Dr. Robert W. Conn, Chair
Fusion Energy Advisory Committee School of Engineering
University of California, San Diego 9500 Gilman Drive
La Jolla, CA 92093-0403

Dear Dr. Conn:

This letter forwards the charge that follows up on a specific recommendation made by your Committee in its report, "A Restructured Fusion Energy Sciences Program." The report calls for a programmatic review to assist the Department in setting technical priorities for the Inertial Fusion Energy (IFE) Program.

Inertial fusion has been reviewed often in the past decade, including the Fusion Policy Advisory Committee in 1990, the Fusion Energy Advisory Committee (FEAC) in 1993, as well as two reviews by the National Academy of Sciences during the 1980s. Questions of scientific merit and appropriate energy relevance have been addressed positively by the p
revious reviews. For the near term, however, we would like you to provide us with an assessment of the content of an inertial fusion energy program that advances the scientific elements of the program and is consistent with the Fusion Energy Sciences Program, and budget projections over the next several years.

Please consider augmenting the expertise of FEAC with appropriate individuals from inertial fusion programs that are active in this country, as well as foreign participants that would be helpful.
I would like to have your recommendations regarding this program by July 1996.
The Department is appreciative of the time and energy provided by the members of FEAC in this continuing effort to improve and orient the fusion energy sciences program to the needs of the times. I will look forward to hearing the Committee's recommendations on this matter.

Sincerely,

Martha A. Krebs
Director
Office of Energy

Research
Enclosure

Charge to the Fusion Energy Advisory Committee
for an Inertial Fusion Energy Review

Since 1990, the fusion program has had a mandate to pursue two independent approaches to fusion energy development, magnetic and inertial confinement fusion. In magnetic fusion, our strategy is to continue to use international collaboration, especially participation in the International Thermonuclear Experimental Reactor, to pursue fusion energy science and technology. In inertial fusion, our strategy has been to assume the target physics is the highest priority activity and would be developed as a part of the weapons research program; and, indeed, the next step in the development of target physics, namely the National Ignition Facility, is proceeding into construction in Defense Programs.

Based on the Fusion Policy Advisory Committee report of 1990, we had taken as our highest priority in inertial fusion energy the development of heavy ion accelerators as the most desirable driver for energy applications. That development program has met all of its milestones and has received numerous positive reviews, including one by the Fusion Energy Advisory Committee (FEAC), which in 1993 recommended a balanced Inertial Fusion Energy program of heavy ion accelerator development, plus other smaller scale efforts, at $17 million per year.

The potential for inertial fusion energy has been judged to be real, but the fusion program no longer has as a goal the operation of a demonstration power plant by 2025. Given that the basic mission of the fusion program has changed from energy development to fusion energy science, and that funding for the entire fusion program will be constrained for some number of years, I would like FEAC to again consider inertial fusion energy and recommend what the new Fusion Energy Sciences program should be doing in support of this future fusion application, and at what level?

# REPORT OF THE FESAC/IFE REVIEW PANEL

July 19 1996.

Panel members.


| | |
|---|---|
| Mohamed Abdou | University of California Los Angeles. |
| Richard Briggs | Science Applications International Co. |
| James Callen | University of Wisconsin. |
| *John Clarke | Pacific Northwest National Laboratory. |
| *Harold Forsen | Bechtel (retired). |
| *Katharine Gebbie | National Institutes of Science and Technology. |
| Ingo Hoffman | Gesellschaft fuer Schwerionenforschung, Darmstadt, Germany. |
| John Lindl | Lawrence Livermore National Laboratory. |
| Earl Marmar | Massachusetts Institute of Technology |
| William Nevins | Lawrence Livermore National Laboratory. |
| *Marshall Rosenbluth | University of California, San Diego. |
| John Sheffield (chair) | Oak Ridge National Laboratory. |
| William Tang/ Ernest Valeo | Princeton Plasma Physics laboratory |

* Members of FESAC.

TABLE OF CONTENTS

ACRONYMS

| | |
|---|---|
| DOE | Department of Energy |
| DP | Defense Programs |
| DPSS(L) | Diode Pumped Solid State (Laser) |
| ER | Energy Research |
| ESTA | European Science and Technology Assembly |
| EU | European Union |
| FEAC | Fusion Energy Advisory Committee |
| FESAC | Fusion Energy Science Advisory Committee (The renamed FEAC June 1996) |
| G | Target Energy Gain |
| GIMM | Grazing Incidence Metal Mirror |
| HIF | Heavy Ion Fusion |
| ICF | Inertial Confinement Fusion |
| ICFAC | Inertial Confinement Fusion Advisory Committee |
| IFE | Inertial Fusion Energy |
| ILSE | Induction Linac System Experiments |
| IRE | Intermediate Research Experiment |
| ITER | International Thermonuclear Experimental Reactor |
| kJ | kiloJoule |
| KrF(L) | Krypton Fluoride (Laser) |
| LANL | Los Alamos National Laboratory |
| LBNL | Lawrence Berkeley National Laboratory |
| LLNL | Lawrence Livermore National Laboratory |
| MFE | Magnetic Fusion Energy |
| MIT | Massachusetts Institute of Technology |
| MJ | MegaJoule |
| NIF | National Ignition Facility |
| OFES | Office of Fusion Energy Sciences |
| PPPL | Princeton Plasma Physics Laboratory |
| RF | Radio Frequency |
| SNL | Sandia National Laboratories |
| TFTR | Toakamak Fusion Test Reactor |

## A. CHARGE TO PANEL

This report provides an analysis by a Fusion Energy Advisory Committee (FEAC) Panel, of future program options for the Inertial Fusion Energy (IFE) component of the Fusion Energy Sciences Program of the Office of Fusion Energy Sciences. The report is in response to the following request to FEAC from the Director of the Office of Energy Research:

"Charge to the Fusion Energy Advisory Committee
for an Inertial Fusion Energy Review.

Since 1990, the fusion program has had a mandate to pursue two independent approaches to fusion energy development, magnetic and inertial confinement fusion. In magnetic fusion, our strategy is to continue to use international collaboration, especially participation in the International Thermonuclear Reactor, to pursue fusion energy science and technology. In inertial fusion, our strategy has been to assume the target physics is the highest priority activity and would be developed as a part of the weapons research program; and, indeed, the next step in the development of target physics, namely the National Ignition Facility, is proceeding into construction in Defense programs.

Based on the Fusion Policy Advisory Committee Report of 1990, we had taken as our highest priority in inertial fusion energy the development of heavy ion accelerators as the most desirable driver for energy applications. That development program has met all of its milestones and has received numerous positive reviews, including one by the Fusion Energy Advisory Committee (FEAC), which in 1993 recommended a balanced Inertial Fusion Energy program of heavy ion accelerator development, plus other smaller scale efforts, at $17 million per year.

The potential for inertial fusion energy has been judged to be real, but the fusion program no longer has as a goal the operation of a demonstration power plant by 2025. Given that the basic mission of the fusion program has changed from energy development to fusion science, and that funding for the entire fusion program will be constrained for some number of years, I would like FEAC to again consider inertial fusion energy and recommend what the new Fusion Energy Sciences program should be doing in support of this future fusion application, and at what level."

## B. REVIEW PROCESS

The panel was briefed by Dr. N. Anne Davies, Director of the Office of Fusion

Energy Sciences (OFES) of the Office of Energy Research, and by Dr. David Crandall, Director of the Office of Inertial Confinement Fusion (ICF) and the National Ignition Facility (NIF) of Defense Programs, on the roles of IFE and ICF in the Department of Energy. A summary was given of previous reviews of the IFE program, including that of the Fusion Policy Advisory Committee (1990) and the FEAC Panel 7 (1993). The panel was asked by Dr.Davies, and agreed to assume, that NIF would be built and that the IFE mission belonged in OFES. Presentations were also heard on the progress and prospects in the various areas of the program from a number of the collaborating institutions. Written comments were received from experts in the field. The agendas of the meetings and a list of contributors are provided in Appendix A.

It was agreed that, given the short timescale for conducting this review, the panel would rely on the extensive technical background provided in the FEAC Panel 7 report, supplemented by the more recent information given in presentations and written comments. Updates to some of the appendices of the Panel 7 report are appended -- Target Physics for IFE (Appendix B), and IFE Power Plant Issues and Needed Breadth of Research (Appendix C).

## C. OVERVIEW

Inertial confinement of plasmas provides an important fusion option with the potential for a competitive power plant. There are two inertial fusion program elements. The OFES/OER/DOE has the mandate to support energy applications through its Inertial Fusion Energy (IFE) program. The ICF program in DP/DOE is motivated by science based stockpile stewardship. The DP program is funded in FY 1996 at about $240 M/year, about 30 times the OFES inertial fusion energy program. Obviously, much of the key reseach will be undertaken in the DP program. The IFE program must concentrate on energy issues not covered by DP, and try to position itself to apply the results of DP research in the energy area. Significant developments in the ICF program continue to provide crucial scientific and technical results that support the IFE component. It is important to capitalize on this symbiotic relationship between IFE and ICF. Further, progress in the IFE program since the 1993 FEAC-7 review has been good, despite its being funded at the $8M per year level rather than the then-recommended $17 M level.

A strong IFE program is a proper and important component of the restructured OFES/DOE program. Challenging and relevant scientific issues need to be resolved, especially in the areas of collective effects in high current accelerators and beam-plasma interactions. With the ICF physics development in Defense Programs, and supporting science and technology and the high repetition rate driver development in the OFES program, the United States is positioned to lead the world in developing IFE science and technology.

The following finding, concerning funding for the IFE program, represents a medial opinion of the Panel. A minority of the Panel would support a more aggressive approach and a comparable minority, a less aggressive approach. The medial position of the Panel is that there should be an increase in the non-driver part of the IFE program beyond the present level to strengthen the scientific and technological understanding of the prospects of IFE and to involve a wider range of institutions in these efforts. The medial opinion is that, to achieve this goal, the funding for the IFE program should be increased to about $10M per year for the next few years. Such an annual budget would allow maintaining the pace of heavy ion accelerator development. In total, the program would provide the breadth of support necessary for initiation around the year 2000 of a construction project for an integrated research experiment using a multi-kJ heavy ion driver with a target chamber.

D. FINDINGS

1. **Progress Since 1993.**

• An opportunity for wider participation and more rapid scientific progress has been created by a substantial declassification in the ICF area funded by DOE's Defense Programs;

• The progress in the preparation of the National Ignition Facility (NIF), for which the Inertial Confinement Fusion Advisory Committee (ICFAC, November 1995) indicated that “as far as ignition is concerned there is sufficient confidence that the program is ready to proceed to the next step in the NIF project....”;

• Excellent progress in:
- the understanding of target physics through the NOVA program;
- heavy ion accelerator technology;
- operation of improved, fusion relevant, laser systems -- KrF (Nike at NRL), the new Omega Upgrade Direct Drive Facility (U. Of Rochester) and diode pumped solid state development (at LLNL);
- operation of light ion systems that support some beam-target interaction assumptions; and
- improved understanding of power plant issues and refinements that could lead to competitive fusion power plant prospects.

2. **Science and Technology.**

The inertial fusion program involves much exciting science and technology, as seen in the continuing developments in the target physics area. Although most of the science of target design and implosion is undertaken in the ICF Program, there are opportunities, because of declassification, for a broadening of the work in the IFE Program. The development of energetic, high current density, space-charge-dominated beams and their focussing onto a target involves fundamental science -- instabilities, beam-plasma interactions, plasma lenses, etc. -- and a great opportunity to compare sophisticated computer models with experiments. These developments will have importance broadly across the accelerator field. The development of the drivers and of power plant systems requires innovative new technologies. Work to date has already led to some significant advances.

The panel finds the work at LBNL to be of high scientific quality and was impressed that the ongoing theory and experiments, even at present funding levels, will contribute significantly to the science base required for heavy ion driver development and beam propagation. The complementary IFE programs at LLNL and other institutions have also made impressive progress.

3. **Challenges.**

Many scientific and technological challenges remain to be overcome before the goal of an economic power plant can be realized. Success is not assured although we see no show stoppers. In rough order of importance, the most critical of these are:

- Overcoming the hydrodynamic instabilities (and possible laser-plasma or beam plasma instabilities), and obtaining adequate symmetry to produce a high gain target yield. We must rely on NIF for the basic experimental proof or disproof.

- Providing viable protection of the target chamber against the X-rays, neutrons, blast, and debris to be expected from the pellet explosion. This may be particularly critical for the final focusing optics of a laser system. An analogous issue for heavy ions is finding an adequate mode for beam transport, compatible with the chamber environment that is present with various wall protection schemes.

- Development of a driver with adequate efficiency, rep-rate, and reliability.

- Mass producing targets at a cost of about $0.25 apiece, including their injection and accurate positioning in the target chamber.

All of the above must of course be done at a cost compatible with economic electricity production.

4. **Timeframe.**

The pace and content of the IFE program is driven by a succession of anticipated events in the DP and OFES programs:

- In the Restructured Fusion Energy Sciences Program, it is envisaged that there will be "a growing portfolio of new experiments . . . "

- By 1999, the International Thermonuclear Experimental Reactor Engineering Design Activity will have been completed, the NIF should be well advanced in its construction phase, assuming the presently proposed schedule is met, and the Tokamak Fusion Test Reactor program at PPPL will be completed. This is a period in which some new initiatives -- including one in IFE -- should be ready for consideration by OFES.

- The proposed NIF program is designed to have the capability to ignite a D-T target in the 2005 timeframe.

5. **Opportunity for the U.S. in IFE.**

A strong IFE program is a proper and important component of the restructured OFES/DOE program. Challenging and relevant scientific issues need to be resolved, especially in the areas of collective effects in high current accelerators and beam-plasma interactions. With the ICF physics development in Defense Programs and supporting science and technology and the high repetition rate driver development in the OFES program, the United States is positioned to lead the world in developing IFE science and technology.

6. **Logic for Heavy Ion Accelerator Driver.**

In agreement with previous reviews of inertial fusion energy by the National Academy of Sciences and two FEAC panels, we consider the heavy ion accelerator to be the most promising driver for energy applications. The reasons include the relatively high efficiencies that are possible with accelerators, exceeding 30%, and the demonstrated high reliability of high power accelerators operating at rep rates of several Hz. In contrast, the best laser options - KrF and DPSS - have efficiencies less than 10%. Among the alternatives for heavy ion accelerators, the induction linac (or possibly the recirculating version) is well matched to the multikiloamp currents and submicrosecond pulse lengths required for inertial fusion.

An alternative accelerator approach is the rf/storage ring driver. This approach fits well within the existing European accelerator programs, and is a valuable complementary program. In a presentation at the review meetings, our European panel member agreed that the induction linac has potential cost advantages in comparison with the rf linac/storage ring approach they are exploring.

In the longer term, breakthroughs in the development of laser targets, including direct drive and other approaches (such as the fast ignitor described below) could modify the decision on drivers. Reassessment of the driver and target should be made on a regular basis.

7. **Need for Integrated Research Experiment.**

Excellent progress has been made in the past by the IFE Program in accelerator development on key issues (e.g., beam bending, merging, pulse compression, final transport) through a series of small scale experiments - closely coupled with theoretical modeling - to understand fundamental aspects of the basic beam phenomenology. These innovative small scale experiments and associated theoretical modeling should continue. However, progress at the level needed to fully evaluate the HIF approach to IFE will also require an integrated experiment capable of resolving the basic beam dynamics issues in the accelerator, studying the final focusing and transport issues in a reactor-relevant beam parameter regime, and evaluating the target heating phenomenology.

With a succession of delays in the funding of the (less ambitious) ILSE project, the IFE team believes a more comprehensive "Integrated Research Experiment" (IRE) should be the focus of the next decade of IFE research and development. The IRE is discussed in more detail in section IID. The overall objective of IRE is to provide the data base needed to support a decision to proceed with the construction of a full scale IFE driver, on a time scale consistent with NIF demonstrations of fusion target performance.

While various options for such a facility have been considered over the years, no particular option has been selected. Consequently, the Panel received only limited information on this topic. Nevertheless, it seems clear that trade studies of various options leading to the development of a conceptual design for the IRE should be a major focus of the heavy ion program over the next two to three years.

8. **Target physics.**

The key scientific issue for any IFE system is target physics. This will not be tested conclusively before the experiments on the NIF. Nonetheless, the best possible simulations are indicated for a program of this importance and scientific value. LLNL has just completed the first succesful "integrated" simulation of a heavy ion driven target. We believe it is important for other groups to develop new codes and perform independent confirmatory simulations as one element in a driver decision. We believe that the recent declassification makes this feasible, and that this essential task could be undertaken by an MFE theory group, providing an important link between the MFE and IFE communities with eventual mutual enrichment. Developing new target physics codes is a challenging multiyear project. In the interim, MFE theorists could contribute to such issues as beam propagation, and participate in target design using existing codes.

9. **Program Needs Derived from Power Plant Studies.**

Several comprehensive, conceptual design and systems studies have been completed. They show the potential for and requirements for IFE to provide competitive power plants. Other than development of the driver, the key issues are:

- Demonstration of high gain at moderate driver energy.
- Development of chamber technology, including wall protection and cavity clearing schemes at power plant repetition rates.
- Development of power plant technologies to provide tritium self-sufficiency, radiation shielding, radiation resistant materials, and low-cost target production.

The IFE program within OFES must have sufficient breadth, beyond driver development, to cover those other areas that are critical to its feasibility and competitiveness. Progress in these areas will influence driver research priorities and should provide the data needed in the near term to perform meaningful experiments on NIF that are important to IFE.

10. **Priorities Outside Heavy Ion Accelerator Development.**
The panel suggests the following priorities for the broader program:

First priority:

- Wall protection scheme evaluations and development.
- Confirmatory simulations of heavy ion driver target performance.

Second priority:

- Cavity clearing technologies at IFE repetition rates.
- Development of the final focussing optics for laser systems. (It is assumed that final focussing and transport studies for heavy ion beams are undertaken as a part of the accelerator development program.)

Third priority:

- Target factory studies.
- Work on rep-rated laser systems. This is an important area but until IFE funding increases substantially, development of only the presently most promising driver can be afforded.
- Shielding, blanket and tritium studies.
- Detailed power plant conceptual design studies. The extensive studies made in recent years have identified the principal issues for IFE. It is time now to concentrate the scientific and technological studies on these specific issues.

11. **Roles of DOE/Energy Research and DOE/Defense Programs, and International Collaboration.**

This Panel has reviewed and commented on the IFE program conducted by the OFES of Energy Research. The program benefits from an essential symbiotic relationship with the ICF program conducted by Defense Programs. The Panel notes that the NIF program expects to offer testing time to a range of institutions and program interests. A 1994 workshop, organized by DP, identified a wide range of IFE relevant issues that could be addressed by NIF. The Panel is not in a position to comment on the balance between the various elements of the DP program, but feels strongly that greater clarification is needed regarding possible implementation of these IFE relevant elements of the DP-supported ICF program.

A joint IFE steering committee between ER and DP, consisting of all interested parties, should review this program on a regular basis.

In addition, such a committee might be used to facilitate international cooperation in IFE. This FESAC/IFE panel did not review the foreign programs, except for a brief discussion of some European developments (see IIC). We note, however, that the French are building a NIF-scale facility, that there is a proposal in Europe to expand IFE, and that there are significant IFE programs in Japan and Russia.

12. **Budgets.**

The position of Panel is that there should be an increase in the non-driver part of the IFE program beyond the present level to strengthen the scientific and technological understanding of the prospects of IFE and to involve a wider range of institutions in these efforts. We believe that this is needed even though there is a large measure of breadth because of related DP-funded efforts. For a total OFES/IFE budget in the range of $8M or greater, this total investment in non-driver science and technology should be $2M - $3M per year.

The following finding, concerning funding for the IFE program, represents a medial opinion of the Panel. A minority of the Panel would support a more aggressive approach and a comparable minority, a less aggressive approach. The medial opinion is that funding for the IFE program should be increased to about $10M per year for the next few years to strengthen the scientific and technological understanding of the prospects of IFE and to involve a wide range of institutions in these efforts. Such an annual budget would allow maintaining the pace of heavy ion accelerator development. In total, the program would provide the breadth of support necessary for initiation around the year 2000 of a construction project for an integrated research experiment using a multi-kJ heavy ion driver with a target chamber. An increased budget in the 1999 timeframe would be required for developing such a proposal.

At the present OFES/IFE budget level of $8M, a significantly increased investment in program breadth is desirable but would be achieved at the expense of a substantial slowing of the pace of development of a heavy ion accelerator. At lower budget levels, the elements of the program would have to be done serially rather than in parallel, delaying the pace of the program beyond that needed to meet the goals above. At some lower level, it would be impossible to mount a coherent driver development program. The FEAC Panel report identified the $5M/year case as one in which "there is no credible program for the development of a heavy ion fusion energy option."

## II BACKGROUND INFORMATION

### A. **Target Physics.**

The gain required for an ion-beam power plant can be estimated from the requirement that the recirculating electrical power should be limited to about 25%, and hence 10% of the output fusion thermal power. For an assumed accelerator efficiency of 35%, gains of about 30 are needed.

Recent LLNL integrated calculations of 2-sided, indirectly driven ion target designs predict a gain of 40-50 with a 6-7 MJ driver capable of focussing to a 6 mm radius spot size. These calculations consider the ion energy conversion to X-rays in the target, and the subsequent radiation transport and pellet implosion. Most of the calculation involves the same physics as that involved in the LLNL NIF laser implosion predictions, which have been verified by LANL simulations. The validity of these codes has been tested against Nova experiments and judged (by ICFAC for example), to provide an adequate basis for proceeding with NIF. We conclude by analogy that an adequate basis of target physics exists for proceeding with consideration of other aspects of an HIF design. A wide variety of possible target designs for HIF requires further study. It is very likely that more optimum designs are feasible. We believe that it would be desirable if independent propagation and target physics codes would be implemented and we recommend that the participation by scientists from one or more MFE groups be encouraged.

There are alternative concepts for IFE reactors. Direct drive targets, while requiring very high uniformity, allow better coupling of driver energy to compressed fuel (by a factor of 2-5) and hence potentially higher gain. Such advantages in gain might allow KrF lasers or DPSSL's to overcome the large efficiency advantages of HIF. Experiments on the Omega facility (University of Rochester) and NIKE facility (NRL) should give some quantitative data on these prospects in the next several years. Direct drive HI targets are in principle feasible, but questions regarding deposition nonuniformity from such sources as beam overlap and multiple-beam interactions have not been adequately evaluated.

Still more drammatic improvements in gain or minimum size may be available with the fast ignitor. Many physics and technology issues remain to be explored, and the first significant data base on this exciting new prospect will become available in the next 2-3 years on Nova.

We conclude that indirect-drive HIF remains the driver option of choice. Enough data should be forthcoming on direct drive and fast ignitor prospects in the next 3-4 years, that it should be possible to better evaluate the prospects of IFE with lasers at that time.

B. **Heavy Ion Accelerator (Progress, Issues and Prospects).**

1.) Progress since 1993 on issues identified by FEAC panel 7 (page 7)

The LBNL injector program has demonstrated the production and acceleration of a single driver-scale ion beam, in a linear geometry. The parameters of the beam are 2MeV, 0.25mC/m (790 mA) of $K^+$, with emittance of 1mm-mr. Beam energy variation (< ±0.15%) is also consistent with the full-scale driver requirements. The goal of producing a multi-beam injector was not met because funding was not provided. A schematic diagram of an accelerator experiment, indicating issues and progress, is shown in the figure below.

Matching a high-current beam into an alternating gradient (quadrupole) channel is important. Experiments are beginning with a 6-quadrupole matching section; 3-D computer simulations project succesful operation.

Transverse beam combining is considered advantageous because it allows for electrostatic quadrupole transport of many beams (at low energy) with small apertures. Once combined (at about 100 MeV), subsequent acceleration and transport is carried out with magnetic quadrupoles that have large apertures. Beam combining experiments have begun at LBNL.

Transport of a low-current space charge dominated beam (mAs) through a 7-quadrupole magnetic focussing system has been achieved successfully at LLNL. Construction has started at LBNL of a high current (800 mA) system.

Recirculation is being investigated; potential advantages include reduced total length, saving on total number of induction modules, and allowing smaller individual induction modules. An overall reduction in cost could thus be realized. Many issues must be dealt with here: beam control is likely to be more difficult; emittance growth in a curving beam with space charge effects needs evaluation; the pulsers must be programmed with a different time history for each pass of the beam;

energy recovery from dipoles appears necessary; and vacuum requirements are significantly more stringent (~ 2 orders of magnitude). A prototype recirculator is being developed at LLNL to address many of these issues experimentally; it is not expected to have a functioning 360 degree ring before FY98.

Final focusing of the beam onto target presents numerous scientific and technical challenges. Preliminary experiments have begun at LBNL; on self-focusing (*plasma lens*), have led to a 20-fold increase in beam intensity; and on laser-induced plasma channel guiding; much more work needs to be done in this area in the future.

In parallel with the experimental investigations, theoretical modeling of beam transport and dynamics has made excellent progress in the last few years. Highlights include: particle in cell simulations of beam merging results; detailed modeling of beam transport through electrostatic quadrupoles, with space-charge effects; simulations of the recirculator approach, which are used to help design the experiments; evaluation of resistive wall mode effects on longitudinal beam stability; numerical studies of chamber focusing and transport, including effects of charge and beam neutralization; investigation of beam-beam interactions for multiple beams converging near the target.

There has been a number of hardware developments. Lower cost ferromagnetic materials have resulted from making better use of industrial products. High repetition rate, reliable, flexible waveform controllers and generators have been developed for beam acceleration. Low-cost pulsed magnetic quadrupoles and a high gradient (100 kV/m) electrostatic quadrupole system has been developed.

The studies described above were carried out primarily to support the design and experimental program of the Induction Linac Systems Experiments (ILSE) accelerator. The advances described above would allow an ILSE-type accelerator to have twice the performance at a similar cost to the original proposal. This experience leads to the expectation that much larger gains in performance will be achieved in the proposed program over the next few years. For these reasons the program is considering an integrated experiment with a 3-30kJ accelerator as the next step.

2.) Issues in the near term program.

- Continued development of ion sources to achieve longer life and lower emittance is needed.
- Development should continue on compact multi-beam, high current injectors.
- A demonstration is required of the injection and multi-pass recirculation of a space charge dominated beam, while maintaining beam quality.

- The maximum transportable current density limits should be determined.
- Validation of beam simulation codes for 100's of lattice periods is required.
- Demonstrations of beam combining are required with validation of codes, and of beam focussing with and without neutralization.
- Development is also required of low cost components and assembly techniques.

3.) Feasibility of Heavy-Ion-Beam-Drive for High-Gain Targets:

It must be demonstrated that high-gain targets can be driven by heavy ion beams. Some modeling has been carried out to investigate this very broad issue, and there is some related information from light ion target designs and simulations. Recent simulations from LLNL, using the modeling developed for NIF, predict adequate gain for ion-beam indirect-drive targets. These simulations are supported by a wide variety of data from the NOVA laser at LLNL. Much of the detailed experimental evaluation of the prospects for ion-driven ignition and gain must await results from NIF. In the meantime, development of indirect drive target designs for NIF, which are ion-beam relevant, should continue.

4) Additional Science & Technology Questions.

a) *Focusability*: The ability to maintain beam quality (focusability) at high current is the principal scientific challenge for the development of HIB drivers. In addition to the topics and progress noted in section 1 above, some additional physics issues worthy of consideration include:

(i) The goal of developing a capability to do "end-to-end (of the accelerator)" simulation of beam propagation is expected to play a key role in optimizing the MJ driver design. A linear driver will pass the beam through of order a thousand lattice periods. Therefore, experimental validation of code accuracy over long times will be important. Existing particle-in-cell (PIC) methods have shown good agreement in short experiments, and have been used to obtain converged results over hundreds of lattice periods. However, maintaining a sufficiently low noise level for long-time accuracy will be computationally challenging. The much longer beam path in a recirculator driver makes it even harder to model. Intermediate tests of understanding in this key area of long-time transport are expected to come from the small recirculator experiments (of order 300 lattice periods) and possibly more efficient "reduced" description simulation methods. Experimentation should help to determine whether piecing together results from separate analyses of carefuly selected elements/accelerator modules is adequate to accurately describe an entire machine.

(ii) The physics and feasibility of self-pinched propagation in the chamber remains an important and open issue. Experiment/theory tests on this subject would be valuable.

(iii) The filamentation of an HIB driver for ICF is an important issue that could benefit from some reexamination. Earlier studies [E. P. Lee, et al. Phys. Fluids 23, (1980) 2095] considered the growth of filaments in a charge-neutralized ion beam propagating through a resistive plasma medium. They concluded that filamentation required higher pressure than the ~ 1 mtorr present in current fusion chamber designs. Although these results are reasonable, powerful new computational capabilities can profitably be used to examine higher density regimes of interest.

b.) *Beam-target interaction*: Intense radiation from the target, produced when the target is heated by the early time portions of the beam, can affect propagation of the remainder of the beam. Langdon et al's calculations [A.B.Langdon, Nucl. Instr. and Methods in Physics Res. A 278, p 68, 1989, and also Carlo Rubbia, Nucl. Instr. and Methods in Physics Res. A278, p 253, 1989] indicates that "photoionization of half the beam by the time it propagates to within 20 cm of the target is likely." A later more accurate kinetic calculation following a slice of ion beamlets, as they merged and hit the target, showed a 5% loss of ion deposition within the intended 3 mm radius spot (A.B.Langdon, Particle Accelerators, Vol. 37-38, p ,175-180, 1992). This calculation assumed no neutralization due to collisional effects and photoionization of vapor in the chamber. Such neutralization effects further reduce the electric field and the trajectory changes. This issue should be included in the examination of all potential focussing schemes.

C. **A European Perspective. Ingo Hofmann, GSI Darmstadt.**

At GSI Darmstadt (a major German national laboratory in heavy ion nuclear and applied research) there exists a laboratory commitment to develop heavy ion drivers and beam physics as well as plasma physics experiments (with heavy ions) towards the goal of IFE based on the RF Linac & Storage Ring concept. This is complemented by a basic science program funded by the Federal Ministery of Research on "High Energy Density in Matter" since 1980 (beam plasma experiments, target theory and driver development), which supports primarily University groups, again with GSI in a lead lab role. Both programs add up to approx. 2 Mio. DM/y. [ An addendum: as far as the relatively "low-level" funding of HIF in Europe one should keep in mind that, generally, salaries of scientific staff are not included and that the GSI facility is a large investment (300 Mio. DM) which came from other sources].

In other European countries (except Russia) there are smaller groups and individuals in a number of institutions who work on different aspects of HIF. I estimate these efforts as presently < 0.5 Mio. DM/y. The feasibility study proposal "Ignition Facility" submitted to the European Union would allow establishment of a formal European collaboration within the "keep-in-touch" position towards ICF (in total 1% of the yearly 200 million ECU fusion budget). Although a "Study Group" has been inaugurated in March 1995, the decision on behalf of the EU is still pending. It should be mentioned here that the report of the recent ESTA (European Science and Technology Assembly) working group, established by the previous Commissioner for Energy Research as a consulting body, was in favour of gradually raising the 1% level for ICF to 10% of the total fusion budget. This is to be seen in part as a consequence of the US declassification in energy related ICF.

In Russia there is a collaboration between Arzamas (their former weapons lab) and ITEP/Moscow with the purpose of using the existing proton/heavy ion synchrotron at ITEP for target experiments at the kilojoule level, which requires some hardware extension to implement a foil stripping device. According to unofficial information this project expects funding at the $10 million. level (in total).

2. Technical Prospects RF vs. Induction Approach

The RF approach is based on broad experience with linacs and storage rings, however not under the extreme beam power density conditions required for HIF. In the European Study we are not yet in a position to say how many storage rings and final beam lines are really needed for a reactor driver. The induction approach is highly innovative and appears to have a larger cost saving potential due to its very high current capabilities. Since both schemes are still in a research phase they need to be pursued as complementary approaches. There is a lot of synergism which opens possibilities for effective collaboration in a number of beam physics issues, including final focusing.

3. Beam Physics - a Science?

In my estimate the LBNL/LlNL beam physics group is doing excellent work and has developed capabilities which are unique in their kind. The codes are used under the special technical boundary conditions of injectors and the induction acclerator, where they have developed an extremely high standard of modeling. Applying their 3-D simulation tools to areas of concern in the larger accelerator community (including the RF approach to HIF) would be an excellent opportunity to foster the links with the broader field and give the group the recognition it truly merits. At the same time, confidence in their simulation tools would build up in the accelerator community. I believe that it is largely the detachment from too specialized an accelerator environment (especially at low energy) which is a condition for recognition of beam physics as science.

D. **Integrated Reasearch Experiment.**

The overall objective of an Integrated Research Experiment (IRE) is: to provide the capability to investigate the science of heavy ion beam/target interactions; and to provide a data base that, together with the results from the broadened base program and NIF, will be sufficient to support a decision to proceed with the construction of a full scale heavy ion IFE driver. The design parameters for this proposed experimental facility are not fixed at this point, although a number of representative examples of facilities at about the right scale have been studied in the past.

The overriding issue in the development of heavy ion accelerators is the transport and beam control of very high power, high brightness ion beams. The generation, axial compression, and merging of multi-beam, high-current, heavy ion beam pulses in the presence of strong electromagnetic interactions with the accelerator structures must be carried out, while maintaining a good beam emittance (brightness). There are no fundamental impediments, but it is clear that a variety of passive and active beam control systems are needed. Experiments at the scale of the IRE are essential to develop the experience and understanding needed before a full scale driver can be designed with confidence.

The induction accelerator technology has demonstrated adequate reliability, rep-rate capability, and efficiencies in moderate scale experiments. The main issue in the technology area is achieving these performance capabilities at a low enough cost to meet the economic goals.

The committee concurs with the IFE Program's description of the science and technology elements that should be included in this integrated experiment:

- The IRE should provide the experimental capability for resolving the basic beam dynamics issues involved in the generation, acceleration, and pulse compression of a heavy ion beam, through the accelerator and through the beam transport to the target chamber.
- It should be capable of studying experimentally a wide range of schemes for focusing and transporting the heavy ion beam onto the target, including vacuum ballistic transport, plasma neutralization, plasma channel transport, and self-focused transport.
- It should provide an experimental evaluation of energy deposition and target heating with heavy ion beams in hot ionized matter, in the temperature regime of a 100 eV or more, including any effects

that radiation from the target might have on the focusing and steering of the ion beam passing through various background gases in the target chamber.

- The operation of this facility, at a rep rate of several Hz, will also provide engineering data on the efficiency, reliability, and costs at a scale that will allow meaningful extrapolation to a full scale induction linac driver.

To achieve these objectives, the IRE should be designed with the flexibility for experimental studies over as wide a range as practical, both in the operational modes of the beam in the accelerator as well as the beam parameter variations possible for final focusing, transport, and target heating studies. For example, with plasma-based ion sources, a range of ion masses is possible in principle, if the appropriate flexibility is provided in the beam transport system.

The challenge faced by the IFE Program in the design of the IRE is how to achieve these objectives at an affordable cost. The general parameter range under consideration is a pulse energy in the range 3 to 30 kilojoules, at a beam voltage of 100 to 300 MeV (with singly charged K, for example). At a pulse length of order 10ns (after compression, at the target) the beam current is several kiloamps. The beam current in the accelerator should then be several hundred amps, sufficient to reach the "heavy" beam loading regime necessary for high efficiency operation of the accelerator cells. It is also necessary to be in this regime to fully evaluate the longitudinal dynamics of the beam in the presence of significant feedback from beam loading of the accelerator cells. This feedback is especially important in understanding the amplification of current waveform fluctuations (klystron-like bunching modes), and the viability of various correction schemes for maintaining smooth pulse waveforms.

To accurately model the phenomenology of a full scale driver in a machine that is about 10-20 x smaller, scaling of several of the key parameters is necessary. Major variables that have a significant effect on the cost include the final beam voltage, the pulse length (or the joules in the pulse), and the ion mass. Over the next two years, trade studies to identify the most promising parameter sets for the IRE should have a very high priority.

Previous designs of a so-called "High Temperature Experiment" (HTE), with

many of the same objectives, explored a similar parameter regime, see for example, "Accelerator Inertial Fusion -- A National Plan for the Development of Heavy-ion Accelerators for Fusion Power", Los Alamos National laboratory Report LA-UR-81-370, Dec. 10, 1981, and
"Heavy Ion Accelerator Research Plan for FY84-FY89", Los Alamos national laboratory Report LA-UR-83-1717, May 1983.

E. **Progress on potential laser drivers for IFE.**

Both KrF and Diode-Pumped Solid-State Lasers (DPSSL's) have potential as drivers for IFE. Although both laser systems have projected laser efficiencies of less than 10% for IFE applications, the projected target gains for Direct Drive targets could be high enough for economical energy production. Although quite speculative, the potential enhanced gain of direct drive targets ignited by a fast ignitor laser beam could further relax the laser efficiency requirements, or reduce the laser energy required for IFE.

Since 1993, significant progress in the ICF Program has been made in developing both the target physics and technology required for Direct Drive IFE with lasers . The NIF is being designed to allow testing of Direct Drive targets. Programs to establish the laser requirements for laser beam smoothing and hydrodynamic instability control are being actively pursued on the recently completed Omega glass laser at the University of Rochester and the KrF Nike laser at the Naval Research Laboratory.

The 60 beam Omega laser is capable of delivering 30-45 KJ of laser light at 0.35 mm in a flexible pulse shape. Omega is the principal U.S. facility for exploring direct drive implosions and will be used for establishing the requirements for direct drive ignition on the NIF.

The 56 beam KrF Nike laser can deliver 2-3 kJ of energy at 0.248 mm to planar targets. Nike will be used primarily for the study of imprinting (target perturbations created by laser intensity variations in the laser beam), and subsequent hydrodynamic instability growth. Individual Nike beams have achieved spatial intensity uniformity of about 1% when averaged over the 4 ns duration of the laser pulse. This a factor of several better than can currently be achieved with glass lasers although improvements planned for Omega are expected to significantly improve its beam quality.

System studies of KrF lasers have concluded that 5-7% efficiency is feasible (perhaps somewhat more if waste heat from the amplifiers is recovered). The Nike laser, which was not designed for efficiency or high repetition rate, operates at about 1.7% efficiency. For IFE, amplifiers would need to be developed which demonstrate the required efficiency, repetition rate and durability.

Flashlamp-pumped Solid-State lasers do not have the efficiency or heat handling capability required for IFE. For example, the NIF, as designed, will operate at about 1/2 % efficiency. However, solid state lasers which use a gas-cooled crystal gain medium, pumped with efficient diode lasers have projected efficiencies near 10%. Many elements of such a system have been demonstrated on a small scale at LLNL. A 2 joule DPSSL at LLNL, which used the crystal Yb:S-FAP as the gain medium, has operated at 25 Hz with gas cooling and has demonstrated an ability to handle heat fluxes in excess of those required for IFE. Larger scale DPSSL lasers would take advantage of the technology developed for the NIF. A major issue for DPSSL's is the cost of diodes. For IFE applications, diode costs of $ 0.10/watt or less are required. Current diode costs are about $10/watt and the cost goal for diodes to be used on the NIF is $1/watt. Diodes have a variety of commercial and military applications and their price is projected to decrease as these markets grow.

A generic issue for laser IFE is protection of the final optics against neutrons, X-rays, and debris from the target and chamber. Grazing incidence metal mirrors (GIMM's) and self-annealing fused silica optics operated at several hundred degrees Centigrade have been proposed as solutions. An OFES sponsored program to further evaluate possible optics protection approaches could help establish criteria for determining laser requirements.

DP is supporting a modest development effort on DPSSL's and a research program on the fast ignitor. At present there is no funding for KrF rep-rated high power amplifier development. Although we are not recommending an OFES program on laser driver development at this time, we do recommend that OFES continue to evaluate progress on laser drivers and direct drive targets in DOE Defense Programs. We also recommend that OFES act to encourage international collaborations with the U.S. on laser driver developments directed toward IFE.

## F. IFE Power Plants (Progress and Needs)

A number of excellent, comprehensive, conceptual design and system studies for IFE power plants have been completed over the last few years. Innovative concepts have been developed through these studies, and they have contributed to providing a greater understanding of the prospects and issues for IFE. These studies have shown the promise of IFE as a competitive energy option. The key technical issues, derived from this work, are listed in Table 1.

The target physics and performance, and target-beam interactions will be addressed primarily by the DP program, partly in the R&D for NIF, and then through experiments on NIF.

Several issues affect the viability of fusion chamber designs for IFE. The first issue concerns the feasibility and performance of a viable wall-protection scheme. A practical IFE system requires protection of the solid chamber wall from rapid degradation due to the extremely high instantaneous heat and particle loads associated with the X-rays and debris from the target explosion. While researchers agree on the need to protect the solid chamber wall, there is no consensus on the best means to achieve this. The two leading schemes proposed for wall protection are : 1) thick liquid layer, and 2) thin liquid layer. In the first scheme, a thick layer of a liquid, e.g. flibe, is formed inside the chamber solid walls to form a "pocket" surrounding the microexplosion. This scheme has the added advantage of also protecting the first wall from neutron damage. Examples of key issues associated with this scheme are:

1) the ability to form a stable and uniform thick liquid layer so as to fully cover the interior surfaces of the first wall,;

2) the feasibility of forming the liquid layer so as to allow holes for the driver beams without exposing the first wall to unacceptable levels of X-rays and debris;

3) the ability to re-establish the wall protection layer after the microexplosion; and

4) the need for this liquid to contain lithium to provide adequate breeding and the ability to clear the chamber from a multi-species liquid (e.g. the molten salt flibe).

Another scheme for wall protection relies on a thin liquid metal film wetting the first wall. This concept allows greater control over liquid feeding and uniformity of the liquid layer. It can use a single-element liquid; for example, lead, which is a neutron multiplier that can also enhance tritium breeding. Examples of issues with this scheme are: a) blast effects, b) flow around geometric perturbations, c) neutron damage and activiation, and d) protection of inverted surfaces. Only a very small effort has been devoted to this critical issue of wall protection. Experiments and modelling are needed to evaluate the scientific and technological issues - fluid mechanics, thermomechanics, and materials response - of the various wall protection schemes

The second IFE issue is cavity clearing at IFE pulse repetition rates. Following each pellet explosion, the cavity (chamber) fills with target debris and material evaporated or otherwise ejected from the cavity surfaces. This material must be removed from the cavity before the next target is injected. This generally requires recondensing condensable gases onto the surfaces of the first wall (or more specifically the surfaces of the wall protection layer) and by pumping non-condensable gases out through large ducts. Power reactors require a repetition rate of ~3-10 pulses per second. Evacuation requirements depend on propagation limits for both targets and driver energy. Base pressure requirements: determine 1) the time to evacuate the chamber; and 2) the level of protection to the first wall (and final optics) afforded by the cavity background gas. Research is needed to better understand clearing requirements, the recondensation process, and to develop design solutions. Some small scale experiments are being planned at universities.

The remaining fusion chamber and target fabrication issues in Table 1 are related strictly to power plant technology feasibility, safety, and economics. They include: demonstration of tritium self-sufficiency in a practical IFE system; demonstration of adequate radiation shielding of all components; thermo-mechanical response and radiation damage of the first-wall/blanket; and demonstration of low cost, high volume target production techniques. The required R&D and the resolution of these last four issues will be greatly influenced by the results of research to resolve the previous issues.

## Table 1

**Top-Level Issues For**

**Inertial Fusion Energy**

| | |
|---|---|
| 1 | Sufficiently High Target Gain at Economical Driver Size:<br>a) G > 30 for indirect drive with ion beams.<br>b) G ~ 100 for direct drive with lasers. |
| 2 | Driver cost, efficiency, reliability, and lifetime:<br>a) Demonstration of the required performance of a driver operated in a repetitive mode.<br>b) Performance, reliability and lifetime of final optics. |
| 3. | Fusion Chamber:<br>a) Feasibility and performance of a viable wall-protection scheme.<br>b) Cavity clearing at IFE pulse repetition rates.<br>c) Tritium self-sufficiency in a practical IFE system.<br>d) Adequate radiation shielding of all componenets.<br>e) Pulsed radiation damage and thermomechanical reponse of first wall/blanket, particularly for concepts without thick liquid protection. |
| 4. | Sufficiently low cost, high volume, target production system. |

G. **Synergy of IFE/ICF and MFE.**

- There is an important synergy in plasma theory and computer modeling as seen in the numerous books on plasma physics; e.g., in such areas as Particle-in-Cell simulations and intense radiation-plasma interactions

- Non-linear plasma instabilities, shock waves and implosion codes, non-neutral plasmas, plasma-wall interactions, and intense ion-beam physics are important common interests

- There is much in common in atomic physics and diagnostic needs, notably in the radiation detection area—mirrors, photo-detectors and lasers.

- Common technology interests include neutron damage resistant materials development and tritium breeding blanket technologies.

APPENDIX A. Charge to Panel, Meeting Agendas, and Contributors.

1. **Charge to Panel.**

2. **Meeting Agendas.**

**a.) FESAC/IFE Review LBNL, June 3-5, 1996.**

**Monday, June 3, 1996**

| | | |
|---|---|---|
| | Welcoming remarks | Director, Charles Shank |
| 8.30 am | Executive Session | |
| 10.15 am | *Break* | |
| 10.30 am | Public Session (all day) | N.Anne Davies (DOE)<br>David Crandall (DOE) |
| 11.15 am | History of IFE:<br>FEAC 7 Panel Report | Bill Hermansfeldt (SLAC) |
| 12.00 pm | Program Overview | Roger Bangerter (LBNL) |
| 12.30 pm | *Lunch* | |
| 1.30 pm | Overview (cont) | |
| 2.15 pm | IFE Target Physics | John Lindl (LLNL) |
| 3.30 pm | Tour of Experiments | LBNL Staff |
| 4.30 pm | Beam Physics Experiments | Simon Yu (LBNL) |
| 6.00 pm | *Adjourn* | |

**Tuesday, June 4, 1996**

| | | |
|---|---|---|
| 8.30 am | Beam Theory | Alex Friedman (LLNL) |
| 9.45 am | IFE Power Plants | Ralph Moir (LLNL) |
| 10.30 am | *Break* | |
| 11.00 am | The European Program | Ingo Hofmann (GSI) |
| 11.45 am | Synergism of IFE, MFE<br>and other ER programs | Grant Logan (LLNL) |
| 12.15 pm | *Lunch and Executive Session* | |
| 1.45 pm | Summary (part 1) | Roger Bangerter (LBNL) |
| 2.15 pm | Invited Comments | John Sethian (NRL)<br>Bill Barletta (LBNL)<br>Stephen Dean (FPA) |
| 3.30 pm | *Break* | |
| 4.00 pm | Invited Comments (cont) | Craig Olson (SNL)<br>Mike Campbell (LLNL)<br>Ken Schultz (GA) |
| 5.00 pm | Public Comments | None |
| 5.05 pm | Summary (part 2) | Roger Bangerter (LBNL) |
| 6.00 pm | *Adjourn* | |

**Wednesday, June 5, 1996**

| | |
|---|---|
| 8.00 am | Executive Session |

12.30 pm *Adjourn*

**b.) FESAC/IFE Review LLNL, June 24-26, 1996.**

**Monday, June 24, 1996**

| | | |
|---|---|---|
| 8.30 am | Executive Session | |
| 12.30 pm | *Lunch* | |
| 1.30 pm | Tour of LLNL facilities | LLNL Staff |
| 3.00 pm | Executive Session | |
| 4.00 pm | Discussion of proposed heavy ion accelerator budgets | Roger Bangerter (LLBL)<br>Alex Friedman (LLNL) |
| 4.45 pm | Executive Session | |
| 6.00 pm | *Adjourn* | |

**Tuesday, June 25, 1996**

| | | |
|---|---|---|
| 8.30 am | Executive Session | |
| 12.30 pm | *Lunch* | |
| 1.15 pm | Fast Ignitor | John Lindl (LLNL) |
| 2.15 pm | Executive Session | |
| 5.45 pm | *Adjourn* | |

**Wednesday, June 26, 1996**

8.00 am. Executive Session
12.30 pm *Adjourn*

3. **Written Contributions.**

a.) Recommendations for Inertial Fusion Energy from the Naval Research laboratory, Stephen Bodner and John Sethian.

b.) Comments on the IFE program from the University of Wisconsin, Robert R. Peterson and Gerald L. Kulcinski.

c.) Comments from the University of Maryland, Martin Reiser and Terry Goodlove.

Appendix B - Status of Target Physics for IFE

**1. Summary of 1993 FEAC Panel 7 target physics findings**
Although there has been major progress in ICF target physics since the 1993 FEAC panel 7 report[1], the two principal findings of that report remain true:

The primary approach to heavy ion fusion (HIF) and the glass-laser-based NIF is the indirect-drive approach. For indirect drive, the capsule implosion and burn physics are the same for both HIF and laser-driven hohlraums. For ion-driven hohlraums heated to the same radiation temperature ($T_R$), the HIF requirements for hydrodynamic instability, implosion uniformity, and pulse shaping can be investigated directly with laser-driven targets. In addition, at the same radiation temperature, x-ray hohlraum wall losses, radiation-driven hohlraum wall motion, and radiation transport for laser-driven hohlraums are directly applicable to HIF. These are the primary issues which affect coupling efficiency and hohlraum symmetry for the baseline HI hohlraums. Because of these similarities, the DP target physics program on the Nova laser at LLNL provides a solid base for calculating most critical elements of HI targets.

Success of the ignition objectives on the NIF will substantially reduce the risk for heavy ion inertial fusion energy (IFE), and these results will play a major role in any decision to develop a full scale HI driver. We believe that the success of the Nova laser target physics program, coupled with the Halite/Centurion[2] underground test results, provide a sufficient target physics base for proceeding with the development of the technology and physics base for HI drivers.

## 2. Progress on Indirect Drive ICF since 1993

### 2.1 Declassification

Of major importance to the general availability of the target physics basis for ICF was the Dec 1993 decison by DOE to largely declassify ICF. Since that time, a large number of articles as well as a comprehensive review of Indirect Drive ICF[3] have appeared in the scientific literature.

### 2.2 ICFAC review of Indirect Drive Ignition Laser Targets for the NIF

The 1990 National Academy of Science review ICF[2] established the Nova Technical Contract (NTC) as a set of target physics goals which would form the basis for a decision to proceed with the NIF. These goals are also largely applicable to HIF, as summarized by the 1993 FEAC Panel 7 report. Since the 1993 FEAC Panel 7 met, the Defense Program advisory committee for ICF, the ICFAC, has extensively reviewed (8 full ICFAC and 4 subcommittee meetings) the ICF Target Physics Program. An extended review of progress on the NTC, which the ICFAC has concluded is essentially complete, is available[4]. In its letter report following it final meeting in November 1995, the ICFAC concluded[5]:

"The overall impression of the committee on the target physics is that there has been remarkable progress in the last six months. During the three years of ICFAC reviews of ICF, the ICF target physics program for ignition has identified and resolved many potential target physics issues. The peer review and collaboration between the two nuclear weapon design laboratories has been largely responsible for the rate of progress in addressing Nova Technical Contract goals. Without major roles for both laboratories in target physics, the credibility of reaching ignition will be significantly reduced. There is a much larger base of attractive designs than at the time of KD1 (decision to proceed with preliminary engineering design of the NIF) and the case for achieving ignition on NIF has been significantly strengthened since that decision. The program has developed a broader set of tools. In all of the critical areas - cryogenic layer production , hohlraum laser plasmas, and implosions - committee members believe that the probability of ignition has increased above 50%, and some believe that it is well above this level. As one committee member put it, the situation has changed from risk reduction to confidence increasing. Although new problems may appear, the committee has seen a high level of ingenuity in the personnel in the program and has confidence that solutions will be found."

**2.3 Integrated Calculations of NIF Ignition Targets**

One of the significant advances of the past 3 years, has been the development, by both Livermore and Los Alamos, of integrated calculations of NIF ignition targets that employ full radiation transport[3,6,7]. These calculations model the laser propagation and absorption, the full hohlraum and the implosion as a single integrated entity. Fig 1 shows the NIF point design which has had the most intensive analysis. Fig. 2 shows the numerical grid at the beginning and at the peak of the laser pulse. The snapshot at peak power also shows the laser rays. Figure 2 does not show the detailed zoning of the fuel capsule but it was included in the calculation. These calculations use the 2D LASNEX computer code which is the workhorse of the ICF indirect drive modeling program. Figure 3 shows the gain obtained from the integrated calculations for different size targets that can be tested on the NIF. These gains are consistent with analytical scaling curves that are indicated for two different hohlraum coupling efficiencies. As indicated in Figure 1, the NIF point designs have about an 11% coupling efficiency. Although such integrated calculations have been a prominent feature of the ICF program since its beginning, the Nova experiments on symmetry demonstrated that it was necessary to utilize full radiation transport, rather than diffusion, in order to accurately calculate implosion symmetry. Although aglorithms for solving the transport equation have been available for many years, significant improvements were required to achieve the required accuracy with reasonable amounts of computer time. With these improvements, it has been possible to do ignition calculations which routinely utilize full radiation transport. These calculations, and the Nova experiments, which have been used to verify the accuracy of the computational techniques, have resulted in a significant improvement in the confidence of the accuracy of the NIF ignition designs noted by the ICFAC report. These techniques have been applied to HIF high gain targets as described below.

**2.4 Development of 3D codes**

Another major advance in the past 3 years has been the development and utilization of 3D codes for hydrodynamic instability and implosion calculations. The nonlinear evolution of the Rayleigh-Taylor instability is inherently 3D, and various features of the radiation asymmetry onto the capsule, particularly on Nova, must sometimes be modeled in 3D. Figure 4 shows the results of planar Rayleigh-Taylor Instability experiments and 3D calculations which correctly model the dependence of the late phase nonlinear evolution of perturbations with different shapes[8]. Fig 5 shows the calculated and measured yield degradation for implosions which used capsules with deliberately perturbed surfaces. The observed yields require 3D calculations to accurately model the results. These results apply directly to indirect drive implosions driven by ion beams.

**3. Target Gain Requirement for IFE**
For an inertial fusion energy (IFE) application, the target/driver combination must meet a minimum product of driver efficiency times gain (hG) where h is the efficiency of converting electrical energy into the driver beam energy and G is the target gain, the ratio of thermonuclear yield to driver energy delivered to the target. For IFE power production, we have:

$$P_{net} = P_{gross} - P_{aux} - P_{driver} = P_{gross}[1 - f_a - 1/(hGMe)]$$

where $P_{net}$ is the net power, $P_{gross}$ is the gross power, $P_{aux}$ is tht power required to run auxilliary systems, and $P_{driver}$ is the power required to run the driver. Also M is the fusion blanket multiplier which is slightly greater than unity because tritium production in lithium is exothermal, and e is the efficiency of converting thermal energy into electricity. The product Me~0.4 in typical power production studies. Since $P_{aux}$ is usually only a few percent of the gross power produced, the fraction of the gross power used to power the driver is approximately 1/hGMe. If this is more than 25-35% of the total power, the cost of electricity increases rapidly. Hence we require hG>7-10. Since ion beam drivers can have an efficiency of 35% or potentially more, we only require a target gain G>20-30. Since currently proposed laser systems, such as KrF or diode-pumped solid state lasers (DPSSLs), have efficiencies of 10% or less they require a target gain G>70-100. At this stage of planning, a saftey margin in the potential target gain of a factor of two or more is important for making a case that can be strongly defended. Although Indirect Drive laser driven targets can potentially reach the lower end of the required gain at a laser energy of about 10 MJ as indicated in Fig. 3, there is no margin for error and the laser size is very large. Direct Drive targets, which will also be tested on the NIF, have potentially higher gain which makes this type of target more attractive for power production with lasers. Potential issues for Directd Drive targets are discussed at the end of this appendix.

**4. Ion Beam Target Designs**
A wide range of ion beam targets, such as those shown in Fig 6, can achieve the required gain and can be matched to accelerator and fusion chamber requirements. The two sided targets in Fig 6 have received the most attention in the HI program because they are well matched to attractive fusion chamber approaches which utilize a first wall protected from neutrons. Such fusion chambers utilize a thick blanket of neutron absorbing material, which also breeds the required tritium, inside of the chamber first wall[9].

**4.1 Localized Radiator Designs - Two-Sided**
Fig. 7 shows the analytically estimated gains[10] (as a function of ion beam focal spot radius for two typical heavy ion ranges) for targets with localized radiators such as those in Fig 6a. These calculations are based on capsule designs being developed for the NIF, and data on radiation transport and hohlraum energetics obtained from Nova experiments. Also shown in Fig. 7 are the capsule energies and required hohlraum temperatures. Capsules with the smallest energy indicated, 0.2 MJ, can be directly tested on the NIF. Symmetry is obtained in these localized radiator designs by

using symmetry shields to remove long wavelength variations in the radiation flux. Similar approaches to controlling symmetry have been successfully tested on Nova[3]. As shown in Fig. 7, the gains are critically dependent on the spot size of the ion beam when it is focused on the target radiators. The HI driver energy required to drive a fuel capsule of a given size depends inversely on the efficiency with which the ion beam energy is converted to x rays. This in turn depends on the focal spot size and range of the ions which determines the mass of material heated by the ions. As the ion range is reduced, less mass is heated for a given spot size. This results in a higher gain for a given spot size or a larger tolerable spot size for a given gain. For idealized radiator designs, 50-80% of the driver energy can be converted to X-rays[1]. Recent more detailed calculations which include full radiation transport and radiator wall motion obtain conversion efficiencies of about 50%. These calculations indicate the radiators with very small spot sizes are likely to suffer from closure due to wall motion. More work is required to fully optimize radiatior designs for these localized radiator designs.

The targets in Fig. 7a are readily adaptable, in principle, to single sided irradiation. If the radiators are constructed with a 90 degree bend prior to entering the hohlraum, the ion beams can come in from a single side while maintaining basically two-sided axisymmetric irradiation of the capsule.

**4.2 Distributed Radiator Designs - Two-Sided**

The distributed radiator design shown in Fig 6b, is suitable for relatively short range ions. This design uses the same capsules as the localized radiator design and NIF, but symmetry is obtained by locating the radiating material where it is required for symmetry. This can be achieved by varying the density and radiator material. Fully integrated design calculations, similar to those that have been done for NIF targets, have been successfully carried out. Fig 8 shows the materials and densities used at the beginning of a particular series of calculations which achieves adequate symmetry and gain of 40 with about 7 MJ of 3.5 GeV Pb ion beam energy[12]. This design uses low density high-z materials for the hohlraum wall in order to maintain near pressure equilibrium between the walls and the foam radiator material. Fig 8 also shows the density contours near peak compression. Such calculations have been made possible by the developments in modeling for the NIF but much less effort to date has been devoted to optimizing the HI targets. When optimized, targets like those in Fig 8 are expected to have gains of 50-70 when drive by 5-7 MJ of ions.

Integrated calculations are also being carried out on the localized radiator designs, but these designs have complicated hydrodynamics in the radiators and internal symmetry shields which has not been fully modeled.

**4.3 Spherical Target Designs**

A range of “symmetrically” irradiated targets such as the target shown in Fig 6c, is also feasible. The potential gain of these targets depends on the degree of “direct coupling” of the ion beam to the fusion capsule. Two designs which indicate the range of target sizes and gains are shown in Fig. 9.

The light ion program at Sandia National Laboratories (SNL) has examined the

design shown in Fig 9a. In this design, the ions are absorbed entirely in the high-z shell and the low density foam outside the fuel capsule[13]. The high-z shell and foam produce x rays which then implode the fuel capsule. The capsule design is largely similar to the NIF target designs, with the exception that the Sandia design has an outer layer of BeO to help provide "internal pulse shaping". This layer can help relax the accelerator pulse-shaping requirements. Because there must be enough material to stop the ions over then entire surface of the target, there is a larger heat capacity of radiator material in these spherical targets than in two-sided designs. This results in lower x-ray production efficiency, and relatively low gain at a large driver energy.
The other extreme in symmetrically illuminated targets is the direct drive target ion target·. In the example indicated in Fig. 9b., the pressure which drives the implosion of the DT layer is generated in the $CH_2$ layer which is directly heated by the ion beams[14]. At early time, there is very little smoothing of nonuniformities which arise because of the overlap of a finite number of ion beams. At later times in the pulse, the $CH_2$ generates enough radiation that radiation smoothing is significant. If sufficient uniformity can be achieved[15], such targets can have very high gain for relatively small drivers. Because both the symmetry and hydrodynamic instability characteristics of this target depend sensitively on details of the ion beam and the illumination geometry, relevant experiments will require a significant scale ion beam machine with many beams.
A 3D radiation transport capability is probably required to accurately calculate the number of ion beams required for symmetry in both of the above designs. The Indirect Drive symmetric target will require fewer beams than the directly driven design. Using a 2D diffusion approximation, SNL has estimated that 12-20 beams will be adequate for their target design. Full transport calculations in 2D are now possible. Further development of the 3D codes mentioned above, planned for next few years, will allow 3D calculations of these ion targets.

**4.4 Ion Beam Coupling Experiments**

The issue of x-ray production using ion beams is currently being addressed by experiments on the PBFA II light ion accelerator at SNL. On PBFA, 1-2 TW/$cm^2$ lithium ion beams have been focused on conical gold targets filled with low-z low density foam. Althoug the temperature achieved in these experiments is less than 100 eV, the measured radiation temperature and x-ray spectrum, as well as the tamping of the gold wall expansion by the foam, are in agreement with calculations.
LASNEX calculations indicate that fusion relevant matter conditions can be achieved with a heavy ion accelerator delivering as little as 1 KJ of energy . Experiments at GSI Darmstadt have produced a 400 mm diameter focal spot uisng an approximately 10 cm focal length z-pinch plasma focus. Using this focal diameter, LASNEX calculations, using 1 KJ of ions with a range of 0.03 g/$cm^2$ delivered in 2 ns, predict temperatures of 250 eV in a gold lined Be cylinder. A wide range of experiments could be carried out with such plasmas. The effect on beam focusing of photo-ionization of the incoming ion beam, caused by target radiation emission, could readily be addressed.

**5. Direct Drive Laser Targets for the NIF**

Although Indirect Drive is the baseline approach to ignition and gain on the NIF, sufficient progress has been made on Direct Drive with lasers over the past 3 years that the NIF the target area is also being configured for Direct Drive as shown in Fig. 10. By moving 24 of NIF's 48 beam clusters, it is possible to achieve the geometric irradiation uniformity of better then 1% required for Direct Drive. The proposed beam arrangement is shown in Fig. 10. The geometric placement of the laser beams, as well as beam power balance and pointing accuracy primarily affects the long wavelength perturbations on the fusion capsule. This geometry is relatively straightforward to specify. The principal target uncertainties for Direct Drive are the imprinting of short wavelength perturbations onto the outside surface of the fusion capsule, and the subsequent growth of these perturbations by Rayleigh-Taylor Instability. This imprinting occurs because all techniques currently used for beam smoothing require some time to become effective. During this startup phase, residual intensity variation across beams imprint surface modulations on the target. The physics of this imprinting is quite complex and is one of the principal research topics for Direct Drive. As the target is accelerated, these modulations are amplified by Rayleigh-Taylor growth. The growth of all perturbations from both target fabrication and laser imprinting grow more rapidly for Direct Drive targets than for Indirect Drive targets of a given compressibility. This difference is related to the much higher ablation rates of Indirect Drive[3]. To reduce the growth rate of instabilities in Direct Drive, the targets are deliberately preheated. However this approach also reduces the possible gain by reducing the compressibility as shown in Fig. 11 for calculations from the University of Rochester[16]. In this Fig, a is the ratio of the pressure in the shell to the Fermi degenerate pressure at the same density. The current baseline target for the NIF has a=3 with a gain of 30 at 1.5 MJ. If a scheme can be developed for reoptimizing the laser focal diameter near the peak of the laser pulse, the gain increases to about 50. Under the same set of assumptions, the gain is estimated to be 130-150 at 10 MJ. Depending on the feasible laser efficiency, this gain is adequate for energy production although the laser is quite large.

The recently completed 60 beam Omega Nd-glass laser at the University of Rochester will be used to establish the understanding required to accurately specify the smoothing requirements and instability growth for Direct Drive on the NIF. The Nike facility at the Naval Research Laboratory will address these issues in planar geometry for a KrF laser.

Direct Drive targets require a uniform distribution of beams over the entire surface of the target as indicated in Fig. 10. Unless some approach can be developed which relaxes this requirement, Direct Drive is incompatible with the protected wall fusion chamber designs discussed above. A major issue for laser driven fusion chambers is survivability of the final optics to x-rays, neutrons, and debris. This issue will be addressed to some extent on NIF, but for a much smaller number of shots than is required for IFE.

Although driver beam imprinting and subsequent hydrodynamic instability growth are common issues for both ion beam and laser beam direct drive targets, the specific mechanisms for imprinting are unique to each driver. Hence the information learned for Direct Drive with lasers will not significantly increase the understanding of Direct Drive ion beam targets.

**6. Fast Ignitor approach to ICF**

A still more speculative approach to ICF, which has potentially high leverage for high gain, is the fast ignitor approach[17]. In the standard approach to ICF, fusion fuel is imploded and subsequently compressed in such a way that a relatively low density hot spot is formed in the center of a dense shell which contains most of the fuel. The hot spot must be large enough to capture the alpha particles and initiate a self propagating burn wave into the main fuel. The performance of these targets is very sensitive to the mix of cold fuel from the surrounding dense shell into the hot spot or asymmetry in the implosion, both of which can quench the burn.

In the fast ignitor approach to ICF, the compression and ignition steps are separated. A conventional driver is used to compress the fuel, but no attempt is made to produce the central hot spot. This relaxes the sensitivity of the implosion to asymmetry and mix. The energy required to ignite the compressed fuel must then be delivered to the compressed core by a separate beam before the core has a chance to expand. While the compression beams can deliver their energy in nanoseconds, the ignitor beam must deliver its energy in about 10 ps into a spot of about 10 mm radius. Because targets which are uniformly compressed require lower density for good burn efficiency, such targets can have a gain which is a factor of several higher than that of standard ICF targets.

The achievable gain will depend on the efficiency with which the fast ignitor beam is capable of delivering its energy to the compressed core. The intensities involved in the fast ignitor pulse are $10^{19}$-$10^{20}$ W/cm$^2$. At these intensities, the laser plasma interaction is highly relativistic.[18] A laser beam capable of delivering greater than 600 joules in 500 fs has recently been completed on Nova. This laser will be used to test key physics issues associated with delivering the ignitor energy to a compressed ICF target.

References:

1.) Fusion Energy Advisory Committee: Advice and Recommendations to the U.S. Department of Energy In Response to the Charge Letter of September 18, 1992, DOE/ER-0594T (June 1993).

2.) Review of the Department of Energy's Inertial Confinement Fusion Program Final Report, National Academy Press, 2101 Constitution Avenue, Washington D.C. (September 1990)

3.) J.D. Lindl, Development of the Indirect-Drive Approach to Inertial Confinement Fusion and the Target Physics Basis for Ignition and Gain, Physics of Plasmas 2 (11),p 3933-4024 (Nov 1995)

4.) See National Technical Information Service Document No. DE96010698 (ICF Quart. Rep. Spec. Iss.: Nova Technical Contract, UCRL-LR-105821-95-4)

5.) V. Narayanamurti, letter to Dr. Victor H. Reis, Assistant Secretary for Defense Programs, on behalf of the Inertial Confinement Fusion Advisory Committee

6.) S.W. Haan, S.M. Pollaine, J.D. Lindl, L.J. Suter, R.L. Berger, L.V. Powers, W.E. Alley, P.A. Amendt, J.A. Futterman, W.K. Levedahl, M.D. Rosen, D.P. Rowley, R.A. Sacks, A.I. Shestakov, G.L. Strobel, M. Tabak, S.V. Weber, G.B. Zimmerman from LLNL and W.J. Krauser, D.C. Wilson, S. Coggeshall, D.B. Harris, N.M. Hoffman and

B.H. Wilde from LANL, "Design and Modeling of Ignition Targets for the National Ignition Facility," Phys. Plasmas 2, 2480 (1995)
7.) Krauser, N.M. Hoffman, D.C. Wilson, B.H. Wilde, W.S. Varnum, D.B. Harris, F.J. Swenson and P.A. Bradley from LANL and S.W. Haan, S.M. Pollaine, A.S. Wan, J.C. Moreno and P.A. Amendt from LLNL, "Igniton target design and robustness studies for the Nation Ignition Facility, Phys. Plasmas 3 (5), p 2084 (May 1996)
8.) M.M. Marinak, B.A. Remington, S.V. Weber, R.E. Tipton, S.W. Haan, K.S. Budil, O.L. Landen, J.D. Kilkenny, and R. Wallace, "Three-Dimensional single mode Rayleigh-Taylor experiments on Nova," Phys. Rev. Lett. 74, 3677 (1995)
9.) R.W. Moir, "The High-Yield Lithium-Injection Fusion-Energy (HYLIFE)-II inertial fusion energy (IFE) power plant concept and implication for IFE," Physics of Plasmas 2 (6) 2447-2452 (1995)
10.) R.O. Bangerter and J.D. Lindl, "Gain calculations for radiatively-driven ion and laser targets", Lawrence Livermore National Laboratory, Livermore, Ca., UCRL-50055-86/87, pp2-160 to 2-168
11.) D.D.-M. Ho, J.D. Lindl, and M. Tabak, "Radiation converter physics and a method for obtaining the upper limit for gain in heavy ion fusion," Nucl. Fusion 34, 1081 (1994)
12.) Max Tabak, Private Communication (1996)
13.) George Allshouse, presentation to ICFAC committee, June 6-8, 1995
14.) Max Tabak, Private Communication (1990)
15.) J. W-K. Mark and J. D. Lindl, "Symmetry issues in a class of ion beam targets using sufficiently short direct drive pulses", AIP Conference Proceedings 152, Heavy Ion Inertial Fusion, Washington, D. C. (1986), p 441
16.) C.P. Verdon, "High-performance direct-drive capsule designs for the National Ignition Facility," Bull. Am. Phys. Soc. 38, 2010 (1993)
17.) Max Tabak, James Hammer, Michael E. Glinsky, William L. Kruer, Scott C. Wilks, John Woodworth, E. Michael Campbell, and Michael D. Perry, "Ignition and high gain with ultrapowerful lasers", Phys. Plasmas p 1626, (May 1994)
18.) S.C. Wilks, W.L. Kruer, M.Tabak, and A.B. Langdon, "Absorption of Ultra-Intense Laser Pulses", Phys. Rev. Lett. 74, 1383 (1992)

## Appendix C

## IFE Power Plant Issues and Needed Breadth of Research

About 50 conceptual design and system studies for IFE power reactors have been carried out over the past 25 years. Eleven of these were driven by heavy ion beams. The most recent studies, PROMETHEUS and OSIRIS were published in 1992 by two industrial and university teams. Each team developed two conceptual designs, one with heavy-ions and the other with a laser-beam driver. Table 1 shows some of the major parameters of several heavy-ion IFE reactor studies.

These studies make it possible to identify the key technical issues for inertial fusion energy power systems. Table 2 lists the key top-level issues. A brief discussion of these issues is given below followed by the subpanel's views on near-term research priorities.

The first issue is demonstrating high gain at moderate driver energy. Most studies require a gain in the range of 70-120 for a driver output energy (transmitted to the target) of ~ 4-7 MJ. It should be noted that reactor design studies have typically focused on high-gain, multi-megajoule incident energy target concepts that are appropriate for economic power production. However, engineering development is cost limited. It therefore is worthwhile to consider if target designs that provide moderate gain (20-50) at low driver energy (1-2 MJ) are justified. Such targets would lower the facility cost associated with IFE engineering testing and fusion power demonstration.

The second issue concerns the feasibility of the indirect drive (ID) targets for heavy-ion and laser-drivers. For heavy-ion drivers some of the issues include: a) the properties of the method used to transport and focus the HI beam to the target, b) the accuracy and reproducibility of the repetitive HI target launch system which injects the ID targets to the center of the target chamber, and c) the ability of the high-z hohlraum cavity to efficiently convert and smooth the radiation incident on the DT capsule.

The issues of imploding an ID target with laser beams include: 1) plasma closure of the entrance apertures to the hohlraum, 2) accurate target tracking and pointing of the multiple laser beams to coincide with the entrance apertures of the moving ID target, and 3) accurate and reproducible indirect drive target propagation from the pellet injector to the center of the target chamber.

The third issue is the feasibility of direct drive targets. There are strong incentives to consider direct-drive (DD) targets because of higher gains. However, the feasibility and performance characteristics of DD targets are presently uncertain.

The fourth key top-level issue relates to the cost, efficiency, reliability and lifetime of the driver. The specific issues for heavy ion drivers are vastly different from those for laser drivers. The attraction of the HI approach to IFE has always been related to the fundamental technical feasibility of building a system with the required properties to drive a pellet to ignition. The basic accelerator technology is well developed, the beam physics is tractable, and existing accelerators have exhibited 25-year lifetimes with 95% availabilities. The key problem for HI is cost. Key issues associated with a HI cost reduction strategy include: a) space-charge limited transport of a bunched beam, and b) high current storage rings for heavy ion beams.

The key issues for the laser driver include:

1) obtaining an adequately high overall efficiency for the laser driver
2) performance, reliability and lifetime of the final laser optics
3) reliability of various components of the laser driver.

The above four issues are concerned with the target and driver. The remaining key issues relate to providing the proper chamber environment and reactor technologies related to energy conversion, fuel (tritium) generation and adequate radiation protection in a viable, reliable, and efficient high temperature system.

The fifth issue concerns the feasibility and performance of a viable wall-protection scheme. A practical IFE system requires protection of the chamber solid first wall from rapid degradation due to the extremely high instantaneous heat and particle loads associated with the X-rays and debris from the target explosion. While researchers agree on the need to protect the chamber solid wall, there is no consensus on the best means to achieve this. The two leading schemes for wall protection are : 1) thick liquid layer, and 2) thin liquid layer. In the first scheme, a thick layer of a liquid, e.g. flibe, is formed inside the chamber solid walls to form a "pocket" surrounding the microexplosion. This scheme has the added advantage of also protecting the first wall from neutron damage. Examples of key issues associated with this scheme are: 1) the ability to form a stable and uniform thick liquid layer so as to fully cover the interior surfaces of the first wall, 2) the feasibility of forming the liquid layer so as to allow holes for the driver beams without exposing the first wall to x-rays and debris, 3) the ability to re-establish the wall protection layer after the microexplosion, and 4) the need for this liquid to contain lithium to provide adequate breeding and the ability to clear the chamber from a multi-species liquid (e.g. the molten salt flibe).

Another scheme for wall protection relies on a thin liquid metal film wetting the first wall. This concept allows greater control over liquid feeding and uniformity of the liquid layer. It can use a single-element liquid; for example, lead, which is a neutron multiplier that can also enhance tritium breeding. Examples of issues with this scheme are: a) blast effects, b) flow around geometric perturbations, and c) protection of inverted surfaces.

The sixth IFE issue is cavity clearing at IFE pulse repetition rates. Following each pellet explosion, the cavity (chamber) fills with target debris and material evaporated or otherwise ejected from the cavity surfaces. This material must be removed from the cavity before the next target is injected. This generally requires recondensing condensable gases onto the surfaces of the first wall (or more specifically the surfaces of the wall protection layer) and by pumping non-condensable gases out through large ducts. Power reactors require a repetition rate of ~3-10 pulses per second. Evacuation requirements depend on propagation limits for both targets and driver energy. Base pressure requirements determine 1) the time to evacuate the chamber, and 2) the level of protection to the first wall (and final optics) afforded by the cavity background gas. Research is needed to better understand clearing requirements, the recondensation process, and to develop design solutions.

The seventh issue is concerned with demonstration of tritium self sufficiency, which is an absolute requirement for an IFE system operated on the DT cycle. Fuel cycle analysis shows issues associated with: a) the magnitude of the required tritium breeding ratio (TBR), and b) the magnitude of the achievable TBR. The required TBR is most sensitive to:

– tritium fractional burnup in the target
– the tritium mean residence time in the target factory
– the number of days of tritium reserve on site
– the doubling time

Studies show the required TBR is in the range of 1.05 to 1.25 depending on the specific value of the above parameters. The achievable TBR will depend on the specific design and materials of the first wall protection scheme, structural and breeding materials and void spaces occupied by penetrations (e.g., for beams).

The eighth issue is demonstration of low cost, high volume target production techniques. Target production for IFE reactors will require technologies which are presently either nonexistent or insufficiently developed for such application. A typical 1000 MW IFE reactor requires on the order of $10^8$ targets per year. Hence, the cost per target needs to be in the range of 0.15 to 0.3 dollars for economic viability.

The ninth issue is demonstration of adequate radiation shielding of all components. The present codes and data provide adequate predictive capability. The issue, therefore, relates more to the ability to design and develop a fully integrated system in which all components are adequately protected from radiation.

The last issue concerns pulsed radiation damage and the thermomechanical response of the first wall/blanket. The severity and nature of this issue will depend, to a large extent, on the viability and specific characteristics of the wall protection scheme. If a thick liquid layer for wall protection proves feasible, then radiation damage and heat loads in the first wall/blanket will be moderate and can easily utilize technologies developed in magnetic fusion. A unique issue in this case may be the need to enhance tritium breeding. On the other hand, if the first wall protection scheme does not prove feasible, then the first wall/blanket issues such as radiation damage and thermomechanical response will become exceedingly critical.

**Table 1**

Major Parameters of Several Heavy Ion
IFE Reactor Studies

| Parameter | HIBALL-II | Cascade | HYLIFE-II | Prometheus-H | Osiris |
|---|---|---|---|---|---|
| Year Publ. | ‘84 | ‘90 | ‘91 | ‘92 | ‘92 |
| First Surface | PbLi | C Granules | FLiBe | Pb | FLiBe |
| 1st Surf. Radius, m | 5 | 5 | .05 | 4.5 | 3.5 |
| Breeding Blanket | PbLi in porous SiC tubes | Flowing Li2O granules | FLiBe jet array | Li2O in SiC structure | FLiBe in porous C cloth |
| Primary Coolant | PbLi | C and LiAlO2 | FLiBe | Pb & He | FLiBe |
| Vacuum Vesel | Ferritic steel | A1 | Stainless st. | Ferritic st. | C/C compos. |
| Accelerator type | RF Linac | Induct. Linac | RIA | Induct. Linac | Induct. Linac |
| Driver Energy, MJ | 5 | 5 | 5 | 7 | 5 |
| Illumination | Cyl. sym. | 2-sided | 1-sided | 2-sided | 2-sided |
| Target Gain | 80 | 75 | 70 | 103 | 87 |
| Yield, MJ | 400 | 375 | 350 | 720 | 430 |
| Rep-Rate, Hz | 5/chamber | 5 | 8.2 | 3.5 | 4.6 |
| Gross Th. Eff., % | 42 | 55 | 46 | 43 | 45 |
| Driver Eff., % | 27 | 20 | 20 | 20 | 28 |
| Net Power, MWe | 946 x 4 | 890 | 1083 | 1000 | 1000 |

**Table 2**

**Top-Level Issues For**
**Inertial Fusion Energy**

| | |
|---|---|
| 1 | Sufficiently High Target Gain at Economical Driver Size:<br>a) G > 30 for indirect drive with ion beams.<br>b) G ~ 100 for direct drive with lasers. |
| 2 | Driver cost, efficiency, reliability, and lifetime:<br>a) Demonstration of the required performance of a Driver operated in a repetitive mode.<br>b) Performance, reliability and lifetime of final optics. |
| 3. | Fusion Chamber:<br>a) Feasibility and performance of a viable wall-protection scheme.<br>b) Cavity clearing at IFE pulse repetition rates.<br>c) Tritium self-sufficiency in a practical IFE system.<br>d) Adequate radiation shielding of all componenets.<br>e) Pulsed radiation damage and thermomechanical reponse of first wall/blanket, particularly for concepts without thick liquid protection. |
| 4. | Sufficiently low cost, high volume, target production system. |

Reasons for IFE Focus on Heavy Ion Driver

Reactor studies have examined fusion energy systems with both heavy-ion and laser drivers. At this stage of inertial fusion R&D, the data base is not sufficient to conclusively select a driver that will ultimately be proven to be the most attractive for fusion energy system application.

However, there are compelling reasons why the IFE program within OFES should focus only on heavy-ion drivers. The key reasons are:

1. the constrained IFE budget permits only partial development of one driver concept

2. many of the issues of the laser-driver are being addressed by the Defense Program (DP)within DOE. HI development is not supported by any program other than IFE.

3. the current data base, albeit limited, indicates that heavy-ion drivers have greater potential for IFE application than laser drivers because: a) HI drivers have much higher efficiency than lasers, b) HI beams have a much higher reliability than laser systems, and c) the feasibility of the final optics for a laser system remains a major feasibility issue.

For the above reasons, it appears prudent to focus the limited IFE resources on the driver to R&D of heavy ions. However, future research results may warrant a new assessment of the driver selection. In particular, if Direct Drive Targets prove feasible, higher gains will be possible and the potential of laser drivers will vastly improve. Such results coupled with advances in laser system performance, e.g. in Diode-pumped solid state and KrF lasers, will make it necessary to reevaluate the selection of the best driver for IFE applications.

Breadth of the IFE Program

The IFE Program within OFES should not be limited to only the driver. IFE effective research requires devoting a part of the resources to some of the other critical scientific and technological issues such as chamber technology because: 1) these issues are critical to the feasibility and attractiveness of IFE, 2) the research results will greatly influence future research priorities for the driver and the driver-target coupling, and 3) data is needed in order to design meaningful experiments on NIF that are of relevance to IFE.