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APPENDIX F
ADDITIONAL COMPARISONS OF OSIRIS AND SOMBRERO

In addition to the comparisons presented in Chapter 9, a qualitative comparison of various aspects of the two designs was made by surveying the scientists and engineers involved in the study. Forms requesting qualitative assessment covered the following categories:

- Physics
- Driver technology
- Reaction chamber
- Breeding material
- Targets and target delivery
- Power conversion

Team members were asked to assign each component within a category a measure of confidence level as seen at the present time. The confidence level is an assessment of the current level of understanding and ability to analyze a problem in sufficient detail and/or the ability to design and build a subsystem that would work as envisioned. The measures for confidence level were high, moderately high, moderately low, and low. Although it is generally true that a low confidence level today will correspond to high development needs (i.e., the time and resources required to achieve the required performance or full development the required technology), this is not always true. There are many instances where issues leading to a low confidence level could be addressed in experiments or development programs of modest cost and duration. (Development needs are discussed in Chapter 7.) The following comparisons are based on the responses of the scientists and engineers directly involved in the study. No attempt was made to normalized the relative pessimism and optimism of the respondents.

F.1 PHYSICS COMPARISON

The physics category has been divided into five general areas: the driver, beam propagation, beam/target coupling and x-ray conversion, target gain, fireball calculations and vaporization, and condensation. Figure F.1 summarizes the overall physics comparison.

F.1.1 Driver

The KrF laser design builds on the physics from Nike and Aurora. The Aurora KrF laser has delivered 10 kJ on target while the needed energy in SOMBRERO is 3.4 MJ. The confidence level in the physics is moderately high. Although high current, large induction linacs have not yet been built, the principle of multiple beam transport has been demonstrated in Livermore Berkeley

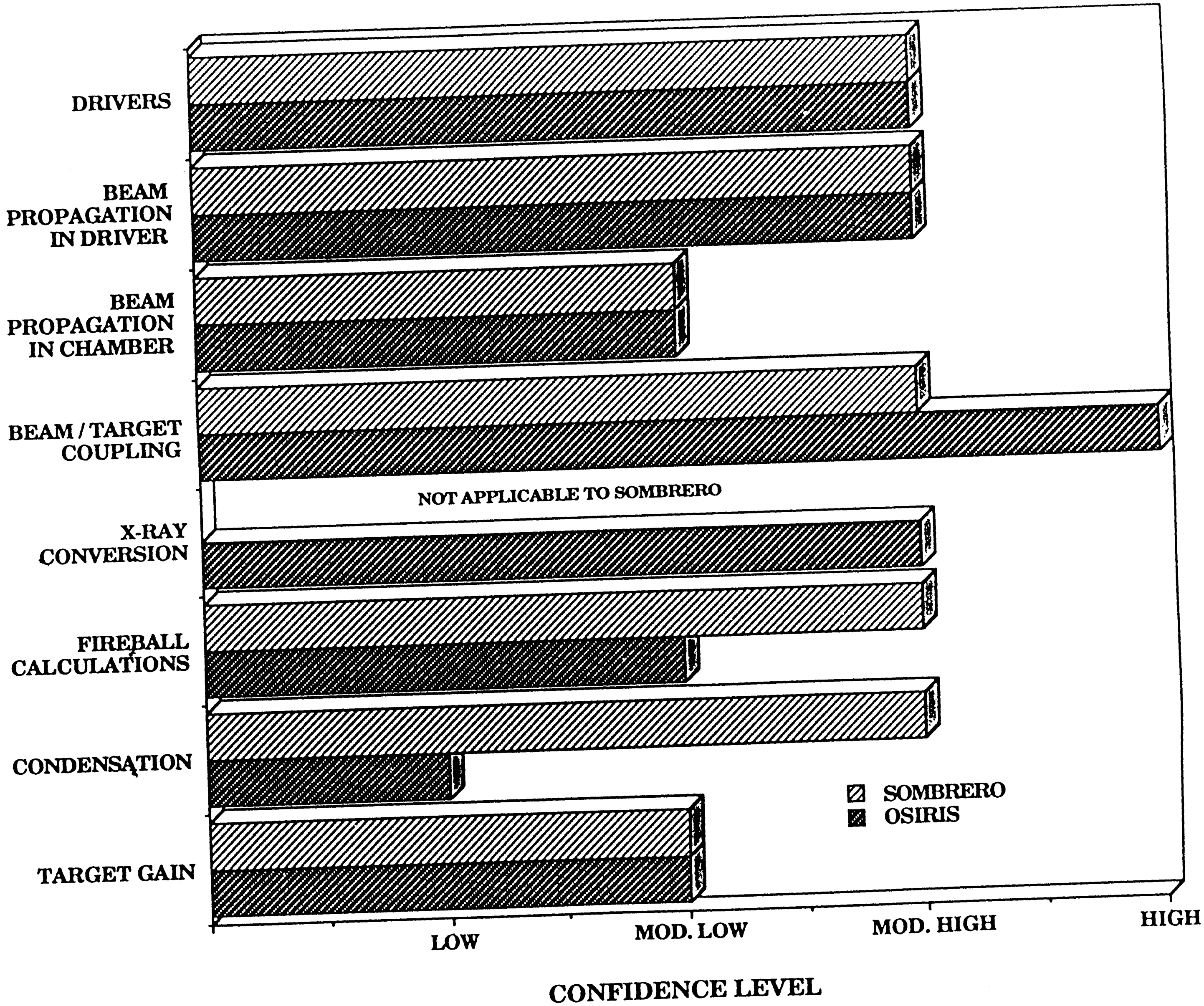

Fig. F.1. Summary of the overall physics comparison.

Laboratory's (LBL) multiple beam experiment (MBE-4). It has a final voltage of 1 MV while the Osiris accelerator will require a voltage of 3.8 GV. Relying on the physics learned from the experiment, the driver has been designed using a conservative approach with singly charged ions and without beam combination or beam separation. Here again, the confidence level in the physics is moderately high.

F.1.2 Beam Propagation

The confidence level for beam propagation through the driver is moderately high for both the HIB driver and the laser. Propagation of the heavy ion beam after it leaves the final optics has a moderately low confidence level. In the case of the laser beam, gas breakdown is an issue of concern, and here the confidence level is moderately low.

F.1.3 Beam Target Coupling and X-ray Conversion

The physics of beam and target coupling is better understood for HIB, rating a high confidence level. Although 1/4 micron wavelength KrF laser light couples to targets better than higher wavelengths, the confidence level is moderately high.

X-ray conversion only applies to the indirect drive targets used by Osiris. Here the confidence level is moderately high.

F.1.4 Fireball Calculations and Vaporization

The confidence level in the Xe gas response to the x-ray and ion deposition in SOMBRERO is moderately high. Ion energy deposition in the Xe gas depends on their in-flight charge state. However, since the initial ions' charge state as they leave the target is not known, this is difficult to determine. The re-radiation of the energy to the SOMBRERO chamber occurs to a large degree in atomic lines, thus, line trapping is a dominant process. The CONRAD code ignores line trapping, but does radiation transport in a multi-group model. It has been found that using many groups in a multi-group model fortuitously gives decent agreement with line trapping calculations. There is a definite need for development of a hydrodynamics code which includes line trapping physics. The reason the confidence level is moderately high is because CONRAD has been benchmarked against shock experiments in Xe gas. Vaporization of the carbon/carbon (C/C) FW is performed with heat transport calculations which have moderately high confidence level, because they rely on the moderately high confidence in the CONRAD simulations. Further, the thermal properties of c/c advanced composites after irradiation are not well known.

The calculations of radiation transport and hydrodynamics in the Flibe cloud vaporized from the Osiris first wall (FW) is rated moderately low confidence, because the chemical kinetics of Flibe at the expected temperatures is uncertain and the optical properties are even more uncertain, due to molecular effects. The complexity of the Osiris geometry reduces confidence in the one-dimensional calculations. However, the confidence level in the vaporization of Flibe is moderately high, because deposition lengths of x-rays are well known. Volumetric vaporization needs study, however, because it is unclear how material behaves when it is at the boiling temperature but below the vaporization energy.

F.1.5 Condensation

The confidence level for condensation in Osiris is low because of the unusual geometry of the chamber and the very complex chemical issues going on. Vaporization in SOMBRERO is essentially non-existent and, therefore, condensation is not an issue, rating a moderately high confidence level.

F.1.6 Target Gain

Target gain will always have a moderately low confidence level until target experiments are performed at reactor relevant driver energies.

F.2 DRIVER TECHNOLOGY COMPARISON

The drivers have been compared in 11 areas. The first four are meant to be analogous subsystems.

	KrF Laser	Heavy-Ion Driver
1.	Front End	Injector
2.	Intermediate Amplification and Multiplexing	Low Energy Transport and Compression
3.	Final Amplification	Acceleration
4.	Demultiplexing and Beam Delivery	Final Transport and Pulse Compression

The remaining seven features (discussed below) are common to both drivers. Figure F.2 summarizes the driver technology comparison.

F.2.1 Front End / Injector

The non-zooming baseline design can easily build on the front end development for the Nike system at NRL as well as the broad band front end work at Los Alamos in recent years. What is needed is a repetitively pulsed front end with well controlled beam spatial and temporal profiles, but it does not have to be efficient. The confidence level is moderately high. 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.

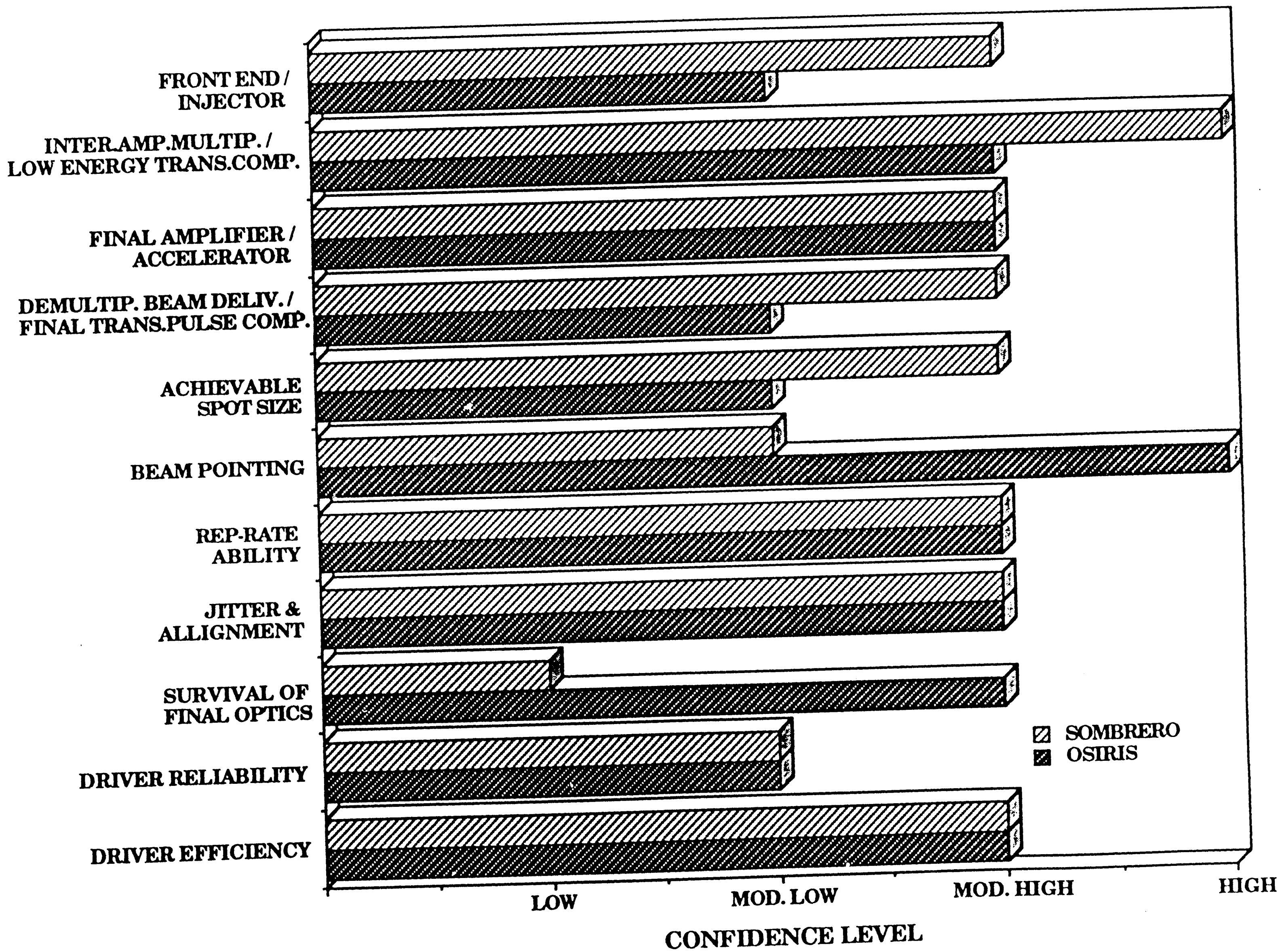

Fig. F.2. Summary of the driver technology comparison.

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. Thus the present confidence level is moderately low.

F.2.2 Intermediate Amplification and Multiplexing / Low Energy Transport and Compression

The intermediate amplifier technology for the KrF laser is similar to the final amplifier but less demanding in stress levels, ASE, flow, acoustics, and optics. Multiplexing is a straightforward use of technology developed in Aurora, Nike, and elsewhere. The new element is repetitive operation and for this the confidence level is high.

The low energy transport in the HI driver has two critical issues relating to quadrupole design: 1) How short can a quadrupole be and still have sufficiently high field quality? and 2) How closely can the quadrupoles be packed in the beginning of the driver? The confidence level is moderately high.

F.2.3 Final Amplifier / Accelerator

Much of the KrF final amplifier technology has been demonstrated in key although restricted domains. What remains is the scaling in size and improvement in operating characteristics for the design point selected. The flow and acoustics parameters have been pushed and will require design verification. The confidence level is moderately high.

High rep-rated accelerators have been operating for decades, albeit for significantly different beam parameters, and there are no accelerators that even approach the currents and charge to mass ratio that is needed in Osiris. However, the confidence level is moderately high.

F.2.4 Demultiplexing and Beam Delivery / Final Transport and Pulse Compression

For this stage the requirements are reasonably straight forward and do not require very sophisticated optics development. What is needed is a carefully engineered component design, mounts, beam control between stages and optimized architecture with regard to re-imaging between stages. The confidence level is moderately high.

The critical issues in the HIB final transport and pulse compression are the lack of experimental data. Although sophisticated modeling of final transport and beam compression has been performed, there is no experimental verification. The confidence level is moderately low.

F.2.5 Achievable Spot Size

It is relatively straight forward to achieve the required spot size with the laser since we image an appropriate front end aperture through the amplifier chain, and the beam quality and diffraction requirements are far from the limits. However, care has to be taken in preserving beam spatial and temporal fidelity in the sequence of amplifying stages. The confidence level is moderately high. For the HIB, beam combination is often ignored in calculating the spot size, and expensive experiments will be needed. The confidence level is moderately low.

F.2.6 Beam Pointing

Typically, beam pointing or steering in lasers is achieved by minor adjustments in mirrors located somewhere in the chain in the beam delivery system. The confidence level is moderately low. In the HIB this requirement is not demanding. A two tesla dipole field extending over one meter can steer the beam 10 cm from the chamber center. The confidence level is high.

F.2.7 Rep-Rate Ability

In the laser, having selected a relatively modest 60 kJ size final amplifier cavity and high J/liter input energy, we have a modest size cavity. At rep-rates <10 Hz, pure e-beam pumping allows for a modest flush factor and flow Mach number resulting in a relatively low pressure drop in the flow system. The confidence level is moderately high. Achieving high rep-rate is not a problem for accelerators which have a good track record in this respect. The confidence level is moderately high.

F.2.8 Jitter and Alignment

We did not study jitter and alignment in detail. However, based on development in related systems (e.g., in SDIO and DoD), our confidence level is moderately high. In the case of the HIB, the same is true, and the confidence level is also moderately high.

F.2.9 Final Optics Survival

The lifetime of the grazing incidence metal mirrors (GIMM) is dependent on the degree of radiation damage relief by annealing. This area has a lot of uncertainty due to lack of data. The confidence level is low. In the HIB, the final quadrupoles and steering dipoles are very well shielded, giving a moderately high confidence level.

F.2.10 Driver Reliability

The reliability of the laser as well as the HIB is very difficult to assert because of the simple lack of experience. There is no information on long duration e-beam pumped excimer lasers.

Similarly, accelerators today do not have to push reliability to a level needed for a power reactor. For this reason, the confidence level for both is moderately low.

F.2.11 Driver Efficiency

The laser driver efficiency is based on code calculations that are tied to a rather extensive data base that includes large and small lasers. KrF kinetics and extraction are areas that has been studied at many laboratories around the world for many years and have received continuous peer review. The SOMBRERO design has parameters that are part of this existing data base, but for which not all parameter values have been simultaneously present. Thus, the confidence level is moderately high. The Osiris induction linac efficiency is also based on evaluations performed at LBL and here, too, the confidence level is moderately high.

F.3 REACTOR CHAMBER COMPARISON

The SOMBRERO and Osiris chambers were compared on eight features: materials and construction, leak tightness, heat transfer, fluid dynamics, clearing at rep-rate, nuclear performance, chemistry and erosion, and lifetime assessment. Figure F.3 summarizes the reaction chamber comparison.

F.3.1 Materials and Construction

Both Osiris and SOMBRERO chambers are constructed from carbon based materials. Osiris is made from a very tight weave of graphite fibers with a very carefully controlled diffusion capability. Both the material survival in the corrosive Flibe environment and the ability to construct and maintain a constant weep potential rate a moderately low confidence level. The SOMBRERO chamber is made from a rigidized 4D and 3D weave C/C composite, where the FW is made of 4D and the remaining blanket of 3D. At the present time the confidence level in the materials and chamber construction is moderately low.

F.3.2 First Wall Protection

This is related to the fireball calculation and vaporization, which were covered in F.1.4.

F.3.3 Leak Tightness

Leak tightness is only relevant to SOMBRERO. There is very little information on the leak tightness of C/C composites: however, SiC components have been made vacuum tight. It is assumed that the inside surface of the coolant channels will have a thin coating of SiC as a sealer. Further, it has been shown in Section 3.2.4.2 that a substantial He gas leak rate of ~920 liters/s can

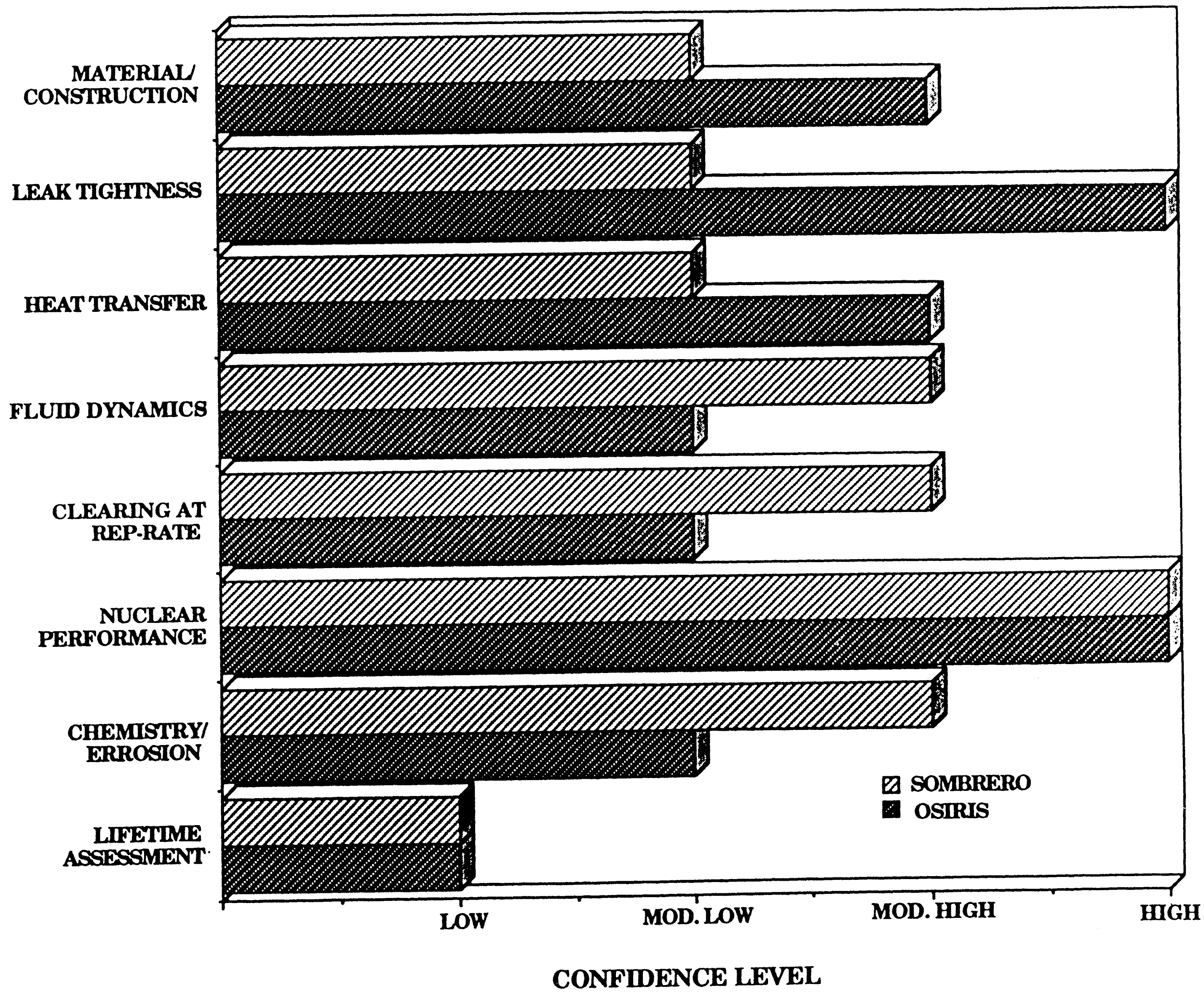

Fig. F.3. Summary of the reactor chamber comparison.

be tolerated without degrading performance. Nevertheless, the confidence level for leak tightness is moderately low.

F.3.4 Heat Transfer

Heat transfer characteristics of Flibe are well known and rate a confidence level of moderately high. There is very scarce information on heat transfer in moving beds. In making use of a continuum in determining heat transfer coefficients, it was necessary to extrapolate effective viscosities to higher values of velocity than are available from experiments. For this reason, heat transfer in SOMBRERO has a moderately low confidence level.

F.3.5 Fluid Dynamics

A critical issue in Osiris is the weeping of Flibe through the FW fabric. Uncertainty about the ability to maintain a uniform layer for the lifetime of the blanket gives this category a moderately low confidence rating. Flow dynamics in SOMBRERO has to do with the movement of the Li_2O particles in the flow channels. These channels are very large, and flow control is at the exit from the channels. Thus the confidence level in this is moderately high.

F.3.6 Clearing at Rep-rate

There is some uncertainty on whether the vapors in Osiris will condense in time between shots, and on this the confidence level is moderately low. SOMBRERO has essentially no evaporation; thus, this is not an issue.

F.3.7 Nuclear Performance

In this area both reactors have a high confidence level.

F.3.8 Chemistry / Erosion

The most detrimental chemical issue in Osiris is the x-ray decomposition of Flibe into the elementary atoms. The recombination of these atoms is difficult to predict without knowing the gaseous reaction rates at high temperatures, but could lead to the formation of LiF, BeF, BeF_2, LiBe and F_2. The chemically reactive fluorine (F_2) formed near the FW would attack the carbon fibers. For this reason, a rating of moderately low is given to the confidence level.

The question of erosion in SOMBRERO is not a concern at the low velocities in the moving bed (115 cm/s), giving a moderately high confidence level.

F.3.9 Lifetime Assessment

The whole area of radiation damage in materials for fusion is in its infancy requiring 14 MeV neutron sources and long development times to accumulate damage rates relevant to power reactors. For this reason, the confidence level for both reactors is low.

F.4 BREEDING MATERIAL COMPARISON

Figure F.4 summarizes the breeding material comparison.

F.4.1 Data Base

The data base for both Flibe and solid Li_2O is pretty well developed, getting a moderately high confidence level and moderately low development needs.

F.4.2 Breeding Potential

Here again the breeding potential for both materials has a high confidence level.

F.4.3 Thermal Performance

Both materials have been proposed for high temperature operation and have excellent thermal characteristics. The confidence level is moderately high for both.

F.4.4 Dissociation/Fragmentation

In the case of Flibe, x-ray dissociation will take place, but the recombination from the elementary atoms is difficult to predict. Thus, the confidence level is low.

Fragmentation in SOMBRERO of the Li_2O is almost certain to occur, but since the material is mobile, the fine fraction will be continuously removed and reprocessed. Just how much fragmentation will occur is hard to predict. Thus the confidence level is moderately low.

F.4.5 Tritium Extraction

Tritium extraction from both Flibe and Li_2O appears to be straightforward getting a moderately high confidence level.

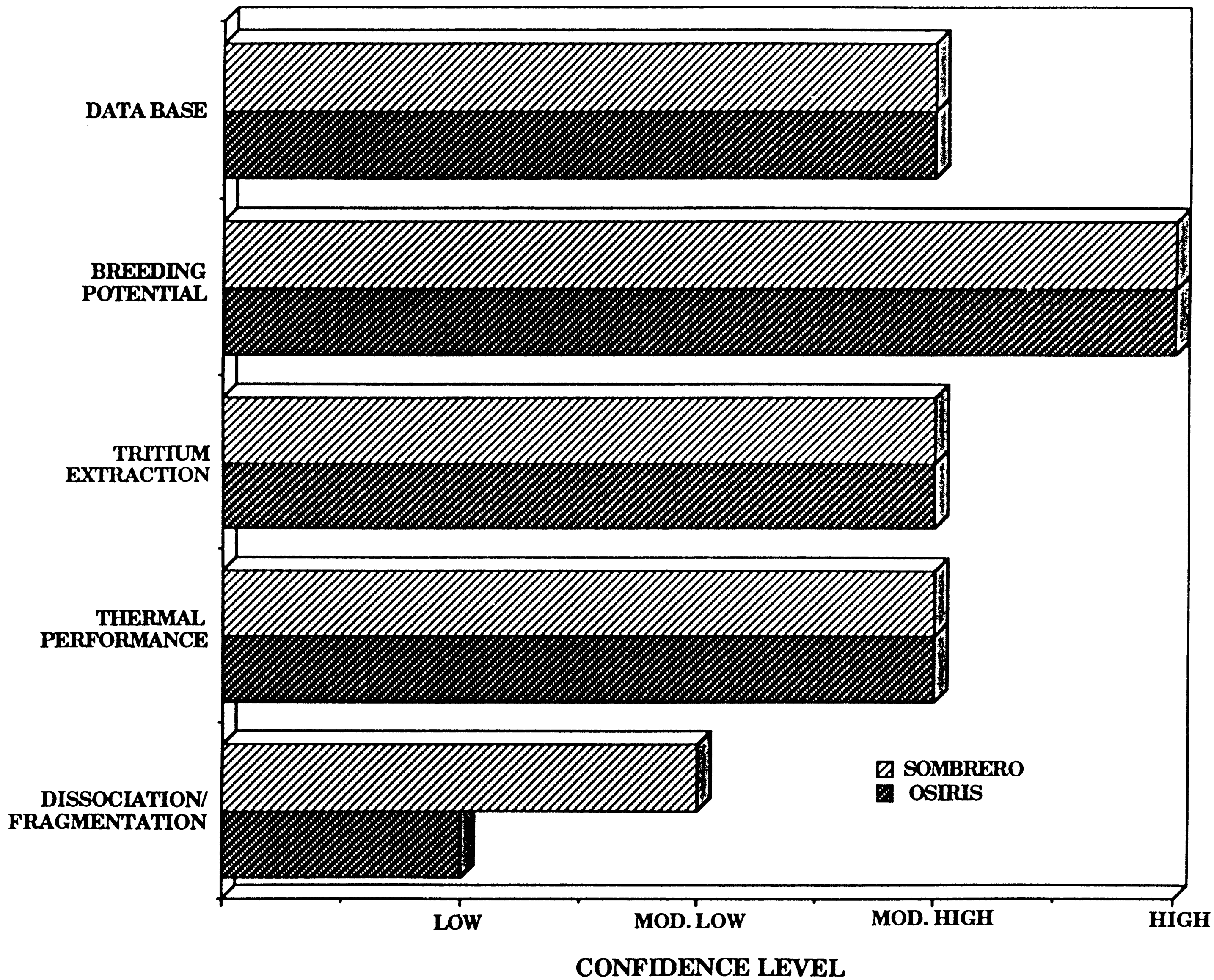

Fig. F.4. Summary of breeding material comparison.

F.5 TARGET AND TARGET DELIVERY COMPARISON

Figure F.5 summarizes the target comparison.

F.5.1 Fabrication at Tolerance

Osiris will be using indirect drive targets, which are generally more complicated than the direct drive targets used by SOMBRERO. It has been demonstrated that very small targets can be fabricated to the required tolerance, but the question still remains on whether they can be mass produced at tolerance. Both targets get a moderately low confidence level.

F.5.2 Tritium Filling

Several schemes for target filling have been demonstrated, but doing it at mass production rates is still very uncertain. Thus the confidence level is low.

F.5.3 Beta or Laser Layering

The confidence level on being able to perform proper layering for thick layers required by reactor scale targets is moderately low.

F.5.4 Alignment on Delivery

Indirect drive targets have to be centered in the chamber and properly oriented with respect to the location of the driver beams. Rifling the injector to provide spin stabilization of the cylindrical target will aid in achieving the proper orientation. The confidence level to do this is moderately high. Direct drive targets do not need a preferred orientation; thus, the confidence level in delivery is moderately high.

F.5.5 Dynamic Survivability

The integrity of cryogenic DT capsules, which are used in both direct and indirect drive targets, under accelerations of >100 g's is untested and uncertain. For indirect drive targets, hohlraum survivability and the ability to keep the capsule precisely within the hohlraum are also issues. The confidence level is low for both direct and indirect designs since there have been no calculations or experiments to address these issue.

F.5.6 Thermal Survivability

The hohlraum gives indirect drive targets a higher thermal inertia than direct drive targets. However, computer calculations indicate that the fuel in both targets can survive without overheating during their flight through the chamber. The ability to maintain a high quality outer

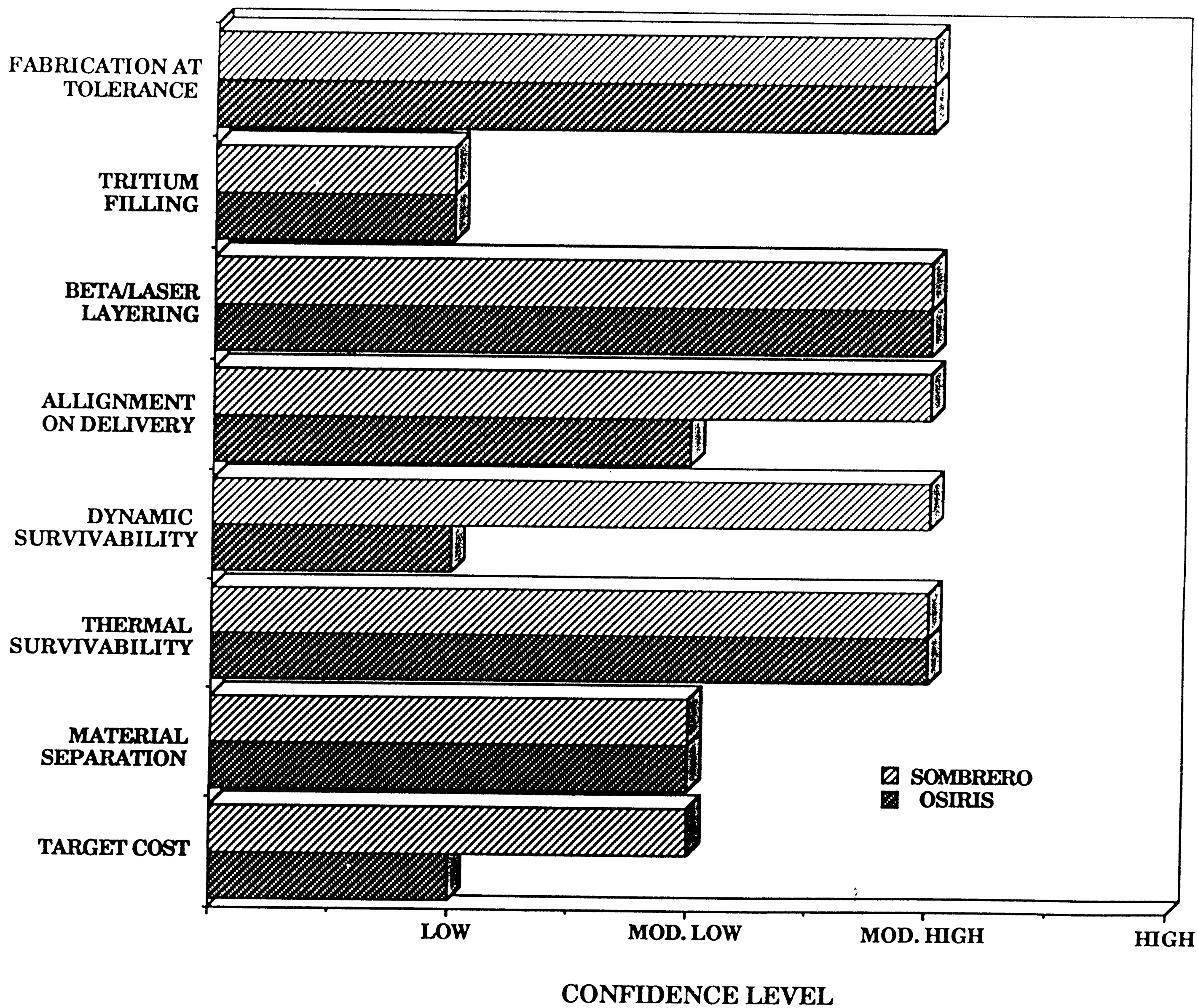

Fig. F.5. **Summary of target comparison.**

surface of the direct drive capsule is more uncertain. The confidence level in these calculations is moderately high.

F.5.7 Material Separation and Reprocessing

Separating the target materials from the Flibe in the case of Osiris and from the vacuum system in SOMBRERO has a moderately low confidence level.

F.5.8 Target Cost

The confidence level in the cost of mass produced targets at tolerance is low for both direct and indirect drive targets.

F.6 POWER CONVERSION CYCLE COMPARISON

Figure F.6 summarizes the power cycle comparison.

F.6.1 Intermediate Heat Exchangers and Steam Generators

Both Osiris and SOMBRERO utilize an intermediate loop of liquid Pb to minimize T_2 diffusion into the steam cycle and eliminate water/breeding material interaction. The confidence level in the IHX and steam generators for both systems is moderately high.

F.6.2 Maintenance of Power Cycle Equipment

Confidence in the ability to maintain power cycle equipment is moderately high since both systems will have hands-on maintenance capability.

F.6.3 Power Cycle and Conversion Efficiency

Both Osiris and SOMBRERO utilize a supercritical pressure double reheat steam cycle, which is state-of-the-art in many fossil-fired steam power plants. The steam conditions are consistent with the conversion efficiencies currently obtained in these plants. Thus, the confidence level for both systems is high.

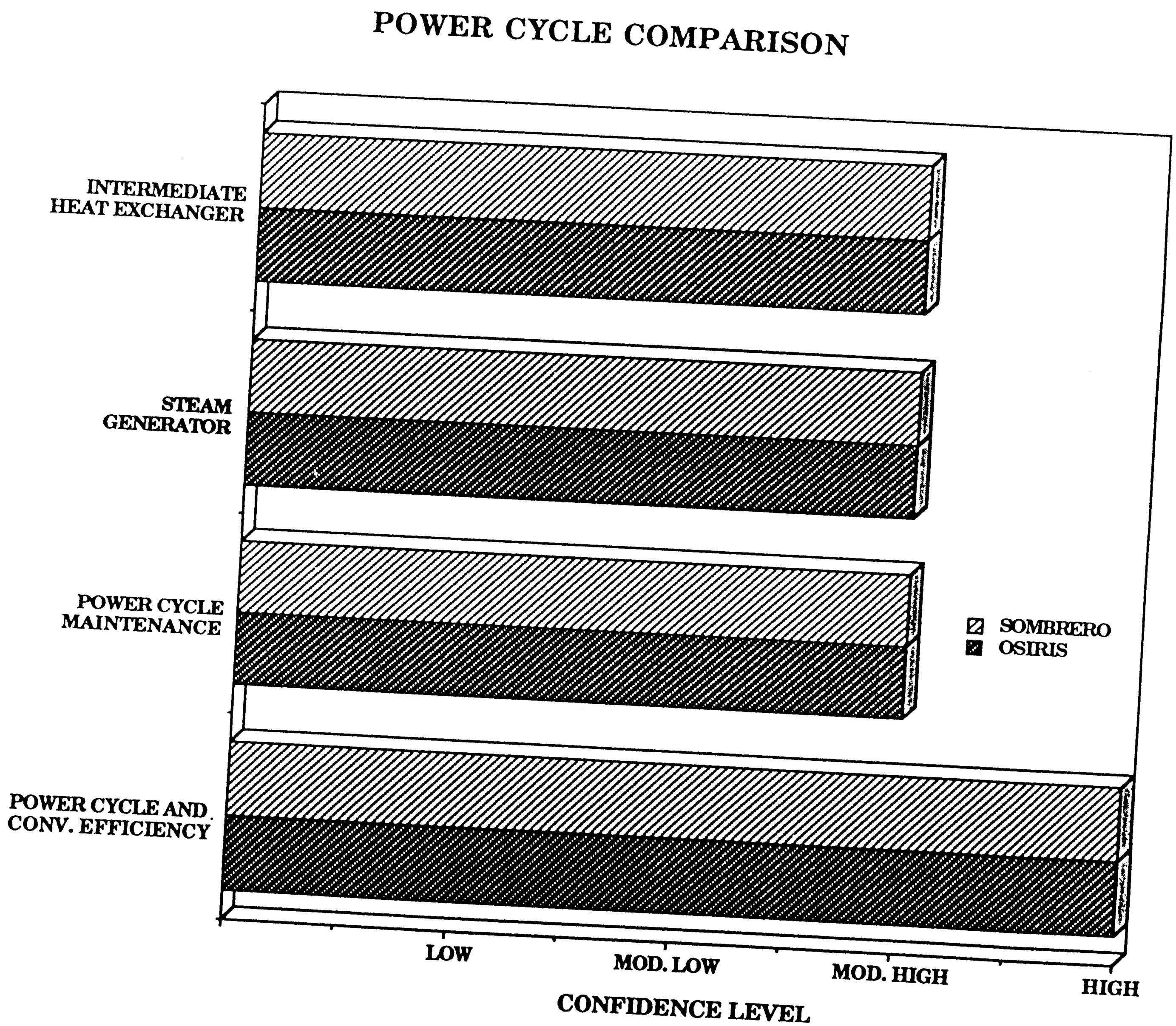

Fig. F.6. Summary of power cycle comparison.

F.7 SUMMARY OF THE COMPARISON SURVEY

In summarizing the major points between the Osiris heavy-ion-driven power plant and the SOMBRERO KrF laser driven power plant, the following can be said:

- Confidence in the driver technology for both systems appears to be even, with the exception of final optics survivability, where Osiris has the definite advantage.

- From the material and construction standpoints, Osiris has advantages of design simplicity and single unit maintenance. However, from the chemical standpoint, Flibe has issues with respect to dissociation and recombination and the potential of the highly reactive fluorine (F_2), formed near the first wall for attacking the graphite fiber.

- First wall protection in SOMBRERO is better understood than in Osiris, although at a price of size and cost. There is considerable uncertainty in the wetting and weeping characteristics of Flibe through the chamber fabric as well as in the rate of condensation.

- The direct drive targets have a slight advantage over indirect drive because there is more uncertainty in the alignment on delivery and dynamic survivability for the indirect drive targets. Indirect drive targets have an advantage in thermal survivability.

- Both reactors have outstanding nuclear performance characteristics.

- Both reactors have excellent safety and environmental characteristics. Osiris, however, has a lower T_2 inventory in the reactor building.

- Although both reactors have a cost of electricity which is competitive with respect to MFE designs, the COE in Osiris is 16% lower than SOMBRERO. The price paid by SOMBRERO for near symmetric illumination and dry wall first wall protection is clearly evident in the economics.

- Finally, it is impossible to say that one design is clearly better than the other. Both designs have definite positive attributes and issues as well. Much more research and development will be needed to confirm the advantages and resolve the issues before a meaningful clear choice can be established.

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