Energy Cost Data Base - A Reference Data Base for Nuclear and Coal-fired Powerplant Power Generation Cost Analysis," U. S. DOE Report DOE/NE-0095 (Sept. 1988).

8.6 M.A. Hoffman, "HYLIFE-II Heat Transport System and Balance of Plant Design, Performance, and Cost Study," UC Davis Final Report No. 2 (Sept. 1991).

8.7 R.W. Moir, "HYLIFE-II Inertial Fusion Energy Plant Design," *Fusion Technol.*, **19**, 617 (May 1991).

8.8 C. Fong, "Update on the Cost of a Linac Driver" Lawrence Berkeley Lab Report (Jan. 1991).

8.9 M.J. Monsler, "A Search for a Minimum Cost Heavy Ion Beam for an Inertial Fusion Test Facility," Sartori Technologies Final Report (Feb., 1987).

8.10. J.H. Pitts et al., "The Cascade Inertial Confinement Fusion Reactor Concept," Lawrence Livermore National Laboratory, UCRL-LR-104546 (Dec. 1990).

8.11 "Cost Reduction Study for the LANL KrF Laser-Driven LMF Design," BDM Report BDM/ABQ-89-0747-TR (Oct. 1989).

8.12 R.L. Miller, R. A. Krakowski, and ARIES Team, "Options and Optimizations for Tokamak Reactors: ARIES," *Fusion Technol.*, **19**, 802 (May 1991).

8.13 J.G. Delene, "Updated Comparison of Economics of Fusion Reactors with Advanced Fission Reactors," *Fusion Technol.*, **19**, 807 (May 1991).