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7.0 TECHNOLOGY ASSESSMENTS

7.1 APPROACH AND METHODOLOGY

Many assumptions have been made during this study about materials capabilities, component availability and performance, and cost. In this chapter we attempt to put all this in perspective and assess the technical issues, development needs, and level of urgency. A semi-quantitative approach is taken with issues weighted on a scale from zero (low) to 100 (high) in increments of 25. The issues and weighting factors are given in Table 7.1.

Table 7.1. Technical Issues and Weights

Technical Immaturity	10%
Critical Technology	30%
High Development Cost	30%
Long Lead Time	20%
% Cost in Experiments	10%

Note that they are defined in terms of concerns (e.g., technical immaturity rather than maturity) so that a high score always indicates a problem. The weightings are obviously judgmental. Technical immaturity is far less important than critical technology (i.e., no alternative technologies or approaches exist) or development cost. These last two are considered the most important. Long lead time is also an issue. An example of an issue with a long lead time would be materials development. Some account is also made of the greater developmental uncertainty when many experiments are required.

The areas covered for Osiris and SOMBRERO are reactor chamber, shielding, final beam transport, coolant and ducting, IHX, steam generator, power conversion, driver, and target fabrication and injection. Other areas are issues generic to IFE that are of concern regardless of the specifics of the reactor chamber and driver: target design and innovations, systems modelling, low activation materials, and remote maintenance. The issues for each reactor concept are discussed and then generic issues are addressed. Tabulations using the criteria in Table 7.1 are then given.

7.2 OSIRIS ISSUES AND DEVELOPMENT NEEDS

7.2.1 Reactor Chamber

The reactor chamber uses a woven carbon fabric blanket with flowing liquid Flibe as neutron absorber and coolant. Flibe also weeps to the surface of the fabric, providing a sacrificial protective layer. Technical issues are rep-rate, fabric weave control, fabric stitching, blanket replacement, effect of shock waves, carbon/Flibe chemistry and surface physics, and tritium extraction from the Flibe. Each of these is discussed below.

Chamber Repetition Rate. The maximum allowable repetition rate for an Osiris chamber will be determined by the rate at which vaporized Flibe can be recombined and condensed. Simple calculations indicate that the vapor pressure returns to a low enough level to allow beam propagation fast enough to allow a repetition rate of up to 10 Hz. If the condensation time is much longer than currently estimated (i.e., by a factor of 10), this would be a feasibility issue for Osiris. A factor of two is not critical since the cost of electricity is relatively insensitive to repetition rate over this range. Uncertainties can probably be removed with analysis and small-scale experiments, so the lead time and costs to resolve this issue should both be small.

Fabric Weave and Flow Control. The unique feature of the Osiris reactor chamber is the flexible fabric first wall, which is protected by Flibe bleeding through the weave. It is important to control this bleed rate with high precision. The correct weave density and fabric construction must be found to allow sufficient flow to coat the surface of the fabric and replenish vaporized Flibe while preventing excess flow that could lead to dripping. If too much Flibe bleeds through it will not run down along the roof but will fall off in a rain. This raises concerns about droplets in the path of the next beam pulse and the possibility of an increase in the vapor pressure due to the presence of heated droplets.

Carbon fabric can be woven over a wide range, from see-through to as tight as a seat belt; therefore, it is likely that the proper weave can be established. It can also be combined with solid carbon, carbon composites, and carbon felt. However, work is required to determine the flow of Flibe through carbon pores. Because Flibe doesn't wet carbon, hydraulic pressure is needed to drive it through the fabric. The required pressure depends on the Flibe surface tension and the characteristics of the carbon fabric. The Flibe droplets must coalesce into a continuous

film and not just bead up. Because of the non-wetting, this film must be supported through capillary tension by the bulk Flibe on the other side. This will require a fairly fine pore structure in the fabric, which places lower limits on hydraulic pressure.

This is a new and untried concept, and much more work is needed to demonstrate its feasibility. The development costs, however, should be low because simple, low cost experiments can validate the concept.

Fabric Stitching. The first wall/blanket is made up of carbon fabric panels stitched together to form a tent-like structure using an air mattress type of configuration to withstand the Flibe pressure. Because the Flibe first makes a high-speed pass down the first wall to limit temperature rise, the blanket assembly will be at least three carbon panels thick, all of which must be reliably stitched together. The stitches should be redundant, lightly stressed, and not exposed to the target X-rays. This technology is quite well established for such things as circus tents.

Blanket Replacement. Blanket fabrication must be done on-site at a location where the new blanket can be readily transported to the reactor vacuum chamber. Assuming annual replacements at most, an entire year is available for fabrication and checkout. Because there will be activation products in the hot Flibe in the bottom pool, remotely controlled removal and replacement systems will be needed.

Shock Waves. Target X-rays and debris will cause surface shocks on the first wall that will propagate into the blanket. Isochoric heating will also cause sudden pressurization of the solid material that will be relieved by expansion from the surface inward. Since any protective Flibe film that forms is likely to be held in place only by capillary tension with Flibe in the pores of the fabric, these complex shocks might be able to blow the film off the surface, creating falling droplets in the chamber. The pressure resulting from X-ray blowoff may overpower inward motion from isochoric heating and keep the film in place. The complex interaction of reflected shocks and bulk blanket motion could strip off the film, especially if its hold on the fabric is tenuous.

The impact of these shock waves is a significant feasibility issue. Because the processes are so complex and so little is known, the current technical maturity is considered low. The development needs may be high, because resolution requires accurate simulation, which is difficult to achieve without experimental verification. While code work can provide some

insight, it is unlikely that financial commitment to this concept would be made without results from quality experiments.

Fabric/Flibe Chemistry and Surface Physics. There are two aspects to the interaction between the molten Flibe and the carbon fabric: (1) chemistry, particularly HF, F_2, and H_2 reactions, and (2) the wetting of carbon by Flibe and possible coatings that may increase it. The compounds in (1) are gaseous and are released by tritium breeding and, possible, by hard X-rays. Unlike solid carbon, micron-sized carbon fiber cannot tolerate much chemical etching. The lack of wetting may be an advantage here, although escaping fluorine gas compounds may still cause problems.

Coating the carbon with another material could solve both the chemistry and wetting problems. Flibe does wet most metals. A thin (monolayer) coating of tungsten or molybdenum, which match carbon's thermal expansion, would solve the wetting and corrosion problems and may not produce that much activation. Because such thin layers may not require matching thermal expansion, boron, B_4C, beryllium, Be_2C, aluminum, and Al_2O_3 are also interesting possible coatings for carbon fabric. Much could be learned with small, inexpensive experiments.

Tritium Extraction. The Flibe exits the Osiris blanket at the top and cascades down the outside of the blanket, releasing tritium to the vacuum pumping system. Since tritium retention in Flibe is very low, in principle most of it can be extracted this way.

With an intermediate heat exchanger, complete removal of tritium from the Flibe stream is not required. It is desirable, however, in order to minimize vulnerable tritium inventory. More work is needed to determine if the cascade flow will remove enough tritium. If it doesn't, separate spray tanks and boost pumps will be needed to provide a fine mist and large Flibe surface area.[7.1]

The overall current technical credibility of this novel reactor concept must be considered to be fairly low. However, because much can be learned from fairly simple and inexpensive experiments, development needs may only be moderate in cost and time.

7.2.2 Shielding

The neutron flux is reduced several orders of magnitude by the Flibe blanket and pool. The exception is the beam penetrations. Biological shielding, which can be room temperature, is required around all sides of the vacuum chamber and possibly around much of the driver final focusing envelope. Almost any low activation material can be used for biological shielding: water, polyethylene, asphalt, sand, or, as in the current design, concrete. The limited amount of heat generated can be conducted to the surroundings. Access to the shielded regions is required for maintenance of the hardware inside.

Biological shielding technology has been well established in existing fusion experiments and in fission reactors. Development requirements should be low, including requirements for high material purity. The primary issue is cost of shield material (not development cost, which should be low), particularly long sections of the final beam transport section of the driver.

7.2.3 Reactor Building

The size and cost of the reactor building depends on the classification of the reactor. If the reactor components are non-nuclear grade, and the reactor is considered inherently safe, and the vulnerable tritium inventory is sufficiently low, then a tin shed will do. Otherwise, 2-3 m thick concrete walls are required. There is a good possibility that the former may be sufficient, or not much more. The main uncertainty is probably the tritium issue. The current design uses thick concrete walls, which also serve for biological shielding. If the N-stamp is eliminated, this shielding could be moved in closer, making it smaller, and a less expensive reactor building could be used. In any event, the current technical credibility of reactor buildings of this modest size is high and development requirements are low.

7.2.4 Flibe Pumps and Ducting

At least two types of Flibe pumps are required: one low and one high pressure. Flibe is compatible with Hastelloy and some stainless steels, and ordinary centrifugal pumps can be used. Graphite seals are especially attractive here, because the non-wetting by Flibe will reduce leakage, and chemical reactions should be minimal provided generated gases are removed upstream. Ducting is low pressure and modest diameter and is, therefore, less challenging than in conventional steam plants. It should be quite simple to provide a tritium barrier around the

pumps and pipes. The pumps and ducts must be thermally insulated, and heater tape is needed to prevent Flibe solidification.

7.2.5 Intermediate Heat Exchanger

The IHX has molten low-pressure Flibe at up to 630°C on one side and molten low-pressure lead or lead-based eutectic at up to 620°C on the other side. These temperatures are those in contact with the tube walls. The total heat transfer area is about 12,000 m^2, which can be met with two transportable heat exchanger cores roughly 4 x 8 x 3 meters in size. Key issues are lead chemistry, tritium permeation into the lead, effect of cross leakage should a tube fail, avoidance of solidification, and draining.

The Blanket Comparison and Selection Study[7.2] found that $Li_{17}Pb_{83}$ was more corrosive to stainless and ferritic steels than pure lithium, suggesting that it is the lead that is causing the problem. With ferritic steel, the temperature limit for lithium is around 600°C while it is below 500° for lithium-lead. With vanadium alloy, on the other hand, over 750° can be tolerated. Elemental additions to the liquid lead like titanium may serve as corrosion inhibitors. It is believed that the titanium reacts with carbon or nitrogen in the steel to form a protective layer of TiC or TiN. This method has generally been more successful than plasma-sprayed coatings, which can flake off. The Liquid Metals Handbook shows liquid lead to be compatible with Type-347 stainless to 630°C and low-alloy chrome-moly steel to 625°C. Inconel, surprisingly, is worse. The key issue is the purity of the lead. Technical credibility is considered moderate, and the development requirements are low.

7.2.6 Steam Generators

The lead side of the steam generator has the same corrosion issues as the IHX. Otherwise, they are similar to those using liquid sodium, which has a substantial technology base. Because the tubes are highly stressed, a key issue is the effect a tube failure has on the IHX. Some fail-safe means of depressurizing, such as blowout plates, must be considered. Like the IHX, the current technical credibility is considered moderate, and the development requirements are low.

7.2.7 Power Conversion System

Despite numerous attempts to develop advanced power conversion systems, conventional Rankine cycles using steam appear to be the best choice with moderate operating temperatures, such as those used with Flibe. Brayton cycles begin to be attractive at higher temperatures.

The main issue for the steam power conversion system is the heat rejection system. Because of the large land area needed for the driver, siting may be restricted to remote areas where cooling water could be limited. Dry air cooling must be considered, and this raises steam condensing temperature from 43°C to about 60°C. With 540°C steam temperature at turbine inlet, this increase in rejection temperature will reduce efficiency from 45% to about 43%, including air pumping loss. Because dry air cooling reduces costs of the site, the cooling towers, and the low pressure turbines (exit pressures are higher), the overall impact on plant economics could be small. These are design issues, however, and require little development.

7.2.8 Heavy Ion Beam Driver

The driver represents the most difficult engineering challenge of the entire IFE power plant. Nothing of this scale has ever been built with the combination of requirements that are discussed below.

Reliability. If we assume unscheduled downtime for the power plants is to be limited to about 10% of total time, and that the driver cannot cause more than about a third of the outage time, then a reliability figure of at least 97% is required. Considering the number of components in the driver, it is clear that the reliability of each must be very high.

Beam Current. While long, high-energy, linear accelerators have been built (e.g., SLAC) none approach the kiloamp beam currents required here. This is largely a physics issue that will have to be resolved early on and will require large, expensive experiments.

Beam Propagation into Chamber. There was considerable discussion during this study as to the type and amount of vapor that could be in the cavity and still have a focussed beam delivered to the target. The greater the allowable vapor pressure of Flibe, the higher the temperatures can be in the chamber region, resulting in higher conversion efficiencies. Low atomic number vapors appear more benign, at least for beam stripping. There is ongoing research into the self-pinched propagation mode at LLNL and NRL, which would allow higher gas pressures. There has also been some discussion of propagation in plasma channels, though

there are many uncertainties in this propagation mode. Because this issue can drive so many aspects of reactor (and BOP) design, it should be resolved early on with a convincing combination of analysis and experiments.

Rep Rate. Single shot accelerators are easier to design than one that must be reliably rep-rated at several Hz. Steady-state cooling is required, and inductor cores will be repeatedly pulsed. Super-conducting magnets must be shielded from AC losses.

Vacuum Maintenance. The beam line must be maintained at 10^{-6} torr while the plasma chamber must be at 10^{-4} torr. Considerable pumping is required at the final focus magnets as well as throughout the long accelerator. Large vacuum systems of this sort already exist in the high-energy physics community. The main issue that could cause vacuum problems is discussed below.

Material Deposition. Flibe vapor, as well as target shell material, will drift into the beam tubes and plate out. The buildup rate must be determined and its effect. In particular, the effect of plating of any electrically conducting material on beam formation and propagation must be determined. It may be necessary to run the beam tubes hotter than the Flibe melting point in order to continuously drain deposited material. Use of shutters can reduce inflow, but with considerable added complexity.

Neutron and Ion Activation. Bending magnets and neutron dumps can virtually eliminate primary neutron propagation down the beam tubes. Scattered neutrons remain a problem for the final focussing and drift compression regions of the driver. Shielding must be added around the bores of the final focussing magnets. The neutrons travel too rapidly to be stopped by mechanical shutters. In addition to neutron activation, some of the high energy ions in the beam can lose their charge and impact the accelerator tube, leading to activation.

The current technical credibility seems low for controlling scattered neutrons and neutralized beam particles, so potential activation of the entire driver is an important issue. Much can be learned here by analysis; therefore, development needs are considered only moderate.

Final Focus Hardware. The final focussing magnets are shielded from primary and secondary neutrons with shielding around the bore. The amount of bore shielding determines how close the final magnets can be spaced, which impacts beam envelope and building requirements. These magnets are quite complex and could be subjected to severe bending loads. The ongoing work on magnet technology in the MFE program is of value here.

Power Supplies. The power supplies for reliable rep-rated operation will be different from the pulsed energy systems used in today's high energy experiments. Issues include their cost, reliability, conversion efficiency, potential for reject heat recovery, and buss network. High energy, rep-rated power supplies are being developed for other applications, for example, SDI.

7.2.9 Target Fabrication

The target factory will need to be fully automated. The production process must have high reliability, high quality control, and low capital and operating costs. Recycling of target material will be required.

7.2.10 Target Injection

In our conceptual design, targets are accelerated at ~ 130-g to about 150 m/s in a 9-m long gas gun accelerator. Targets must survive (i.e., maintain required quality specifications) the acceleration and transit to the center of the chamber. The target injection and tracking systems must be protected from the damaging effects of the fusion energy pulse with distance and/or shielding. The injector must be highly reliable and position the targets accurately in time and space with the correct orientation. The tracker must supply targeting information to the driver early enough to allow for beam steering and pointing.

Several approaches exist that could potentially meet the injection and tracking requirements, but none has been built and tested. While frozen hydrogen has been accelerated to typical IFE parameters, precision multi-layer fuel capsules have not. Calculations indicate that the outer plastic shell protects the cryogenic fuel from overheating during transit through the hot chamber. The effects of heating on the ablator surface finish requires further analysis and / or experimentation.

7.3 TECHNOLOGY ASSESSMENT RATINGS FOR OSIRIS

Table 7.2, which extends for several pages, shows a graphical summary of the primary criteria discussed in Section 7.1: technical immaturity, critical technology, development cost, lead time, and amount of experimental effort. They are ranked from low (0) to high (100), and a weighted average, the overall urgency factor, is given at the end of each issue. Critical

technology (no other options exist) and development cost weigh highest, followed by long lead time. Less weight is given to technical immaturity and the extent of experimental effort required. The entries are displayed such that the further to the right an entry is, the greater the attention it should have.

In general, issues scoring 50 or greater are of considerable importance while those with 25 or less can be deferred. In the reactor chamber, issues scoring 50 or greater in overall urgency are chamber rep-rate, chemistry and surface physics, blanket replacement/repair, shock waves, and tritium. None of the BOP-related issues score very high. A number of driver issues score 50 or greater: reliability, beam current, beam propagation, rep rate, vacuum maintenance, final focus, and power supplies. Target fabrication and injection also scored 75 in 'overall urgency.

Table 7.2. Technology Assessment for Osiris

OSIRIS - REACTOR CHAMBER

CHAMBER REP-RATE:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)				●	
Critical Technology (30%)					●
High Development Cost (30%)		●			
Long Lead Time (20%)		●			
% Cost in Experiments (10%)			●		
Overall Urgency Factor			★		

FABRIC WEAVE CONTROL:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)				●	
Critical Technology (30%)		●			
High Development Cost (30%)	●				
Long Lead Time (20%)	●				
% Cost in Experiments (10%)				●	
Overall Urgency Factor		★			

FABRIC STITCHING:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)		●			
Critical Technology (30%)		●			
High Development Cost (30%)	●				
Long Lead Time (20%)	●				
% Cost in Experiments (10%)				●	
Overall Urgency Factor		★			

Table 7.2 (continued)

OSIRIS - REACTOR CHAMBER (continued)

BLANKET REPLACEMENT/REPAIR:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)					●
Critical Technology (30%)			●		
High Development Cost (30%)		●			
Long Lead Time (20%)		●			
% Cost in Experiments (10%)				●	
Overall Urgency Factor			★		

EFFECT OF SHOCK WAVES:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)				●	
Critical Technology (30%)					●
High Development Cost (30%)			●		
Long Lead Time (20%)			●		
% Cost in Experiments (10%)				●	
Overall Urgency Factor				★	

FABRIC/FLIBE CHEMISTRY AND SURFACE PHYSICS:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)			●		
Critical Technology (30%)					●
High Development Cost (30%)		●			
Long Lead Time (20%)	●				
% Cost in Experiments (10%)				●	
Overall Urgency Factor				★	

Table 7.2 (continued)

OSIRIS - REACTOR CHAMBER (continued)

TRITIUM EXTRACTION:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)					●
Critical Technology (30%)		●			
High Development Cost (30%)			●		
Long Lead Time (20%)		●			
% Cost in Experiments (10%)			●		
Overall Urgency Factor			★		

OSIRIS - SHIELDING

	Low 0	25	50	75	High 100
Technical Immaturity (10%)			●		
Critical Technology (30%)		●			
High Development Cost (30%)		●			
Long Lead Time (20%)	●				
% Cost in Experiments (10%)		●			
Overall Urgency Factor		★			

OSIRIS - REACTOR BUILDING

	Low 0	25	50	75	High 100
Technical Immaturity (10%)		●			
Critical Technology (30%)	●				
High Development Cost (30%)	●				
Long Lead Time (20%)	●				
% Cost in Experiments (10%)	●				
Overall Urgency Factor	★				

Table 7.2 (continued)

OSIRIS - FLIBE PUMPS AND DUCTING

	Low 0	25	50	75	High 100
Technical Immaturity (10%)			●		
Critical Technology (30%)		●			
High Development Cost (30%)	●				
Long Lead Time (20%)	●				
% Cost in Experiments (10%)		●			
Overall Urgency Factor		★			

OSIRIS - INTERMEDIATE HEAT EXCHANGER

	Low 0	25	50	75	High 100
Technical Immaturity (10%)		●			
Critical Technology (30%)	●				
High Development Cost (30%)		●			
Long Lead Time (20%)	●				
% Cost in Experiments (10%)		●			
Overall Urgency Factor		★			

OSIRIS - STEAM GENERATOR

	Low 0	25	50	75	High 100
Technical Immaturity (10%)		●			
Critical Technology (30%)	●				
High Development Cost (30%)		●			
Long Lead Time (20%)	●				
% Cost in Experiments (10%)			●		
Overall Urgency Factor		★			

Table 7.2 (continued)

OSIRIS - POWER CONVERSION

	Low 0	25	50	75	High 100
Technical Immaturity (10%)	●				
Critical Technology (30%)	●				
High Development Cost (30%)	●				
Long Lead Time (20%)	●				
% Cost in Experiments (10%)	●				
Overall Urgency Factor	★				

OSIRIS - HIB DRIVER

RELIABILITY:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)					●
Critical Technology (30%)					●
High Development Cost (30%)			●		
Long Lead Time (20%)			●		
% Cost in Experiments (10%)				●	
Overall Urgency Factor				★	

BEAM CURRENT:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)				●	
Critical Technology (30%)					●
High Development Cost (30%)				●	
Long Lead Time (20%)				●	
% Cost in Experiments (10%)					●
Overall Urgency Factor				★	

Table 7.2 (continued)

OSIRIS - DRIVER (continued)

BEAM PROPAGATION INTO CHAMBER:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)				●	
Critical Technology (30%)				●	
High Development Cost (30%)				●	
Long Lead Time (20%)			●		
% Cost in Experiments (10%)			●		
Overall Urgency Factor				★	

DRIVER REP RATE:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)		●			
Critical Technology (30%)				●	
High Development Cost (30%)			●		
Long Lead Time (20%)			●		
% Cost in Experiments (10%)				●	
Overall Urgency Factor			★		

VACUUM MAINTENANCE:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)		●			
Critical Technology (30%)				●	
High Development Cost (30%)		●			
Long Lead Time (20%)		●			
% Cost in Experiments (10%)				●	
Overall Urgency Factor			★		

Table 7.2 (continued)

OSIRIS - DRIVER (continued)

MATERIAL DEPOSITION:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)			●		
Critical Technology (30%)		●			
High Development Cost (30%)		●			
Long Lead Time (20%)		●			
% Cost in Experiments (10%)				●	
Overall Urgency Factor		★			

NEUTRON DAMAGE / HEATING:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)			●		
Critical Technology (30%)			●		
High Development Cost (30%)		●			
Long Lead Time (20%)		●			
% Cost in Experiments (10%)	●				
Overall Urgency Factor		★			

FINAL FOCUS HARDWARE:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)				●	
Critical Technology (30%)				●	
High Development Cost (30%)			●		
Long Lead Time (20%)			●		
% Cost in Experiments (10%)				●	
Overall Urgency Factor				★	

Table 7.2 (continued)

OSIRIS - DRIVER (continued)

DRIVER POWER SUPPLIES:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)			●		
Critical Technology (30%)			●		
High Development Cost (30%)			●		
Long Lead Time (20%)		●			
% Cost in Experiments (10%)			●		
Overall Urgency Factor			★		

OSIRIS - TARGET FABRICATION

	Low 0	25	50	75	High 100
Technical Immaturity (10%)				●	
Critical Technology (30%)					●
High Development Cost (30%)				●	
Long Lead Time (20%)			●		
% Cost in Experiments (10%)				●	
Overall Urgency Factor				★	

OSIRIS - TARGET INJECTION

	Low 0	25	50	75	High 100
Technical Immaturity (10%)				●	
Critical Technology (30%)					●
High Development Cost (30%)			●		
Long Lead Time (20%)		●			
% Cost in Experiments (10%)				●	
Overall Urgency Factor				★	

7.4 SUMMARY OF DEVELOPMENT PRIORITIES FOR OSIRIS

Table 7.3 gives a summary of the above discussion and a tabulation which distills it by listing current technical credibility (i.e., the current state-of-the-art) for each item, as well as development needs for reactor applications. It also shows a ranking of the development priorities for each major subsystem and, where appropriate, for issues within the subsystem. The development needs are not necessarily the inverse of technical credibility, because, in many cases, rather simple experiments can resolve major issues. The level of expense and difficulty has been included, as has the impact of the issue on reactor performance and cost.

Not surprisingly, the driver ranks first in development priority. Part of this is due to the enormous potential expense and part because of the limited development paths: RF or induction and once-through or recirculating. Because the driver is truly the tail wagging the dog, the primary IFE effort must go here, at least for now.

The target factory ranks second, because so little is known about economic fabrication of complex indirect targets. Hopefully, the current work on target fabrication will help. Nevertheless, a concerted effort must be undertaken to scope out a reactor-relevant target factory in some detail.

While one might expect the reactor chamber to top the list, it is preceded by the two above partly because the development needs can probably be met with less expense, and if the Osiris concept simply doesn't work, there are many other reactor concepts to fall back on. This is not true with the driver and target factory.

Target injection and tracking doesn't rank as high as expected in development priority partly because of the relatively modest scale experiments that are required and because of related technology existing in the MFE and SDI programs.

The remaining items lie some distance down the development priority scale although there are certainly numerous design issues that must be addressed.

Table 7.3. Osiris Development Priorities

ITEM	CURRENT TECHNICAL CREDIBILITY	DEVEL. NEEDS	DEVEL. PRIORITY
DRIVER	**LOW**	**HIGH**	**1**
Beam Current	Moderate	Moderate	1
Beam Chamber Propagation	Low	Moderate	2
Economics	Low	High	3
Neutrons	Low	Moderate	4
Final Focus	Moderate	Moderate	5
Reliability	Low	High	6
Rep Rate	Moderate	Moderate	7
Vacuum Maint.	High	Low	8
Mat'l Deposition	Moderate	Moderate	9
Power Supplies	High	Low	10
TARGET FABRICATION	**LOW**	**HIGH**	**2**
REACTOR CHAMBER	**LOW**	**MODERATE**	**3**
Fabric/Flibe	Low	High	1
Rep-rate	Low	Mod	2
Shocks	Low	High	3
Weave Control	Low	Low	4
Stitching	High	Low	5
T Extraction	Moderate	Low	6
Blanket Replacement	High	Low	7
TARGET INJECTION	**MODERATE**	**MODERATE**	**4**
IHX	**MODERATE**	**LOW**	**5**
STEAM GENERATOR	**MODERATE**	**LOW**	**6**
FLIBE PUMPS/DUCTS	**HIGH**	**LOW**	**7**
SHIELDING	**HIGH**	**LOW**	**8**
REACTOR BUILDING	**HIGH**	**LOW**	**9**
POWER CONVERSION	**HIGH**	**LOW**	**10**

7.5 SOMBRERO ISSUES AND DEVELOPMENT NEEDS

This is the companion section to Section 7.2 and gives a technology assessment of the SOMBRERO reactor concept. The areas covered are the reactor chamber, shielding, final optics, Li_2O transport and ducting, IHX, steam generator, reactor building, power conversion, laser driver, and target factory and injection.

7.5.1 Reactor Chamber

The reactor chamber has cylindrical symmetry and is built up of layers of carbon composite plates between which flows Li_2O granules fluidized by 2 atmospheres of helium gas. Low pressure xenon gas in the chamber absorbs target soft X-rays and debris so that wall vaporization is avoided. Technical issues are carbon structure fabrication, leak-tightness including detection and repair, fireball/blast response, Li_2O heat transfer, Li_2O and carbon structure erosion, fluidized flow, and neutron lifetime.

Carbon Structure Fabrication. The chamber structure is made up of concentric layers of carbon-carbon composite with increasing panel thickness as one moves away from the first wall. Carbon composites are fabricated by infiltrating built-up carbon fabric with an appropriate hydrocarbon that carbonizes upon heating. An oven is therefore required, and panel size are therefore limited by oven size. It may be possible to preform panels in an oven with a limited infiltration so that they have some stiffness, and then assemble the reactor and do the remaining infiltration in-situ. The chamber then becomes its own oven. This would be necessary for seamless fabrication. If the chamber is built up of individual panels, the joints must be sealed to prevent helium leakage. An SiC coating is postulated, which would have to be done after assembly.

The current technical credibility of large, vacuum-tight carbon-carbon structures is at most moderate. The level of development needed to establish the necessary feasibility is also moderate and should not be overly expensive because developing the necessary procedures (e.g., using the chamber as an in-situ oven) can be developed on a modest scale.

Leak Tightness and Detection. Assuming the vacuum chamber has fairly high pumping capacity, thousands of pinhole-sized leaks of 2 atmosphere helium can be tolerated. Double sealing of the first wall is almost certainly required. Some ductility of the seal material would help; using brittle SiC as the seal material will be troublesome. If a large leak occurs, means must be available for detection of the leak location and repairing it. The question also remains about how much helium is acceptable in the target chamber. Laser propagation may actually be so tolerant to helium that vacuum pumping is in the high-speed viscous regime.

Remote Maintenance and Assembly. Although low activation materials are used throughout, there will be short-term activity that must be considered when changing out blankets. Trace impurities can generate longer-term activity severely restricting access to the chamber. The technology of remote manipulation, assembly, and repair must be extended to accommodate very large subassemblies. This technology is proceeding in other areas such as remotely-piloted vehicles and aircraft for the military, and telerobots for space applications.

Fireball/Blast Response. While the chamber gas prevents vaporization of the first wall surface, the expanding fireball in that gas will subject the wall to a blast effect. The dynamic stresses and induced vibrations raise concerns about damage (e.g., cracking) to brittle seals. Further analysis and experimental verification will be required to address the effects of pulsed loading on the composite structure and seals.

Li_2O Heat Transfer. The high thermal capacity and substantial mixing of the Li_2O greatly increases the heat transfer capacity of the low pressure helium gas. The gas can flow upward at sufficient velocity so that the granules just lift off of each other and flow down much like a fluid. There is a wide body of heat transfer data for this type of flow, and relatively simple experiments could refine it for these specific conditions. Because carbon temperatures can be much higher than the Li_2O, fairly high heat transfer rates are possible with moderate heat transfer coefficients.

Li_2O and Structure Erosion. Lithium oxide is not very hard and will wear down by transport against a hard surface like silicon carbide. Pure carbon structure, if used instead, will also wear. Granule to granule impact and impact with ducts and heat exchanger tubes also cause breakup of this relatively weak material. Means will have to be provided to extract fractured granules and fabricate new ones. Other lithium bearing ceramics, such as lithium aluminate, may be worth considering if Li_2O ends up being too soft and weak. Coatings on the granule, such

as silicon carbide, can also be considered. The New Production Reactor for Savannah River was designed to use $LiAlO_2$ particles coated with SiC, and this technology may be useful here.

Fluidized Flow. Fluidized flow of the Li_2O granules has been discussed above with respect to heat transfer. Helium carrier gas is used to fluidize the granule flow through the reactor and the IHX and to carry the granules upward to the top of the reactor and the top of the IHX. When properly fluidized, granule beds behave much like liquids and can readily flow though complex ducting.

This technology is well established in the chemical industry for large-scale transport of solid particles. It, therefore, has high technical credibility. Development needs are expected to be low centering mainly on design issues like the erosion discussed above and on helium recovery and pumping power.

Beam Propagation into Chamber. The allowable vapor density in the chamber is much higher for lasers than for ballistic propagation of ion beams. In SOMBRERO, 0.5 torr Xenon stops all the soft X-rays, eliminating first wall vaporization altogether. Yet the chamber radius is still very large. Tradeoffs are needed to determine if a higher gas density, coupled with a smaller radius, will still give adequate beam propagation. Also, because leakage into the chamber of the helium carrier gas is a possibility, could a high helium density be used to protect the wall instead of the xenon? Answers to these questions are likely to require experiments as well as analysis.

7.5.2 Shielding

The carbon chamber and Li_2O granules provide primary shielding, and the reinforced concrete biological shield and building structure provide the rest. Beam dumps behind the final mirrors stop primary neutrons coming from the chamber penetrations. Key issues are the absorption of neutrons scattered back from the beam dumps and activation of the concrete building - primarily from impurities in the concrete. Codes exist now that can perform the required level of analysis. High purity concrete and reinforcement are available. Much of the work being done in the MFE program can be leveraged here.

7.5.3 Final Optics

The final optics consist of final focussing mirrors and glancing incidence metal mirrors (GIMMs). The GIMMs are used to bend the optical path so as to move the focusing mirrors away from the neutron line-of-sight. Critical issues are cost, neutron lifetime, and pointing accuracy and stability. The first two are, of course, related. In SOMBRERO, GIMMs are placed 30 m from the target and the final focus mirrors are 50 m away. The primary neutron dumps also serve as support for the focusing mirrors. This arrangement may allow both mirrors to last the life of the plant, assuming the GIMMs can be periodically annealed. The GIMMs are polished metal and should be able to take 10^4 times more neutron fluence than the coated final focus mirrors.

There are 60 beam ports. Preliminary cost estimates (see Chapter 8) suggest that each glancing incidence/final focus mirror combination may cost $0.2 million per set, giving a total cost of $12 million. If costs are in fact this low, then incentive exists to bring the optics in closer, replacing them more often and reducing the cost of the large reactor building.

Little experimental data exists on neutron damage of optical surfaces and possible recovery by annealing. Little exists on boundary mixing for multilayer mirrors, which could be critical. These data will be difficult to obtain in anything but a full-scale IFE reactor, because it is likely that both energy fluence per pulse as well as cumulative fluence are important.

Pointing accuracy is a very critical issue. For example, a 2% deviation of a 5 mm spot size over 50 m is an angular deviation of only 2 μrad. Mirrors must not only be rigidly mounted with near total vibration and thermal isolation, but active optics must be employed which account for small motions and deviations in target trajectory. Because of the doubling effect of reflected beams, both types of mirrors must be twice as accurate as the beams. Fortunately, much of the technology developed during the SDI program is applicable here.

7.5.4 Lithium Oxide Transport and Ducting

Transport of Li_2O through the reactor has already been discussed. The granules must also be transported though the ducting and IHX. As with the reactor, granule erosion and fracture are key issues, particularly during the high-speed elevating portion of the circuit. Also, ducting must be designed to avoid settling points. Helium recovery and pumping power must be considered as well.

There are a number of ways of coating Li_2O (e.g., with SiC) to reduce erosion. Also, alternate materials such as lithium aluminate could be used. The fluidized bed technology already in place can be exploited to design ducts and helium pumps. Issues are related more to design than to development. Therefore, technical credibility is considered high and development requirements fairly low.

7.5.5 Intermediate Heat Exchanger

The liquid lead side of the IHX is similar to that for Osiris. Provided oxygen content is kept very low, liquid lead is compatible with iron, mild steel, and stainless steel up to about 630°C. The maximum surface temperature on the lead side is 617°C. The granule side is a fluidized flow heat exchanger, which has a well-established technology behind it. Although the IHX is fairly large, because it is low pressure on both sides, tube walls can be thin and total mass is moderate. Costs are expected to be quite acceptable. Suitable barriers exist for the small amount of tritium that diffuses from the Li_2O during transit.

7.5.6 Steam Generator

The steam generator is similar to the one for Osiris. Low pressure liquid lead flows on one side and supercritical steam on the other. Maximum wall temperature is under 600°C. As with the IHX this temperature is acceptable with stainless steel (but not with inconel), provided oxygen is excluded, perhaps with an O_2 scavenger in the loop.

7.5.7 Reactor Building

The 100-m diameter (and high) reactor building provides vacuum barrier, optics support, and supplementary biological shielding as well as protection of the reactor chamber from the outside world. While thick concrete buildings in this size range exist, none are known to have all of these requirements. Critical issues are cost, contamination by tritium and activation by scattered neutrons, decommissioning, and the ability of such a large structure to accurately support the optics with minimal deflection due to ambient temperature swings and induced vibration.

Optics support has been discussed above, and care should be taken to avoid double counting. All of the other issues appear tractable. For example, scattered neutrons can be

absorbed by using borated concrete in the inner biological shield, which has much lower mass. The vacuum can be moderate, on the order of one torr.

As discussed above, there is a strong tradeoff between final optics cost and life and reactor building cost. For example, cutting the building diameter and height in half would bring the focusing optics in to a point where they would have to be replaced perhaps four times in 30 years, rather than being lifetime components. This may well be cost effective since the reactor building cost may drop by a factor of four. On the other hand, this would place more severe demands on the GIMMs.

7.5.8 Power Conversion

The power conversion is nearly the same as that used in Osiris, supercritical steam with about 45% net efficiency. Because the laser driver takes up less land area than a heavy ion beam, siting may not be as constrained and, therefore, less effort may be needed in the area of dry air cooling. If the laser heat loss can be recovered for feedwater heating (as is assumed in our design, the power conversion efficiency is increased to about 47%.

7.5.9 Driver

As with the heavy ion beam driven reactor, the laser driver for SOMBRERO is the most expensive and most challenging component of the reactor plant. Key issues are reliability and component lifetime, beam stability, rep rate, efficiency/energy recovery, noise suppression, chemistry/toxicity, and cost.

Reliability and Component Lifetime. The driver consists of 64 beams total, of which 4 are spares. Full-time operation is then possible when the reliability of all individual beams exceeds 94%, not a very demanding figure provided beams can be switched in and out at will. The plasma cathode patented by Textron shows promise, but further development is needed. Similarly, high voltage pulsed power systems have not yet demonstrated the ability to last the lifetimes required for a power plant. Other components such as blowers, heat exchangers, and noise suppressors are relatively low-tech and should have sufficient reliability.

Beam Stability. The final optics stability is a major issue as was discussed above. The stability of the rest of the beam is also critical. Successive beams must consistently follow the same paths. This is not trivial considering the high level of turbulence, heating and noise in the

laser gas flow system. Gas temperature uniformity is critical. The entire system must be mounted on the equivalent of a large optical bench. Beams leaving the laser must pass through thermally homogeneous helium or vacuum; active optics control are required to maintain beam quality and pointing accuracy. Over two decades of work in these areas can be brought to bear, as well as more recent work during the SDI program. Many of these issue are design, rather than development, related.

Rep-Rate. The rep rate issue permeates through all of the other issues listed here. While small-scale repped KrF lasers have been developed for laboratory use, continuous repped operation day in and day out will introduce new problems, such as pulsed energy systems and heat removal, that need to be addressed.

Efficiency/Energy Recovery. The projected KrF laser efficiency is in the 7-8% range, which should be acceptable for power reactors with high gain targets. A two percentage point gain in powerplant efficiency can be realized by recovering a portion of the waste heat with feedwater heating. Whether or not this is worth the added complexity depends on its impact on capital cost, reliability, and increases in coolant pumping power. Many issues here are design, rather than development, related.

Noise Suppression. With the high flow speeds, acoustic noise is an issue with KrF lasers. Acoustic suppression entails considerable bulk and expense. Noise level in the laser cavity must be low enough not to perturb beam propagation. Considering the high level of development in noise suppression in small repped lasers, and in other areas (e.g., aircraft engines) technical credibility is high and development needs are expected to be low although some effort at cost reduction would be beneficial.

Chemistry/Toxicity. Even small amounts of free fluorine can cause problems, because fluorine is the most reactive of all the elements and is toxic at below 1.0 ppm. It is, therefore, important that the entire flow system be well-sealed. Despite these hazards, safe handling techniques have been developed elsewhere, and it is now possible to transport liquid fluorine by the ton.

7.5.10 Target Fabrication

Direct-drive targets for KrF lasers should be easier to fabricate than the indirect targets for heavy ion beams, because direct-drive targets do not use a hohlraum. Nevertheless, the

technical credibility of fabrication of direct-drive targets at high rep-rate is currently low, and development requirements are quite high.

7.5.11 Target Injection

Target injection requirements and concerns are comparable to those discussed for Osiris.

7.6 TECHNOLOGY ASSESSMENT RATINGS FOR SOMBRERO

Table 7.4 below is the SOMBRERO counterpart of the summary table for Osiris. The issues are generally similar with some differences due to the type of reactor chamber and driver. While Osiris is very leak tolerant, leak-tightness is an issue in SOMBRERO. While shock waves are a concern in the high vacuum Osiris chamber, fireball and blast response, while requiring consideration, does not appear to be a serious issue for SOMBRERO. The final optics of the KrF laser are a more serious concern than the final focus hardware is for the heavy ion beam; however, mass flow up the beam lines, which was a major concern for Osiris, is not a concern for SOMBRERO.

The Overall Urgency Factor is a weighted average of the five issues listed (weights are given in Table 7.1). In general, values of 50% or over deserve serious consideration, especially if lead time is shown to be long.

Table 7.4. Technology Assessment for SOMBRERO

SOMBRERO - REACTOR CHAMBER

CARBON STRUCTURE FABRICATION:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)				●	
Critical Technology (30%)				●	
High Development Cost (30%)		●			
Long Lead Time (20%)			●		
% Cost in Experiments (10%)				●	
Overall Urgency Factor			★		

LEAK TIGHTNESS AND DETECTION:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)					●
Critical Technology (30%)				●	
High Development Cost (30%)	●				
Long Lead Time (20%)		●			
% Cost in Experiments (10%)				●	
Overall Urgency Factor			★		

REMOTE MAINTENANCE AND ASSEMBLY:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)			●		
Critical Technology (30%)				●	
High Development Cost (30%)			●		
Long Lead Time (20%)		●			
% Cost in Experiments (10%)				●	
Overall Urgency Factor			★		

Table 7.4 (continued)

SOMBRERO - REACTOR CHAMBER (continued)

FIREBALL / BLAST RESPONSE:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)			●		
Critical Technology (30%)			●		
High Development Cost (30%)		●			
Long Lead Time (20%)		●			
% Cost in Experiments (10%)		●			
Overall Urgency Factor		★			

Li_2O HEAT TRANSFER:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)	●				
Critical Technology (30%)			●		
High Development Cost (30%)		●			
Long Lead Time (20%)	●				
% Cost in Experiments (10%)			●		
Overall Urgency Factor		★			

Li_2O AND STRUCTURE EROSION:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)				●	
Critical Technology (30%)				●	
High Development Cost (30%)			●		
Long Lead Time (20%)		●			
% Cost in Experiments (10%)				●	
Overall Urgency Factor				★	

Table 7.4 (continued)

SOMBRERO - REACTOR CHAMBER (continued)

FLUIDIZED FLOW:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)		●			
Critical Technology (30%)			●		
High Development Cost (30%)		●			
Long Lead Time (20%)	●				
% Cost in Experiments (10%)			●		
Overall Urgency Factor		★			

BEAM PROPAGATION INTO CHAMBER:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)				●	
Critical Technology (30%)			●		
High Development Cost (30%)		●			
Long Lead Time (20%)			●		
% Cost in Experiments (10%)			●		
Overall Urgency Factor			★		

SOMBRERO - SHIELDING

	Low 0	25	50	75	High 100
Technical Immaturity (10%)			●		
Critical Technology (30%)		●			
High Development Cost (30%)		●			
Long Lead Time (20%)	●				
% Cost in Experiments (10%)		●			
Overall Urgency Factor		★			

Table 7.4 (continued)

SOMBRERO - FINAL OPTICS

	Low 0	25	50	75	High 100
Technical Immaturity (10%)					●
Critical Technology (30%)					●
High Development Cost (30%)			●		
Long Lead Time (20%)			●		
% Cost in Experiments (10%)				●	
Overall Urgency Factor				★	

SOMBRERO - Li_2O TRANSPORT AND DUCTING

	Low 0	25	50	75	High 100
Technical Immaturity (10%)		●			
Critical Technology (30%)		●			
High Development Cost (30%)		●			
Long Lead Time (20%)		●			
% Cost in Experiments (10%)			●		
Overall Urgency Factor		★			

SOMBRERO - INTERMEDIATE HEAT EXCHANGER

	Low 0	25	50	75	High 100
Technical Immaturity (10%)			●		
Critical Technology (30%)	●				
High Development Cost (30%)		●			
Long Lead Time (20%)	●				
% Cost in Experiments (10%)			●		
Overall Urgency Factor		★			

Table 7.4 (continued)

SOMBRERO - STEAM GENERATOR

	Low 0	25	50	75	High 100
Technical Immaturity (10%)		●			
Critical Technology (30%)	●				
High Development Cost (30%)		●			
Long Lead Time (20%)	●				
% Cost in Experiments (10%)			●		
Overall Urgency Factor		★			

SOMBRERO - REACTOR BUILDING

	Low 0	25	50	75	High 100
Technical Immaturity (10%)				●	
Critical Technology (30%)				●	
High Development Cost (30%)			●		
Long Lead Time (20%)	●				
% Cost in Experiments (10%)		●			
Overall Urgency Factor			★		

SOMBRERO - POWER CONVERSION

	Low 0	25	50	75	High 100
Technical Immaturity (10%)	●				
Critical Technology (30%)		●			
High Development Cost (30%)	●				
Long Lead Time (20%)	●				
% Cost in Experiments (10%)	●				
Overall Urgency Factor	★				

Table 7.4 (continued)

SOMBRERO - LASER DRIVER

RELIABILITY AND COMPONENT LIFETIME:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)			●		
Critical Technology (30%)				●	
High Development Cost (30%)					●
Long Lead Time (20%)					●
% Cost in Experiments (10%)				●	
Overall Urgency Factor				★	

BEAM STABILITY:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)		●			
Critical Technology (30%)				●	
High Development Cost (30%)				●	
Long Lead Time (20%)			●		
% Cost in Experiments (10%)				●	
Overall Urgency Factor				★	

REP RATE:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)			●		
Critical Technology (30%)				●	
High Development Cost (30%)			●		
Long Lead Time (20%)			●		
% Cost in Experiments (10%)				●	
Overall Urgency Factor			★		

Table 7.4 (continued)

SOMBRERO - LASER DRIVER (continued)

EFFICIENCY/ENERGY RECOVERY:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)		●			
Critical Technology (30%)	●				
High Development Cost (30%)		●			
Long Lead Time (20%)	●				
% Cost in Experiments (10%)		●			
Overall Urgency Factor		★			

NOISE SUPPRESSION:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)		●			
Critical Technology (30%)		●			
High Development Cost (30%)		●			
Long Lead Time (20%)	●				
% Cost in Experiments (10%)			●		
Overall Urgency Factor		★			

CHEMISTRY/TOXICITY:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)		●			
Critical Technology (30%)		●			
High Development Cost (30%)	●				
Long Lead Time (20%)	●				
% Cost in Experiments (10%)			●		
Overall Urgency Factor		★			

Table 7.4 (continued)

SOMBRERO - LASER DRIVER (continued)

DRIVER - COSTS:

	Low 0	25	50	75	High 100
Technical Immaturity (10%)					●
Critical Technology (30%)				●	
High Development Cost (30%)				●	
Long Lead Time (20%)			●		
% Cost in Experiments (10%)				●	
Overall Urgency Factor				★	

SOMBRERO - TARGET FABRICATION

	Low 0	25	50	75	High 100
Technical Immaturity (10%)				●	
Critical Technology (30%)					●
High Development Cost (30%)			●		
Long Lead Time (20%)			●		
% Cost in Experiments (10%)				●	
Overall Urgency Factor				★	

SOMBRERO - TARGET INJECTION

	Low 0	25	50	75	High 100
Technical Immaturity (10%)			●		
Critical Technology (30%)					●
High Development Cost (30%)		●			
Long Lead Time (20%)		●			
% Cost in Experiments (10%)				●	
Overall Urgency Factor			★		

7.7 SUMMARY OF DEVELOPMENT PRIORITIES FOR SOMBRERO

Table 7.5 gives a summary of the above discussion and lists technical credibility of the current state-of-the-art for each item, as well as development needs for reactor applications. It also shows a ranking of the development priorities for each major subsystem and, where appropriate, for issues within the subsystem. The development needs are not necessarily the inverse of technical credibility, because, in many cases, rather simple experiments can resolve major issues. The level of expense and difficulty has been included, as has the impact on reactor performance and cost.

As with the Osiris reactor, the driver ranks first in development priority. The key issue is costs, which translates into technical issues like material selection, fabrication techniques, and tolerances. Reliability and component lifetime are related to costs, of course, but they have been separated out here as an issue that will require considerable development. The remaining driver issues have moderate to low development needs.

Target fabrication and injection rank 2nd and 4th, respectively, primarily because of the newness of the technology. Being simpler than hohlraum targets, direct drive targets should be easier to fabricate.

The reactor chamber appears to have fewer development problems than the driver/target systems. The key issues here are sustained leak tightness and erosion. The first depends on the allowable helium density in the target chamber, which will certainly be much higher than the allowable xenon density, and on the pumping capacity of the vacuum system.

The final optics concerns rank fifth in development priority to the driver, because the problems here are less severe and because there are fewer of them. Final optics problems center around pointing stability and neutron damage. The last could be a show stopper if lifetimes are much less than our estimates.

The reactor building, although very large, is technically fairly credible. Key issues are cost, vacuum maintenance, dimensional stability, and activation from scattered neutrons.

The remaining issues (i.e., Li_2O transport, IHX, steam generator, shielding, and power conversion) are all quite credible today and require little costly development.

Table 7.5 SOMBRERO Development Priorities

ITEM	CURRENT TECHNICAL CREDIBILITY	DEVEL. NEEDS	DEVEL. PRIORITY
DRIVER	**LOW**	**HIGH**	**1**
Costs	Low	High	1
Reliability	Moderate	High	2
Rep Rate	Moderate	Moderate	3
Efficiency	Moderate	Low	4
Beam Stability	High	Moderate	5
Chemistry	High	Low	6
Noise	High	Low	7
TARGET FABRICATION	**LOW**	**HIGH**	**2**
REACTOR CHAMBER	**MODERATE**	**MODERATE**	**3**
Leak Tightness	Low	Moderate	1
Carbon Fabrication	Moderate	Moderate	2
Li_2O Structure and Erosion	Moderate	Moderate	3
Fluidized Flow	High	Low	4
Blast Response	High	Low	5
Li_2O Heat Transfer	High	Low	6
TARGET INJECTION	**MODERATE**	**MODERATE**	**4**
FINAL OPTICS	**MODERATE**	**MODERATE**	**5**
REACTOR BUILDING	**MODERATE**	**MODERATE**	**6**
Li_2O TRANSPORT	**HIGH**	**LOW**	**7**
IHX	**HIGH**	**LOW**	**8**
STEAM GENERATOR	**HIGH**	**LOW**	**9**
SHIELDING	**HIGH**	**LOW**	**10**
POWER CONVERSION	**HIGH**	**LOW**	**11**

7.8 GENERIC IFE ISSUES

Some of the issues discussed here have been touched on in previous sections and some have not. They are pulled out separately here to emphasize that they are not specific to any reactor/driver combination and must be pursued for the general benefit of IFE.

7.8.1 Target Design Innovations

While this study pointedly avoided getting into target design, it became clear that this issue can significantly impact the design of the plant. In particular, pushing the knee in the gain curve toward lower driver energies and reducing illumination uniformity requirements could greatly reduce plant cost and complexity. If HIB and KrF laser cost estimates remain at the level predicted in this study, $100-200/Joule, then getting reasonable gains with about 2 MJ driver energy would give very reasonable plant costs. Factored into this, of course, is rep-rate. This could increase to fairly high levels. For example, with 2 MJ driver and a target gain of 60, target yield is only 120 MJ, and a 20 Hz repetition rate is required for 2400 MW of fusion power. This impacts target injection, chamber design and clearing, and driver power conditioning. While it is likely that these issues will force an upper bound on rep-rate, one can always look at lower total thermal power levels. This would be a great attraction initially until investors feel confident enough to fund larger power plants.

Illumination requirements had some impact on Osiris, but a great impact on SOMBRERO. Single-sided illumination would eliminate bending magnets in Osiris, and reduce beam growth due to momentum spread, but the cost savings is likely to be small. Some bending will still be needed to dump neutrons. If polar illumination requirements could be reduced for SOMBRERO, then the very expensive reactor building could be substantially reduced. The ideal situation is to have all laser beams on the ground. Then final optics can be placed as far away as desired, and optics support is made much easier. This would require considerable innovation in target design, perhaps involving cylindrical, rather than spherical symmetry.

These are just some of the issues relating to targets. Clearly, future activities should keep the ultimate reactor requirements in mind, with every effort aimed toward lower cost and greater simplicity. Further interaction between target designers and reactor designers could lead to much more attractive power plants.

7.8.2 Reactor Modeling

The results from this study underscore the importance of integrated modelling of IFE reactors. Systems codes, using distillations of more complex analyses, provide invaluable parametric scans that show where optima and sensitivities actually lie. This provides a good counterbalance against intuition, which is often wrong. Reactor design studies, like this one, show the necessary development critical paths and, conversely, where work can be curtailed.

Most important is timeliness. Results must be early enough to influence large, expensive development programs before commitments are made. In the MFE program, early reactor modeling had little influence, because they paralleled the experiments. Now that the models exist and are quite sophisticated, they are having a substantial impact in the planning of large experiments like ITER. We need to have similar models in place soon, so they can influence planning for near term experimental facilities.

When performed in sufficient depth, modelling of reactor and driver systems can give at least a relative costing of the various components. This is valuable in showing where emphasis should be placed in the development program. Clearly, the results are sensitive to the values used as installed unit costs (e.g., $/kg, $/Joule, $/Watt). This is where much care is required to ensure that the best values available are used. Where cost uncertainties are great, sensitivity studies are important. Often, similar components can be found in other areas like the fission, high energy physics, and space, military and SDI programs. Unit costs found here can be used after suitable adjustment for the fusion environment.

7.8.3 Low Activation and Neutron-Resistant Materials

This issue permeates all of fusion. Even in the unlikely case of D-^{3}He fuel working, there are enough neutrons to cause activation concerns. With D-T, both activation and lifetime are issues. There are two ways of dealing with these problems:

Liquid First Wall/Blanket. Enough liquid blanket is placed in front of the first material wall that most of the neutrons don't reach it. This is the approach in HYLIFE,[7.3] HYLIFE-II[7.4] and the LIFE reactor discussed in Appendix D. Almost any material compatible with the liquid can be used with little activation and lifetime usage. This is a very appealing approach in that the need for specially developed materials for fusion is essentially eliminated.

It does, however, place constraints on the reactor design. Coolants need to be low activation, contain lithium, and be capable of high temperature operation without excess vapor pressure in the chamber. Possible candidates are liquid lithium, lithium-lead, and Flibe. Lithium has chemical hazard concerns, and lithium-lead has concerns about polonium production (although one could possible remove it using a side stream). The use of Flibe avoids the safety concerns of liquid lithium and the activation concerns of lithium lead. Fortunately, Flibe has a considerable data base from the molten salt reactor program.[7.5]

Geometries are generally limited to cylindrically symmetric with axis vertical for gravity flow systems and horizontal for rotating systems. This places constraints on illumination, which is especially difficult with vertical flow because the streams must be parted to get the beams through. The rotating LIFE and Cascade (which uses granules instead of liquid) reactors have natural beam access through the ports.

Low-Z Ceramics. Materials containing low atomic number materials like carbon, silicon, hydrogen, lithium, beryllium, boron, aluminum, oxygen, and fluorine (but not nitrogen) have little long-life activation from fast neutrons. Unfortunately, for high temperature use the only engineering materials containing these elements are brittle ceramics. The materials of greatest interest to fusion[7.6] are carbon and graphite, silicon carbide (SiC), alumina (Al_2O_3), boron carbide (B_4C), beryllium carbide (Be_2C), and beryllia (BeO). Composites of these, such as carbon-carbon, SiC-SiC, and carbon-SiC are also being investigated. The brittleness of ceramics is mitigated by using ceramic-ceramic composites that have high fracture toughness.

Osiris uses low activation graphite in a way that eliminates the brittleness problems, as a fabric. Flibe is allowed to bleed through to provide a wetted wall. There are, however, issues concerning Flibe wetting and chemistry, as discussed above.

SOMBRERO uses large composite or graphite panels with SiC as a sealant. The sealing requirements are modest because (1) the gas to be sealed is helium, of which a fairly large quantity can probably be tolerated in the chamber, and (2) the gas pressure is no more than two atmospheres. Nevertheless, the sealing issue is critical to the success of the concept.

Ceramic composites have the promise of providing fracture toughness and a modicum of ductility. Carbon-carbon, SiC-SiC, and carbon-SiC are all being investigated using chemical vapor infiltration. One interesting feature is the ability to prepare a preform consisting of laid-up fabric and a small amount of matrix infiltration. This preform has a stiffness similar to

styrofoam and can be machine-finished with conventional tooling. It can then be further infiltrated to near full density and possess essentially the final desired dimensions. This could possibly be done in SOMBRERO with final infiltration done in-situ. The chamber would serve as its own oven.

These composites can be densified to up to 90% of theoretical density. The infiltration process requires residual porosity and permeability; therefore, they are not leak tight. Solid surface coatings are required, preferably in multiple, loosely bound layers for redundancy. For high pressure use, they are best used as an outer structural layer for solid ceramic pressure tubes and ducts.

General Atomics (GA) is looking at a carbon fiber/SiC matrix composite called "VCS" (Vapor-Carbon-Silicon) that uses annealed vapor grown carbon fibers in a CVD SiC matrix. The fibers have an axial thermal conductivity approaching diamond. They are also more resistant to fast fission neutrons than SiC. In a 50% matrix with isotropic fibers, thermal conductivity would be about that of copper. The composite could take heat fluxes of around 40 MW/m^2-cm thickness at up to 1100°C. It could take substantial neutron doses and not be inclined to absorb tritium. GA has made preforms that are readily machinable. General Motors is pursuing development of the fibers for automotive use.[7.7]

The ability of the first wall/blanket material to withstand fast neutrons impacts the minimum first wall radius and the frequency of change-outs. The neutron lifetime is defined as that operating interval beyond which the material can no longer perform its function. Much then depends on what this function is. The lifetime can be longer if loads and stresses are light, if allowance can be made for dimensional changes due to neutron irradiation, and if the material can be periodically cycled down to room temperature during shutdowns. Much of the thinking that went into the Osiris and SOMBRERO design concepts included these principles.

There are metallic, weldable materials that need to be pursued even though their activity is higher, because they are easier to fabricate into large, leak-tight assemblies. Among them are ferritic steels, vanadium alloys, and possibly other austenitic stainless steels besides 316. Innovations such as dispersion-strengthening of stainless steels should be explored. Most likely, near-term reactors will be made of welded metal. Because of the long lead times required to have a new material approved for use in construction, material research must begin well before reactor construction designs.

7.8.4 Remote Maintenance

Use of low activation materials is more valuable in reducing long-term waste storage than in providing manned access to the reactor chamber immediately after shutdown. Yet, in a power reactor, such access is required if availability is to remain high. While mentioned in the Osiris and SOMBRERO assessments, it is called out as a generic issue here, because it tends to be ignored, or it is assumed that the technology will be available when the time comes.

Remote maintenance can borrow heavily from the fission program, the remotely-piloted vehicle and aircraft programs, from NASA's telerobot program, and from the industrial robotic manufacturing and AI programs. However, there are issues specific to each design concept that require specially-tailored remote maintenance approaches. Removing the drained fabric blanket from Osiris, for example, requires different remote maintenance scenarios than leak detection and repair in SOMBRERO. While many of these issues are design, rather than developmental in nature, we should at least be able to see the way toward viable remote maintenance systems.

7.9 TECHNOLOGY ASSESSMENT RATINGS FOR GENERIC ISSUES

Table 7.6 shows a semi-quantitative technical assessment for the four generic issues discussed above. The table follows the format of the Osiris and SOMBRERO assessment.

All of these are critical in that they impact all elements of IFE powerplant development. Innovations in targets, or discoveries from reactor modelling, for example, could move the program in totally unexpected directions. For this reason, lead times are considered long so that results can impact the program before long-term commitments or premature down-selections are made.

It is important to look at the individual entries in Table 7.3 (and the other tables, for that matter), and not just the overall urgency factor. For example, while the last is fairly low for reactor modelling, criticality is high and lead time is long. Development cost, however, is very low compared to other items. This suggests an on-going, low-level effort in reactor modelling so that results can influence the IFE development program.

Low-activity, neutron-resistant materials must be vigorously pursued without delay at a fairly high level, unless a commitment is made to reactor designs that have thick "healable" flowing liquid or granule blankets like HYLIFE, Cascade, or LIFE. A main attraction for fusion

is the ability to design reactors with low radioactivity and little radioactive waste. If this is ignored, fusion will be much more difficult to sell to the voting public.

Remote maintenance, while critical, can borrow from other programs. Effort is required, however, to tailor it to the IFE program.

Table 7.6. Technology Assessment for Generic IFE Issues

TARGET DESIGN INNOVATIONS

	Low 0	25	50	75	High 100
Technical Immaturity (10%)				●	
Critical Technology (30%)				●	
High Development Cost (30%)		●			
Long Lead Time (20%)				●	
% Cost in Experiments (10%)			●		
Overall Urgency Factor			★		

REACTOR MODELING

	Low 0	25	50	75	High 100
Technical Immaturity (10%)		●			
Critical Technology (30%)				●	
High Development Cost (30%)	●				
Long Lead Time (20%)				●	
% Cost in Experiments (10%)	●				
Overall Urgency Factor		★			

Table 7.6 (continued)

LOW ACTIVITY, N-RESISTANT MATERIALS

	Low 0	25	50	75	High 100
Technical Immaturity (10%)				●	
Critical Technology (30%)				●	
High Development Cost (30%)			●		
Long Lead Time (20%)				●	
% Cost in Experiments (10%)				●	
Overall Urgency Factor				★	

REMOTE MAINTENANCE

	Low 0	25	50	75	High 100
Technical Immaturity (10%)			●		
Critical Technology (30%)				●	
High Development Cost (30%)		●			
Long Lead Time (20%)		●			
% Cost in Experiments (10%)			●		
Overall Urgency Factor			★		

7.10 SUMMARY

We have performed technology assessments two ways:

1. Qualitative task prioritization
2. Semi-quantitative assessment of development issues and urgency

While target and driver development dominate, there are several other tasks that should be pursued in parallel, but generally at a lower level. These tasks can impact driver and target development. In particular, reactor modelling and parametric studies, fusion materials, reactor chamber concepts, and beam delivery all synergistically impact the overall program. They should be supported on a continuous, but moderate, level.

A detailed development plan devised by a task force consisting of contractors, DOE, and the laboratories would provide a valuable road map to commercialization and ensure that nothing gets left out.

7.11 REFERENCES FOR CHAPTER 7

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