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10 CONCLUSIONS AND RECOMMENDATIONS

10.1 INTRODUCTION

The primary objective of the IFE Reactor Design Studies was to provide the Department of Energy with an evaluation of the potential of inertial fusion for electric power production. Based on the results of these studies, we conclude that IFE has the potential of producing technically credible designs with environmental, safety, and economics characteristics that are every bit as attractive as magnetic fusion. Realizing this potential will require additional research and development on target physics, chamber design, target production and injection systems, and drivers.

10.2 OSIRIS POWER PLANT

Osiris Chamber

The Osiris chamber features a very compact, low-activation chamber that uses ceramic material in a flexible, leak-tolerant configuration. The blanket consists of a porous carbon fabric filled with Flibe for cooling and tritium breeding. The Flibe coats the fabric surface, and vaporized Flibe is condensed in a pool at the bottom. The materials and technology needed to construct this blanket exist today. The Osiris vacuum vessel is protected from neutron damage and is a lifetime component. The fabric first wall is replaced periodically (about every two years), but the procedure for doing so is very simple – the entire blanket assembly is drained of Flibe and lifted out the top of the vacuum vessel.

We recommend additional research and development on several aspects of the Osiris design to address unresolved issues, as described below.

First Wall Design. While the materials exist to construct the fabric first wall, research is needed to determine the correct fabric weave to control the flow of Flibe through the fabric first wall. Since Flibe does not wet carbon, it may be difficult to maintain a uniform coating on the first wall. Effects of fabric design parameters and the possibility of using thin wettable metallic coating should be examined. The lifetime of the first wall will be determined by neutron damage and chemical corrosion by free fluorine; the lifetime limits are uncertain and require more research.

Chamber Dynamics. Osiris uses a spray of Flibe at the cold-leg temperature to condense the material vaporized on each shot. Two-dimensional modeling of vapor flow and benchmark experiments are needed. Calculations indicate that recombination of the Flibe after dissociation by the fusion energy pulse will not limit the rep-rate. This should be verified experimentally.

Tritium Recovery and Control. A more detailed analysis of the amount of tritium that can be recovered directly from the Osiris chamber is needed. If all the tritium can not be released by the cascading flow behind the blanket, vacuum disengagers as used in HYLIFE-II will be needed. Vacuum pumping along the beam lines near the chamber are need to prevent the flow of tritium and other radioactive materials into the accelerator. Modeling and small-scale experiments are needed to demonstrate the viability of maintaining the required vacuum conditions.

Vacuum Chamber Structure. The Osiris vacuum chamber is made of carbon/carbon (C/C) structures. The technology to produce large composite structures needs further development.

HIB Driver

The design of the induction linac driver emphasized cost reduction. Costs were reduced by operating at the maximum transportable current in order to minimize length. The 5 MJ driver uses a propagation mode in the accelerator with constant beam radius, quadrupole strength, and quad length – all of which encourage cost-reducing mass production. Twelve beams of Xe^{+1} are accelerated through common cores to a final voltage of 4.8 GeV. Compact Nb_3Sn superconducting quads are used in a standard FODO propagation mode. Complexities from beam combination, separation, or recirculation are avoided. The beams are almost completely neutralized with co-injected electrons just prior to entering the chamber. This gives a relatively small spot size (2.3 mm) and a target gain of ~87. The high-current, low voltage configuration of the accelerator leads to a relatively low cost ($120/J direct cost) design. The high driver efficiency (28%) gives a low recirculating power fraction of only 7%.

We recommend continued development of heavy-ion driver system technology in several areas. Near-term, small-scale research should continue in the following areas:

Injector Development. Because such a large fraction of driver elements are located early in the driver, significant cost savings are possible with improved injector performance. Increasing the injector current and/or voltage would reduce the length and required elements for the low-energy section of the driver by greatly increasing the acceleration gradient allowed by the velocity-tilt limit. Because the normalized emittance for the entire driver and the emittance contribution to the achievable spot size at the target are set by the injector, it is imperative that low-emittance, high-current injectors be demonstrated.

Quadrupole Array Development. Uncertainties in driver cost and transportable current at low energies could be greatly reduced by a prototype design program for superconducting quadrupole arrays. Transportable current at low driver energies is determined by the limits on how short a high-quality quadrupole can be and by how close quadrupoles can be placed without destructive interference of the end fields. Careful design and measurement of short quadrupoles would better establish these limits. In addition, design and demonstration of a single compact quadrupole array would greatly increase the credibility of size and cost estimates for the entire driver.

Larger experimental programs, such as ILSE, are needed to verify beam scaling and could establish the feasibility of aggressive design options. Recommended experiments are:

Current Transport Limits. MBE-4 has demonstrated the ability to accelerate multiple beams, but a longer driver such as ILSE would also demonstrate high-current transport, scaling of transportable current with voltage, and velocity-tilt limits on acceleration gradients.

Beam Combination and Separation Experiments. Transport and combination or splitting magnets could be added to the end of an ILSE-like accelerator to examine the achievable beam quality after beam combination or separation. As we have shown, neither of these options is necessary for heavy-ion drivers to be credible, but both options could lead to cost reductions once their feasibility is proven.

Beam Bending Experiments. There is great uncertainty concerning the feasibility or performance of a recirculator. One set of uncertainties concerns loss of beam quality in the bending magnets, another concerns resonant instabilities, and a third set concerns maintaining vacuum quality. Scalable experiments on an ILSE-scale device with either a recirculating accelerator section or a loop of quadrupoles and dipoles following the accelerator could give a great deal of information on the feasibility of recirculating drivers. As with beam combination and separation, recirculation is not necessary for heavy-ion drivers, but it could lead to cost reductions.

Drift Compression and Focusing Experiments. A proven accelerator will still need proven final focusing and transport to be of use as an IFE driver. Modeling and scaling of the behavior of high-energy, high-current beams under drift compression and final focusing will greatly benefit from scaled experiments with lower-energy beams.

Power Conversion and Balance of Plant (BOP)

The power conversion system for Osiris is a conventional super-critical steam cycle giving 45% efficiency. A low-pressure liquid lead intermediate heat exchanger provides pressure isolation and prevents the possibility of direct contact between the primary coolant, which contains tritium and other activated material, and the steam system. It appears that the BOP design for Osiris is technically viable, and there do not appear to be any issues that can not be adequately resolved.

The use of an intermediate heat transport loop was adopted for this study as a conservative measure. However, to reduce plant cost and complexity associated with a intermediate coolant and additional equipment, the use of a duplex-tube steam generator approach should be evaluated in more detail. If found appropriate, the technology for this kind of steam generator should be developed in conjunction with the Advanced Liquid Metal Reactors program.

10.3 SOMBRERO POWER PLANT

SOMBRERO Chamber

SOMBRERO chamber is an attractive, high temperature chamber design. It avoids the problem of first wall vaporization by protecting the wall with a low density inert gas (xenon). The first wall and chamber are constructed of a low-activation C/C composite. Granules of Li_2O flow though the chamber and are circulated as the primary coolant. The design retains the advantages of solid breeders while eliminating the problems associated with static blankets. The feasibility of the flowing blanket and fluidized recirculation are within the capabilities of existing industrial practice. The chamber is constructed of 12 independent first wall and blanket modules that must be replaced approximately every five years.

Additional research and development are recommended for SOMBRERO. Some of the key areas are listed below.

First Wall and Chamber Design. Experimental verification of the effectiveness of the first wall protection scheme is recommended. The development of the capability to manufacture larger C/C composite structures is essential to the design concept. Radiation damage tests with composite materials to determine material lifetime the effects on thermal conductivity are needed. A materials development program for this class of materials is needed for both IFE and MFE.

Laser Propagation. If the xenon gas density is too high, breakdown can occur which would reduce the amount of energy delivered to the target. Experiments to quantify the limits on the density of the gas are needed at the correct wavelength and intensity. The implications on target performance if breakdown occurs near the target also need additional study.

Flowing Blanket. Several aspects of the flowing breeding blanket would benefit from further study. Additional experiments on the heat transfer capabilities of the flowing bed examining a wider range to the operating variables and materials should be carried out. The issues of granule break-up and erosion of the blanket and heat transfer components need study.

Tritium Control. Since tritium is present in the xenon gas that fills the reactor building, it is essential that the building walls do not absorb tritium. Verification of the ability of coatings to prevent absorption is needed.

Power Conversion and BOP

The power conversion system for SOMBRERO is the same as for Osiris, except the intermediate heat exchanger has Li_2O granules instead of Flibe on the primary loop side. The system utilizes waste heat from the laser amplifiers to increase the gross conversion efficiency from 45 to 47%. The balance-of-plant design for SOMBRERO appears to be technically viable. Conceptual solutions have been identified for the major issues. The interface between the laser and the chamber (i.e., the optical train needed to deliver the beams) places significant demands on the design and construction of the reactor building.

As with the Osiris design, a closer look at the feasibility of a duplex wall steam generator (instead of using an intermediate heat exchanger) is advised.

The layout of the final optics adopted for this design is determined by the requirement for reasonable lifetimes of the mirrors. Grazing incidence metal mirrors (GIMMs) have been chosen as the final optics with the dielectric focusing mirrors located out of the line of sight. There are almost no data on radiation damage of either metal or dielectric optics in high energy neutron fluences. It is clear that the damage threshold of these optics under neutron illumination is one of the major uncertainties in this design. If the optics were to have higher fluence tolerances than assumed, then the optics could be placed closer to the target and the whole structure reduced in size. This could reduce the cost of the SOMBRERO reactor building significantly. Thus obtaining radiation damage data is critical.

The CaF windows located on the floor of the reactor building separate the reactor building environment from the beam handling area while letting the laser beams pass through with minimum absorption. While these windows are not in the direct line of sight for neutron irradiation, they will receive some scattered neutron fluence. Neutron damage data is also needed for these optics.

KrF Driver

The KrF driver system we have designed has an overall efficiency of 7.5% and the use of waste heat from the amplifiers increases the power conversion efficiency by ~2%. (This is equivalent to an effective laser efficiency of > 9%.) We have achieved this high KrF system efficiency by

1) careful overall optimization of the final amplifier design parameters,
2) use of high pump rate kinetics to achieve high intrinsic efficiency,
3) use of low inductance e-beam system design to allow low rise/fall time losses,
4) use of a recently patented and demonstrated plasma cathode in the e-beam that is capable of efficiencies limited only by the gas/foil albedo, and
5) operation at high Joules/liter, which allows efficient waste heat utilization.

Our design uses 60 kJ amplifier cavities that are pumped for 600 ns from two sides with 600 kV, 40 A/cm^2 e-beams that are 1×2 meter in dimension. The cavities operate in a 2-pass extraction mode. This is a relatively small size that has high efficiency due to low amplified stimulated emission, excellent fill factor, and low flow power. The small size promises to keep development cost at a minimum for full-size demonstration of key components.

We feel our design represents the best of the possible approaches, given current data on the KrF system. We have not extrapolated physics, but we have made reasonable and defensible projections for technology development, based on scaling demonstrated technology. Our approach also has the advantage of representing sensible evolution of the technologies developed in Aurora (e-beam pumped 2-pass amplifiers with angular multiplexing for pulse compression), Nike (non-echelon integrated spatial incoherence for smooth beam profiles on high gain direct drive targets), and EMRLD (DoD technology for repped e-beam pumped excimers of excellent beam quality).

We recommend continued development of the KrF driver system technology in the following areas:

Repped e-Beam. The plasma cathode technology should be scaled from 10×30 cm to 1×2 m, and the design optimized for 5 to 10 Hz operation. Operation of a 1×2 m, 600 kV, 40 A/cm^2, 600 ns e-beam with cable-based pulse power should be the final milestone of this effort.

60 kJ Amplifier Module. Demonstrate 10 Hz operation with angular multiplex extraction over at least part of the 600 ns gain duration. Perform an extensive characterization of the operating parameters and develop an understanding of issues for the next generation design, particularly to extend foil lifetime.

Zooming Front End. Develop and test a front end design capable of changing aperture diameter by about two in periods of order 6 ns, with simultaneous control of the power output as required for optimum target implosion.

KrF Kinetics. Demonstrate the high intrinsic efficiency predicted by our codes for 400 kW/cm^3 pump rate for 600 ns, and thus also demonstrate the 30 J/liter design.

Neutron Effects on Optics. With a 14.1 MeV neutron test facility, develop and test designs for the grazing incidence metal mirrors and the dielectric-coated final focusing mirrors.

Cooled Optics. Develop and test designs in the 10×20 cm size operating at 5 J/cm^2 and 10 Hz in the UV.

Lifetime Testing of Critical Components. Besides the neutron effects and the optics fluence and average power testing, there are a number of other components, such as the e-beam cathodes, pulse power switches, and so forth that should be tested.

Overall System Design. The present program was a minimal size effort to accomplish the goals; there is much that should be worked out to the next level of detail to improve the confidence level and guide the subsequent developments.

10.4 TARGET SYSTEMS

Target Production

The target production facility design was motivated by the objectives of high reliability, high safety, and low capital cost. The facility uses controlled microencapsulation for shell production, fuel filling by cryogenic injection, and layer formation by pulsed laser heating and temperature-controlled gas jets. The building area required for target fabrication is quite compact. The production process is expected to have high reliability because there is 100% redundancy in the production lines. The total tritium inventory is low (~300 g) as a result of using rapid fill and layering techniques.

The proposed technologies are speculative and require significant technology development.

Shell Production. Controlled microencapsulation has been demonstrated for small-sized capsules. The process must be scaled up to demonstrate that high quality can be maintained for larger targets characteristic of the high yield targets used for power plants.

Fuel Filling. The proposed cryogenic fill technique has a great advantage in that the fill time is very short (~minutes), and thus the tritium inventory associated with the fill step is small. The technology has not been demonstrated and significant uncertainties exist. Small-scale experiments should be carried out to begin addressing the issues associated with this process.

Fuel Layering. The use of pulsed lasers and cold gas jets has been demonstrated for small targets. Development is needed to see if this technique can be scaled up to be used with larger targets and thicker fuel layers.

Target Injection, Tracking and Beam Pointing

Existing gas gun technology can meet the acceleration and positioning requirements of the IFE applications. The proposed design uses a sabot to protect the target from damage during the acceleration processes. Laser Doppler interferometer and laser tracking station are used to monitor the target trajectory and can provide pointing information in enough time to actively point the beams for each shot. The tracking and pointing requirements can be met with existing technologies. The most critical issues have to do with operating the injector with cryogenic targets.

Small-scale tests should be carried out to demonstrate the integration of the technologies required for target injection, tracking, and beam pointing. The test could be conducted in a phased approach by first developing the gas gun injector, adding tracking systems, and finally demonstrating beam pointing and interception of a target with a low energy ion or laser beams. Operation with cryogenic targets, but not necessarily DT, will be required.

Target Survivability

The target is protected from physical contact with the accelerator by a sabot. Once the target leaves the accelerator, the sabot flies off. As the target travels through the chamber, it is subjected to aerodynamic and radiative heat loads. For indirect drive targets, the hohlraum provides a thermal barrier to protect the fuel capsule. Direct drive targets will have to remain in the sabot for a longer time or incorporate additional thermal protection (e.g., a sacrificial layer of frozen gas on the outer surface of the capsule), especially when used in high temperature chambers such as SOMBRERO. More work is needed to demonstrate the integrity of the DT fuel layer and capsule during acceleration and transit through the chamber.

Experiments are needed to develop appropriate sabot designs that can protect the capsule during acceleration. The integrity of cryogenic hydrogen layers should also be examined to determine acceleration limits for targets. Experiments with schemes to protect the targets from heat loads during injection are also needed.

10.5 ENVIRONMENTAL AND SAFETY ASSESSMENT

Both Osiris and SOMBRERO have attractive environmental and safety characteristics. Both achieve a level of safety assurance of one, and the chamber, breeder, and shielding materials will qualify for disposal as Class A or C low level waste. These results are due to the use of only low-activation materials for the first walls, breeding blankets, and chamber structures. As previously mentioned, minimizing the tritium inventory in the target factory is also an important aspect in achieving the high safety rating.

To realize potential environmental and safety advantages of these designs, the low-activation structural materials used for the SOMBRERO first wall, blanket, and chamber structure and for the Osiris vacuum chamber will require significant technology development. The carbon fabric used for the Osiris first wall and blanket is currently available, but as discussed above, development the proper weave density for flow control is need.

10.6 RELIABILITY, AVAILABILITY, AND MAINTAINABILITY

At a conceptual level of evaluation, the remote maintenance of the Osiris and SOMBRERO reactors appears feasible. However, a detailed evaluation of the remote replacement or refurbishment of the reactor components should be performed to identify the development needs for any special remote maintenance equipment. In addition, "design for remote maintainability" should be factored into the program from the beginning of conceptual designs rather than retrofitting at later stages.

At this stage of the IFE reactor development, a definitive assessment of the reliability, availability, and maintainability (RAM) can not be performed until an in-depth evaluation of the key systems and components is made. In addition, in-depth evaluations are needed on the integrated design and performance of the driver, target, reactor, and the balance-of-plant.

An overall plant availability goal of 75% is assumed here for the IFE reactor plants so as to be comparable to other large electric power generating systems. To be able to meet this target goal, it appears that both concepts require significant improvements in the availability of the constituent systems and components. A detailed RAM assessment is needed to identify the extent of the improvement and to aid in planning future development efforts.

10.7 ECONOMIC ASSESSMENTS

The estimated cost of electricity (COE) for the Osiris power plant is about 16% lower than the COE for the SOMBRERO power plant. The economics for both plants are attractive compared to previous inertial and magnetic fusion reactor designs. The use of low-activation materials and low volatile tritium inventory eliminates the need for N-stamp materials and reduces the estimated construction costs.

The attractive economics are the result of properly integrating the proposed technologies (lower cost heavy ion driver, more efficient KrF laser, good target gain performance, etc.). Continued systems analysis is useful to help identify those areas with high leverage for affecting system performance and bottom line costs. A continuing effort in power plant systems analysis that incorporates the latest information on reactor, driver, and target technologies and performance is recommended. Further work is also recommended to normalize the cost estimates with other IFE and MFE studies so that they can be compared on a more consistent basis. For high leverage systems and subsystems, more detailed designs and cost estimates are warranted.