CONTENTS

9.0 COMPARISON OF OSIRIS AND SOMBRERO DESIGNS

9.1 INTRODUCTION

In this chapter, we give quantitative comparisons of some of the key design features and operating parameters of Osiris and SOMBRERO. We also highlight key advantages and issues of two approaches. No attempt was made to rate and rank the two concepts using a numerical scoring system as in studies such as BCSS[9.1] and ESECOM.[9.2] Both designs have major uncertainties and require significant technology development. At this time, there is no clear choice for the best concept. More meaningful comparisons and judgments of attractiveness can be made after some of the critical issues are addressed and the technologies are developed further.

The design comparisons in this chapter follow the outline of this report; chamber designs, power conversion and plant facilities, driver designs, target systems, environmental and safety, and economics are compared. Each comparison consists of a tabular summary of the key features, parameters, and/or results for each design, followed by a descriptive comparison of the features and some of the key issues for the two designs.

More detailed comparisons can be found on technology development requirements (Chapter 7), environment and safety (Chapter 5), and economics (Chapters 8). In addition, Appendix F gives the results of a survey of our scientists and engineers in which they were asked to assign qualitative "confidence level ratings" for various aspects of the two designs.

9.2 CHAMBER AND VACUUM SYSTEMS

9.2.1 First Wall Protection

Table 9.1 contrasts the key design features of the Osiris and SOMBRERO chamber designs. Osiris and Sombrero use different methods to protect the first wall material. The Osiris design uses a sacrificial layer of molten Flibe which must be replaced between shots. The SOMBRERO first wall is protected from target x-rays and ion debris by 0.5 torr of Xe, which spreads out the energy deposition time and prevents vaporization of the C/C composite. The two design choices were driven by the great difference in the required gas pressures assumed for final beam transport the two drivers. The background gas limits for laser drivers are determined by electrical discharge breakdown of the gas and are much higher than the particle transport limits for heavy-ion beams. Although various high-pressure transport modes (pinch-modes, plasma channel transport, etc.) have been proposed for heavy-ion beams, the most conservative calculations (ballistic transport) require very low background gas pressures to avoid excessive beam loss.

Table 9.1. Chamber Designs for Osiris and SOMBRERO

	Osiris	SOMBRERO
Yield (MJ)	432	400
Rep-Rate (Hz)	4.6	6.7
Fusion Power (MW)	1987	2677
Total Thermal Power (MWt)	2504	2891
First Wall Material	Liquid Flibe, Woven Graphite Fabric	4-D Weave, C/C Composite
X-ray and Debris Protection	Weeping Flibe	3.25 torr-m of Xe
Impulse on FW, Pa-s	90	2.1
FW / Blanket Replacement	Suspended fabric removed with roof	Chamber sections lowered, rotated, and removed
Breeding Material	Molten Flibe	Li_2O Granules
Blanket Thickness (m)	0.7	1.0
Chamber Outer Wall Material	C/C Composite	C/C Composite
Outer Wall Radius (m)	6.5	7.5

Because of the complex chemical kinetics of the Flibe cloud vaporized from the Osiris first wall, radiation transport and hydrodynamics calculations for Osiris are much more complicated than those for SOMBRERO. This leads to greater uncertainty in the fireball and vaporization calculations for Osiris, but in both cases the uncertainties are more likely to affect design parameters (e.g., achievable rep-rate, minimum wall radius) than concept credibility.

Both chamber designs assume carbon-based structural materials, which require further development.

9.2.2 Blanket Designs

Blankets used in fusion reactors must provide heat transport and tritium breeding; in addition, they should minimize potential hazards resulting from activation and chemical hazards. The blankets used in Osiris and SOMBRERO use different approaches to meet these design goals. Osiris uses flowing molten Flibe channels for breeding and heat transport, as well as for replenishing the sacrificial protection layer for the first wall. SOMBRERO, in contrast, uses a fluidized flow of solid Li_2O particles in a helium purge gas to get the advantages of both a solid breeder and a moving blanket.

The fluid dynamics and heat transport rates for the Flibe cooling channels used in Osiris are well established. However, issues connected with the weeping rate of Flibe through carbon fabric and the vaporization behavior of the sacrificial Flibe surface require more experimental and developmental work.

In the SOMBRERO design, blanket concerns are separated from issues associated with chamber dynamics, but assumptions on heat transfer rates and fluidized flow need to be verified by further experimental work.

9.2.3 Nuclear Performance

Nuclear parameters for the two chambers are compared in Table 9.2. Both Osiris and SOMBRERO have a very robust breeding ratio. However, because there is a large quantity of Be in the Flibe, the energy multiplication is higher than in Li_2O. First wall damage, He production, and estimated chamber life are all functions of the chamber radius. Since the first wall radius in Osiris is 3.5 m as compared to 6.5 m in SOMBRERO, the damage rate in Osiris is higher, and the first wall lifetime is lower. There is considerable uncertainty in the estimated first wall lifetime for both systems, because of the scarcity of damage data for the materials in question.

Table 9.2. Comparison of Nuclear Parameters for Osiris and SOMBRERO

	Osiris	SOMBRERO
Tritium Breeding Ratio	1.24	1.25
Overall Energy Multiplication	1.26	1.08
Maximum First Wall Damage (dpa/FPY)	42	15.3
Maximum He Production (appm/FPY)	10,600	3,770
Estimated Chamber Life (FPY)	1.8	5
Estimated Life of Final Optics (FPY)		
Steering Dipoles	40	
Grazing Incidence Mirror		1.7 - 40
Estimated Life of Next-to-Final Optics (FPY)		
Final Quadrupoles	40	
Final Focusing Mirrors		45
Maximum First Wall Surface Heating (MW/m^2)	3.9	1.5
Maximum First Wall Nuclear Heating (W/cm^3)	30.9	10.9
Maximum Breeder Nuclear Heating (W/cm^3)	66.5	12.9

The final and next-to-final optics in Osiris are well shielded and can survive the lifetime of the reactor (30 to 40 full-power-years (FPY)). In SOMBRERO, the grazing incidence mirror is subjected to direct line of sight neutrons, and its life will depend on the degree of recovery by annealing. However, the final focusing mirror is out of the line-of-sight of primary neutrons. Furthermore, the primary neutrons are directed into neutron traps; thus, the final focusing mirror has a full reactor lifetime even if limiting fluence to the dielectric coating is only 10^{18} n/cm^2.

9.2.4 Vacuum System Designs

Key vacuum system characteristics are compared in Table 9.3. While the vacuum systems for the two reactors are vastly different, both are current state-of-the-art. SOMBRERO requires a high pumping capacity at relatively high pressure (0.5 torr) pumping system while Osiris needs a lower capacity system at a much lower pressure (10^{-5} torr). In addition to the low pressure pumps needed for Osiris, some combination of isolation shutters and high speed pumps will be needed to isolate the lower pressure (10^{-8}) beam lines from the chamber. The development needs for such a system are high. SOMBRERO will have 50 pumping stations each with a capacity of 3×10^4 l/s. Roots pump with capacity of 10^4 l/s are available today, so a factor of three extrapolation is reasonable. The development needs for this will be modest. Although the pumping system for SOMBRERO requires less development than that for Osiris, the leak tightness of the carbon panels and seams in SOMBRERO will need to be established.

Table 9.3. Comparison of Vacuum System Characteristics

	Osiris	SOMBRERO
Atmosphere in Chamber	F, Li, Be, He	Xe, He
Steady State Pressure (torr)	10^{-5}	0.5
Evacuated Volume (m^3)	$1.2 \times 10^{3*}$	8.9×10^5
Driver Pressure Requirement (torr)	10^{-8}	NA
Pumping Speed (l/s)		1.4×10^6
Type of Chamber Pumps	Turbomolecular	Roots pumps
Type of Beam-line Pumps	Cryopumps	NA
Driver Beam-line Isolation	Needed	Not needed

*Exclusive of beam lines

9.3 POWER CONVERSION SYSTEMS

Table 9.4 contrasts the power conversion system parameters for Osiris and SOMBRERO. Both reactors use a lead intermediate loop to reduce tritium flow to the steam in the secondary loop and a double reheat steam cycle to maximize the power conversion efficiency. The differences result from the choice of primary coolant and the differences in gross power.

Table 9.4. Power Conversion Systems for Osiris and SOMBRERO

	Osiris	SOMBRERO
Power Balance		
Power Conversion Eff. (%)	45	47
Total Thermal Power (MWt)	2504	2891
Gross Electric Power (MWe)	1127	1359
Primary Loop		
Coolant	Flibe	He w/ Li_2O granules
Temperature Range (°C)	500 - 650	550 - 700
Tritium Inventory (g)	1.0	162
Tritium Removal	Vacuum Pumping	Adsorption of HTO vapor
Intermediate Loop		
Coolant	Lead	Lead
Temperature Range (°C)	400 - 600	400 - 600
Number of IHXs	4	4
IHX Rating (MWt)	625	725
Secondary Loop		
Coolant	Water / Steam	Water / Steam
Temperature Range (°C)	286 - 538	286 - 538
Cycle	Double Reheat	Double Reheat
Peak Steam Pressure (MPa)	24	24
Number of Steam Generators	2	2
S.G. Rating (MWt)	1250	1450
Number Turbine Generators	1	1
T.G. Rating (MWe)	1130	1360
T_2 Permeation to Steam Cycle (Ci/day)	1.0	15

The solubility of T_2 in Li_20 is roughly 50 times higher than in Flibe. That coupled with the factor of 2.1 larger breeder inventory in SOMBRERO accounts for the large difference in tritium inventories in the two designs. This also accounts for the factor of 15 difference in the steady state T_2 permeation into the steam cycle.

The SOMBRERO reactor requires a larger gross power than Osiris because heavy-ion drivers require less power than KrF lasers for a given fusion power. (The ratio of fusion thermal power to required driver power is given by the product of the driver efficiency, the target gain, and the blanket energy multiplication factor.) In order to improve the net efficiency of the SOMBRERO power conversion cycle, waste heat from the laser driver is used in a feedwater heater for the secondary loop.

9.4 BUILDING VOLUME COMPARISON

The volumes of the power plant buildings are compared in Table 9.5. As can be seen, SOMBRERO has a much larger reactor building than Osiris. This is, of course, typical of a direct drive system, which requires a large number of beams using symmetric illumination and the distance required to protect the dielectric optics. The accelerator tunnel and the tunnel service building together have a volume of 3.4×10^5 m^3 whereas the KrF laser building volume is 7×10^5 m^3. The major difference is that the Osiris accelerator is spread over several kilometers. Osiris also has a separate IHX building, while in SOMBRERO the IHX enclosure is inside the reactor building. The steam generator, turbine generator, and auxiliary buildings are comparable in size for both systems.

Table 9.5. Comparison of Building Volumes

	Osiris	SOMBRERO
Reactor Building Volume (m^3)	1.2×10^4	9×10^5
Accelerator Tunnel Volume (m^3)	2.2×10^5	
Laser Building Volume (m^3)		7×10^5
Tunnel Service Building Volume (m^3)	1.2×10^5	N/A
Maintenance Building Volume (m^3)	2.1×10^4	3.1×10^4
IHX Building Volume (m^3)	4.8×10^3	In reactor building
Steam Generator Building Volume (m^3)	2.9×10^4	3.1×10^4
Turbine Generator Building Volume (m^3)	1.3×10^5	1.3×10^5
Auxiliary Building Volume (m^3)	1.8×10^4	1.9×10^4

9.5 DRIVER SYSTEMS

Needed driver performance parameters for the two designs are shown in Table 9.6. Both drivers are far larger than present-day experiments and require a great deal of development work. The KrF laser builds on the Nike and Aurora experiments. The Aurora laser has delivered 10 kJ on target, while the needed energy for SOMBRERO is 3.4 MJ. The principle of multiple beam transport has been demonstrated in Lawrence Berkeley Laboratory's multiple-beam experiment (MBE-4). This experiment has a final voltage of 1 MV, while the needed acceleration voltage for Osiris is 3.8 GV. Predicted driver efficiencies for both driver are based on extrapolations of experimental data and are probably achievable with engineering development. However, accurate estimates for driver reliability for either system are not possible, because the relevant experience base does not exist.

Table 9.6. Driver Parameters for Osiris and SOMBRERO

	Osiris	SOMBRERO
Driver Energy (MJ)	5.0	3.4
Driver Efficiency (%)	28.2	7.5
Repetition Rate (Hz)	4.6	6.7
Power Consumption (MWe)	82	304
Illumination Geometry	Indirect (12 beams, 2 sided)	Direct (60 beams, uniform)

9.5.1 Heavy-Ion Driver

High rep-rated, high energy, accelerators have been operating for decades, but there are no accelerators that approach the required beam currents and powers needed for Osiris. The needed injector currents in the HIB driver are high. Modeling by the Child-Langmuir law has considerable uncertainties. It may be possible to build injectors with current densities much higher than those given by the Child-Langmuir law, but they will require significant development.

Low energy transport of heavy-ion beams is limited by how closely together the focusing quadrupoles can be placed. The achievable linear packing density for magnetic quadrupoles is limited by the field cancellation of adjacent quadrupoles and by the limits on achievable field quality for short magnets. It may be desirable to use electrostatic quadrupoles, which can have much higher linear packing densities at low driver energies.

The critical issue for final HIB transport, pulse compression, and final focusing is the lack of experimental data. Sophisticated modeling of final transport and final focusing has been performed, but there is no experimental verification in the high-current regimes of interest.

Final beam pointing requirements are not demanding (a 2 T dipole field 1 m long can steer the beam ± 10 cm at the chamber center), but the control systems needed for beam alignment, steering corrections, and final pointing will require development.

9.5.2 KrF Laser

Required front-end development work for SOMBRERO's driver can build on experience of the Nike system at NRL as well as recent work done at Los Alamos National Laboratory. What is needed is a repetitively pulsed front end with well controlled beam spatial and temporal profiles, but front-end efficiency can be low. A generic means of achieving stepwise approximation to continuous zooming has been devised for this study; it is likely that a continuous zooming approach can be achieved.

The critical concerns of stress levels, ASE, flow, acoustics, and optics are the same for the intermediate amplifier and the final amplifier, although the demands are much greater for the final amplifier. Intermediate amplification and multiplexing use technology developed in Aurora, Nike, and elsewhere, but the need for high-repetition rate will introduce additional concerns. Flow and acoustic parameters for the final amplifier are critical and will require design verification.

The requirements for demultiplexing and beam delivery do not require sophisticated optics development, but the component mounts, beam control between stages, and optimized architecture with regard to re-imaging between stages will require engineering development work.

Although the required spot sizes are far from diffraction limits, there are still significant issues for the final focusing of laser beams. To prevent destructive interference of the beams, care has to be taken to preserve beam spatial and temporal fidelity in the sequence of amplifying stages.

Beam pointing or steering in lasers is typically achieved by minor adjustments in mirrors located somewhere in the chain in the beam delivery system. Although research on high-speed active mirrors exists, significant development work is needed.

9.6 TARGET SYSTEMS

Although it has been demonstrated that very small targets can be fabricated to tolerances required for IFE, there has been no mass production of targets. Mass production of high tolerance targets, high production rate schemes for tritium filling of targets, and beta or laser layering of thick targets are all unproven and require significant development for both reactor concepts. The integrity of cryogenic DT capsules under acceleration of > 100 g is untested and uncertain.

There are some differences in the concerns for direct and indirect targets. Indirect targets, such as those used in Osiris, are more complicated than the direct targets used in SOMBRERO and may place more severe constraints on the allowable acceleration during target injection. Unlike direct targets, indirect targets must be injected with a preferred orientation. There may or may not be differences in the severity of the requirements for target centering and shot timing for the two types of targets. Indirect drive targets have a higher thermal inertial and less concern for surface quality than direct drive targets, but calculations indicate that both targets can avoid overheating during their flight through the chamber.

9.7 OPERATION AND MAINTENANCE COMPARISON

Characteristics related to plant operation and maintenance are given in Table 9.7. The lifetime of the reactor chambers based on our best estimate from radiation damage are 1.8 FPY and 5.0 FPY for Osiris and SOMBRERO, respectively. However , the Osiris first wall is subjected to much greater pulsed loadings as can be seen from the impulse and peak pressures levels. We expect the flexible fabric wall to be able to withstand the higher impulse, but the effect on the first wall lifetime is uncertain. Removing the chamber in Osiris as a single component of ~43 tonnes simplifies the replacement operation. Parenthetically, most of the mass is in the vacuum chamber cover; the internal chamber structures (fabric blanket and supports) amount to only ~30% of the lifted mass. The SOMBRERO chamber is made up of 12 modules, each weighing 39 tonnes. The chamber is designed for individual modules to be taken out and replaced separately.

Table 9.7. Comparison of Operation and Maintenance Related Characteristics

	Osiris	SOMBRERO
Maximum Impulse on First Wall (Pa-s)	90	2.1
Peak Pressure on First Wall (MPa)	36,900	0.012
Frequency of Chamber Replacement (FPY)	1.8	5.0
Number of Components in Chamber	1	12
Maximum Component Mass (tonnes)	43	39

9.8 ENVIRONMENTAL AND SAFETY COMPARISON

9.8.1 Tritium Parameters Comparison

Key parameters related to the use of tritium in the two reactors are given in Table 9.8. The solubility of T_2 in Li_2O is ~50 times higher than in Flibe. That coupled with the factor of 2.1 larger inventory in SOMBRERO accounts for the tritium inventory difference between the two systems. This also accounts for the factor of 15 difference in the steady state T_2 permeation into the steam cycle. But even at 15 Ci/d, this permeation rate is very low. The total amount of T_2 in the reactor buildings (including the inventory in the breeders) is 12.4 g in Osiris and 182.6 in SOMBRERO, respectively. This difference is also due to the large inventory in the SOMBRERO reactor breeding material.

Table 9.8. Comparison of Tritium Parameters

	Osiris	SOMBRERO
Total Breeder Inventory (tonnes)	940	2000
Tritium Inventory in Breeder (g)	1	162
T_2 Permeation into Steam Cycle (Ci/d)	1	15
Total T_2 Inventory in Reactor Building (g)	12.4	182.6
Tritium Inventory in Target Factory (g)	~ 300	~ 300

9.8.2 Environmental and Safety Analysis

Important environmental and safety parameters are compared in Table 9.9. Both Osiris and SOMBRERO have excellent safety features. They have the same radwaste classifications. For the Flibe material to have a radwaste classification of A, it must be converted to a stable solid form. The confidence level for achieving that is moderately low. Routine T_2 releases are similar for both reactors. An accidental release of all the tritium in the reactor building (a highly unlikely event) produces a whole body early off-site dose at the reactor boundary (1.0 km) of 0.129 rem for Osiris and 2.22 rem for SOMBRERO. Similarly, an accidental release of all the T_2 in the target factory will produce a whole body early off-site dose at the site boundary of 2.34 rem. These values are below the 5 rem level where evacuation plans are needed and far below the 25 rem value recommended for this study by the oversight committee as a threshold for the avoidance of early fatalities.

Table 9.9. Comparison of Environmental and Safety Parameters

	Osiris	SOMBRERO
Maintenance of Chamber Components	Remote	Remote
Maintenance of Power Cycle Components	Hands-on	Hands-on
Chamber Radwaste Classification	A	A
Shield Radwaste Classification	A	A
Breeder Radwaste Classification	A	C
Routine T_2 Release (Ci/d)	91.5	93
Maximum Dose to Exposed Individual from Routine Release (mrem/y)	2.43	0.93
Total T_2 Accidental Release (g)	12.4	182.6
T_2 Accidental Release from Target Factory (g)	260	260
Accidental Whole Body Early Off-Site Dose at 1 km (rem)	0.129	2.22

9.9 ECONOMIC COMPARISON

Key economic parameters are compared in Table 9.10. The economics of Osiris are more favorable than of SOMBRERO. There are several reasons for this, but the main ones are the relative sizes of the chamber, the reactor buildings, and the efficiencies of the drivers. A dry wall chamber is the only viable FW protection scheme for laser drivers, which must guard against condensation of any kind on the mirrors. Inherently, this makes them large and costly. The structures and site facilities are a factor of two higher for SOMBRERO due in large part to the symmetric illumination requirement. The reactor plant equipment is 22% higher for SOMBRERO than for Osiris. The reactor chamber, breeding material, and heat transfer equipment are all higher priced. The equipment related to power generation, such as the turbine plant equipment, electric plant equipment, miscellaneous plant equipment, and heat rejection are all higher for SOMBRERO because it has to produce 232 MWe more than Osiris to make up the difference in the driver efficiency (7.5% KrF laser vs. 28.2% accelerator). The driver costs are almost even, but the KrF laser has a higher cost on a $/J basis. It is interesting to note that the gross-electric unit cost is slightly lower for SOMBRERO than Osiris; however, when the driver power is subtracted, the net-electric unit cost is 15% lower for Osiris. The bottom line is that the cost of electricity for Osiris is ~16% lower than for SOMBRERO.

Table 9.10. Comparison of Economic Parameters

	Osiris (M$)	SOMBRERO (M$)
Land and Land Rights	11.6	10.5
Structures and Site Facilities	137.6	276.5
Reactor Plant Equipment	504.2	615.5
Turbine Plant Equipment	225.8	256.3
Electric Plant Equipment	66.2	70.0
Miscellaneous Plant Equipment	18.5	19.9
Heat Rejection Systems	44.8	52.0
Driver	587.5	579.1
Total Direct Costs	1596	1879
Indirect Costs	1057	1244
Time Related Costs	438	516
Total Capital Costs	3091	3639
Unit Capital Costs ($/kWe - gross)	2743	2678
Unit Capital Costs ($/kWe - net)	3091	3639
Constant Dollar Cost of Electricity (¢/kWh)		
Return on Capital	4.54	5.35
Operation and Maintenance	1.00	1.25
Fuel	0.02	0.02
Decommissioning	0.05	0.05
Total	5.61	6.67

9.10 REFERENCES FOR CHAPTER 9

9.1 D.L. Smith et al., "Blanket Comparison and Selection Study - Final Report," Argonne National Laboratory, ANL / FPP-84-1 (Sept. 1984).

9.2 J.P. Holdren et al., "Report of the Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy," Lawrence Livermore National Laboratory, UCRL-53766 (Sept. 1989).