Journal of Fusion Energy, Vol. 13, Nos. 2/3, 1994

Fusion Energy Advisory Committee (FEAC): Panel 7 Report on Inertial Fusion Energy[1]

Ronald Davidson,[2] Barrett Ripin, Mohamed Abdou, David E. Baldwin, Robert Commisso, Stephen O. Dean, William Herrmannsfeldt, Edward Lee, John Lindl, Robert McCrory, Wayne Meier, Gregory Moses, Farrokh Najmabadi, Craig Olson, Peter Paul, Thomas Romesser, Stanley Schriber, and John Sheffield.

1. INTRODUCTION AND BACKGROUND

1.1 Panel Charge and Review Process

The charge to FEAC Panel 7 on inertial fusion energy (IFE) is encompassed in the four articles of correspondence (Appendix A). To briefly summarize, the scope of the panel's review and analysis adhered to the following guidelines:

- Consistent with previous recommendations by the Fusion Policy Advisory Committee (FPAC) and the National Academy of Science (NAS) panel on inertial fusion, the principal focus of FEAC Panel 7's review and planning activities for next-generation experimental facilities in IFE was limited to heavy ions.
- The panel considered the three budget cases: \$5M, \$10M, and \$15M annual funding at constant level-of-effort (FY92 dollars), with a time horizon of about five years.
- While limiting the analysis of next-generation experimental facilities to heavy ions, the panel assessed both the induction and rf linac approaches, and factored European plans into its considerations as well.
- Finally, the panel identified high-priority areas in system studies and supporting IFE technologies, taking into account how IFE can benefit from related activities funded by the Office of Fusion Energy and by Defense Programs.

It is also important to emphasize that the panel's technical assessment was limited to heavy ions and IFE, and the findings and recommendations were formulated in this isolated context. The panel did not evaluate the relative status and prospects for inertial fusion energy as compared with magnetic fusion energy, nor the relative technical merits of fusion by heavy ion drivers as compared with fusion in specific magnetic confinement geometries such as tokamaks or stellarators. Nor did it reevaluate the relative merit of heavy ions as compared to other potential drivers, such as KrF, light ions, or diode-pumped lasers.

The panel received extensive technical briefings from experts in the field, including a summary of the European heavy ion fusion program by Ingo Hofmann of the GSI Laboratory in Darmstadt. In addition, Dr. Marshall Sluyter, Acting Director, Office of Inertial Confinement Fusion (ICF) provided the panel with an update of the status and plans in the ICF program supported by the Department of Energy's Defense Programs (DP).

Finally, a subpanel consisting of Baldwin, Davidson, Lindl, McCrory (Chair), Ripin, Rosenbluth and Sheffield was convened to assess the status of target design and target physics issues pertaining to heavy ion

[1] This report presents the technical assessment, findings and recommendations on inertial fusion energy prepared by FEAC Panel 7. It is *not* a report by the Fusion Energy Advisory Committee.

[2] Princeton University Plasma Physics Laboratory, P.O. Box 451, Princeton, New Jersey 08543.

0164-0313/94/0900-0233\$07.00/0

fusion. Research in this area is carried out under the auspices of DOE Defense Programs.

The organization of this report is the following. In Sec. 1.2, for completeness, a short history of heavy ion fusion is provided. Panel findings and recommendations are summarized in Sec. 2, and these are based on an analysis of the technical status and requirements presented in Sec. 3. Appendix B provides the response by the full FEAC to the DOE charge letter (Appendix A).

1.2. A Brief History of Heavy Ion Fusion

The heavy ion fusion approach to inertial fusion energy (IFE) is a synthesis of the progress in the science and technology of high energy particle accelerators and in the theory and experiments of inertial confinement fusion (ICF). The attraction of heavy ion fusion is that, by using low-charge-state heavy ions (e.g., singly-charged cesium), very high power levels can be delivered to small fusion pellets from ions with ranges short enough to stop in the pellet. A 5 GeV cesium ion would have a range of about 0.1 g/cm^2 as would a 10 GeV lead ion. The required currents, while greater than have been accelerated before in high energy ion beams, are still within the range that can be accelerated and focussed by conventional accelerator techniques.

Heavy ion fusion began with work at high energy physics laboratories including especially Brookhaven National Laboratory (Al Maschke), Argonne National Laboratory (Ron Martin), and Lawrence Berkeley Laboratory (Denis Keefe). The first international workshop in heavy ion fusion was held in Berkeley in 1976. Originally, three accelerator systems were studied; rf synchrotrons, rf linacs with storage rings, and single-pass induction linacs. As the target requirements became better understood, the rf synchrotron approach was dropped because the kinetic energy required to inject sufficient current was essentially the same as the final beam current.

The U.S. heavy ion fusion program concentrated on the induction linac because it requires a smaller initial investment to make meaningful demonstration experiments. Other reasons for favoring the induction linac included lower estimated construction costs, resulting in lower cost for commercial power, and a greater margin for achieving the necessary beam quality. European and Japanese laboratories are still pursuing the rf linac/storage ring approach in efforts that largely complement the U.S. program.

In its early years, heavy ion fusion received funding from high energy physics in the Office of Energy Research and from inertial confinement fusion in Defense Programs. Beginning in FY84, heavy ion fusion was concentrated in a program called Heavy Ion Fusion Accelerator Research (HIFAR) in Basic Energy Sciences. As a result of recommendations by the Fusion Policy Advisory Committee, the HIFAR Program was moved to the Office of Fusion Energy where it has become the primary element in a new IFE Program. Throughout this period, target physics issues and designs specific to the heavy ion approach have continued to be investigated by Lawrence Livermore National Laboratory at a relatively small level-of-effort.

An emphasis on heavy ion drivers for IFE is readily understandable. For engineering and economic feasibility, drivers must be both reliable and efficient. They must also have a high pulse repetition rate (several pulses per second) and long life (about 30 years). Existing ICF drivers, such as lasers and light ion accelerators, are excellent for near-term research, but at present are limited to a low repetition rate, typically a few shots per day. Therefore, the development of efficient, high-repetition-rate drivers is desirable for power production by IFE. During the past decade, nearly all high-level DOE and congressionally-mandated committees have identified heavy ion accelerators as the most promising driver approach for power production by IFE. These reviews included assessments by the Fusion Policy Advisory Committee[1] and by JASON.[2] As noted above, the accelerators, designed to use heavy ions such as xenon or mercury, are similar in many respects to the large accelerators that are used worldwide for basic research in high energy and nuclear physics.

Several reactor studies have been funded by Germany, Japan, DOE's ICF program, and most recently, the Office of Fusion Energy. These studies have developed conceptual designs for heavy ion fusion power plants that have attractive environmental, safety, and economic features.

2. PANEL FINDINGS AND RECOMMENDATIONS

This section provides a summary of the panel's principal findings and recommendations. These are based on the panel's more detailed assessment of the technical status and requirements presented in Sec. 3, as well as an analysis of the ILSE Project and physics program and the heavy ion fusion development plan.

2.1. Panel Findings

As a starting point, the panel concurs with many of the statements on inertial fusion energy (IFE) made by the Fusion Policy Advisory Committee (FPAC) in its 1990 report. Specifically, the panel notes the following statements by FPAC:

> The promise of an inertial fusion energy program (IFE) seems to us to be sufficient to begin investment now in a small collateral program covering those areas not required for the DP (Defense Programs) program, e.g., repetition-rated, efficient drivers and reactor studies.

> For energy applications, there are additional critical problem areas that must be successfully addressed: (1) pellets must be designed that yield high gain and can be cheaply produced, efficiently driven, and stably imploded; (2) efficient, high-power drivers must be developed that can be operated at useful repetition rates; (3) reactor chambers must be designed that contain the micro-explosion products and adequately protect the driver.

> At present these (reactor concepts) are at a preliminary level, and there are inadequately resolved issues that need attention, such as target fabrication costs, final optics or focussing magnet protection, attainable driver efficiencies, and chamber environment.

A principal finding of the panel, which frames the context for this review, can be stated succinctly as follows:

- The Department of Energy has not established an IFE program that resembles remotely the one envisioned by FPAC. Ostensibly this has been due to stringent funding allocations for fusion as a whole. The Office of Fusion Energy (OFE) has commissioned two industry-led IFE reactor designs. Both of the industry-university teams considered reactors based on heavy ion and KrF laser drivers. The final reports have not yet been released, and the studies have been terminated.

In the remainder of Sec. 2.1, we delineate a summary of the panel's key findings consistent with the technical assessment in Sec. 3 and the recommendations that are formulated in Sec. 2.2.

Status

- Numerous reviews, including recent reviews by the National Academy of Sciences[3] and the Fusion Policy Advisory Committee, have recommended heavy ion fusion as the most promising driver approach for IFE.
- The U.S. heavy ion fusion accelerator development program is concentrated at Lawrence Berkeley Laboratory, with an FY93 budget of about $6M. Smaller supporting programs are carried out at the Lawrence Livermore National Laboratory, the University of Maryland, the Naval Research Laboratory, and the Stanford Linear Accelerator Center.
- The National Energy Policy Act directs the Secretary of Energy to conduct a fusion energy program to demonstrate the practicality of commercial energy production by 2010, including research and development of inertial confinement fusion energy and development of a heavy ion inertial confinement fusion experiment. This effort requires the resolution of both driver technology and target physics issues. These two topics are strongly coupled.
- Target physics and some supporting heavy ion research are conducted by DOE's Defense Programs, with the largest single activity located at Lawrence Livermore National Laboratory. Livermore has adopted heavy ion fusion as the leading candidate driver for IFE. Beam propagation studies and light ion fusion target experiments at Sandia National Laboratories also support heavy ion fusion development.
- The ICF program has used data from both laboratory experiments and underground nuclear explosion experiments at the Nevada Test Site. The latter program, called Halite/Centurion and conducted jointly by Lawrence Livermore National Laboratory and Los Alamos National Laboratory, demonstrated excellent performance, putting to rest fundamental questions about the basic feasibility of achieving high gain. The Halite/Centurion program performed experiments at higher energies than those available in the laboratory. The National Academy of Sciences review of the ICF program concluded that the Halite/Centurion experiments had met their objectives and that further uncertainties in achieving ignition could best be studied in laboratory experiments. Because of this recommendation, Defense Programs has scheduled no more experiments in the Halite/Centurion program. The details of these experiments remain classified.

- The National Ignition Facility (NIF), using a glass laser, has received Key Decision Zero (KD-0) approval from DOE in January, 1993. Events, including both technical progress and changes in the world political scene (such as restrictions on nuclear testing), raise the prospects for accelerated progress in the Defense Programs' inertial confinement fusion program.
- As part of KD-0 for the National Ignition Facility, the justification for mission need approved by the Secretary of Energy reaffirms the importance of the energy mission of ICF: "The most significant long term potential commercial application of ICF is the generation of electric power. The NIF is essential to demonstrate central hot spot ignition and propagating burn, the basis for high gain ICF targets. Furthermore, the NIF can establish the driver requirements for high gain targets. The fusion output of the NIF will enable the exploration of many of the materials and technology issues for power reactors, which can result in an optimal development program and the most environmentally benign reactor design. Furthermore, the availability of the NIF in the early part of the next century is required to meet the National Energy Strategy goal of a demonstration plant in 2025."
- The primary approach to heavy ion fusion and the glass-laser-based National Ignition Facility is the indirect-drive approach. For indirect drive, the capsule implosion and burn physics are the same for both heavy ion fusion and laser-driven hohlraums. For ion-driven hohlraums heated to the same radiation temperature (T_r), the 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 heavy ion fusion. These are the primary issues which affect coupling efficiency and hohlraum symmetry for the baseline heavy ion hohlraums. Because of these similarities, the DOE Defense Programs' target physics program on the Nova laser at Livermore provides a solid basis for calculating most critical elements of heavy ion targets.
- Success of the ignition objectives on the National Ignition Facility will substantially reduce the risk for heavy ion IFE, and these results will play a major role in any decision to develop a full-scale heavy ion driver. The success of the Nova laser target physics program, coupled with the Halite/Centurion underground test results, are expected to provide a sufficient target physics basis for heavy ion drivers. Without an accelerated effort in the heavy ion fusion program, particularly an accelerated ILSE project with its related experimental goals, the Office of Fusion Energy will not be prepared to move forward with a full-scale driver for IFE until long after the demonstration of ignition.
- If the Department of Energy could bring the long-standing ICF declassification issue to closure, facilities and scientists outside the United States could accelerate addressing some of the issues presently inadequately understood in heavy ion hohlraum/target physics.
- The Department of Energy has not established a balanced IFE development program as recommended by FPAC. In the present program, nearly all funds for IFE directly or indirectly support heavy ion accelerator development.
- IFE reactor studies have highlighted that the technical feasibility of IFE requires solutions to key technological challenges. It appears likely that no major IFE initiatives (such as the Intermediate Driver Facility, IDF) will be approved unless there is high confidence that these key technical areas are being resolved or can be resolved.
- IFE technology research has been limited largely to reactor studies. The DOE's ICF program has supported a small but continuing effort in this area, but the studies sponsored by the Office of Fusion Energy have been terminated. Nearly all of the reactor design parameters are based upon analysis, rather than experimental evidence. At this time, the difference between viable and non-viable design concepts lies within the bounds of uncertainty, a situation that will not change as long as untested analytical estimates of complex phenomena are used to predict reactor performance.

Technical Accomplishments

- The high-current requirements of heavy ion fusion resulted in the first analytical and numerical simulation studies for the current-carrying capability of a periodic-focussing system.

- The Single Beam Test Experiment (SBTE) at Lawrence Berkeley Laboratory confirmed the optimistic predictions of the numerical simulations and showed that it is possible to transport currents with space-charge forces that very nearly cancel the focussing forces.
- A variety of ion sources have been studied with especially good results from thermionic emitters for cesium and other alkali metals. Cesium is an acceptable ion for heavy ion fusion.
- The multiple-beam induction linac was invented at Lawrence Berkeley Laboratory to permit transporting more current than could be accommodated in a single transport element. The multiple-beam concept was demonstrated in the Multiple Beam Experiment (MBE-4) with four beams.
- To demonstrate longitudinal compression of the beams, the acceleration modules in MBE-4 were ramped, with the fields rising slowly with time as the beam passes through the accelerating gaps. Current amplification has been demonstrated for the first time in MBE-4.
- Three-dimensional numerical simulation techniques have been developed (with contributions from the Naval Research Laboratory, the University of Maryland, Lawrence Berkeley Laboratory, and Lawrence Livermore National Laboratory) to aid in establishing tolerance limits and to assist in the design of bending systems. Bending magnets are required for transport to a target chamber and possibly for a recirculating induction accelerator. Bending is also needed to combine beams for greater efficiency in the use of accelerating and focussing systems.
- Beginning with the Heavy Ion Fusion Systems Assessment (HIFSA)[4], a national effort led by Los Alamos National Laboratory, and continuing with recent studies commissioned by the Office of Fusion Energy, systems studies for the induction linac approach show that the cost of electricity for a heavy ion fusion reactor compares favorably with other advanced energy technologies, including magnetic fusion.
- The design of a next-step facility in the development of heavy ion accelerator technology, called Induction Linac Systems Experiments (ILSE) was completed by Lawrence Berkeley Laboratory and reviewed for project readiness by DOE. The ILSE project was given Key Decision Zero (KD-0) approval but was not given Key Decision One (KD-1) approval pending the recommendations by the Fusion Energy Advisory Committee.

Technical Issues

- For accelerator drivers, the main scientific issue is beam quality. The emitted ions from a thermionic source have a transverse temperature of about 0.1 eV. To permit focussing onto a fusion target of about 3 mm radius, the transverse temperature of the beam should not exceed about 1 keV prior to final focus. A similar requirement on the longitudinal momentum spread is needed to permit focussing the beam without excessive chromatic aberrations.
- For reactor systems, a main technical issue is maintaining and restoring the environment needed for beam transport in and near the reactor chamber with a repetition rate of about three to ten shots per second. Another important issue is the development of an effective first-wall for the reactor. Several different first-wall protection schemes have been studied. They have different implications for the beam transport system.
- For the final focussing systems, the main technical issue is dealing with the reactor medium and with the interaction of the beam with the target. For example, ionizing radiation from the target can strip electrons from the incoming beam during the last few tens of centimeters of travel to the target. The beams will be charge and current neutralized in the final transport to the target.
- Finally, it must be demonstrated that high-gain targets can be driven by ion beams. There are other important target issues, such as the cost for mass production of targets that conform to the exacting tolerances required for high gain.

Prospects for IFE

- High energy accelerators, when used to accelerate significant current, have the efficiency needed for a practical commercial power plant. They also have other necessary characteristics of long life, high reliability, and more-than-adequate pulse repetition rate. For economical power pro-

duction, the accelerator driver should cost less than $1B.
- Research and demonstration projects are needed to confirm the cost and performance of heavy ion fusion accelerators. More speculative approaches, such as a recirculating induction linac, have great potential for reducing costs further.
- Inertial fusion reactor concepts use reformable-fluid first-wall protection, resulting in low chamber stress and low radioactive inventory for the reactor materials. Shallow burial would be permitted according to current regulations.
- The natural separation between the reactor and the accelerator, and the independence of the target fabrication technique and facility from the rest of the plant, provide many options for solving engineering and scientific problems. Hands-on maintenance for most of the accelerator facility is possible.
- Heavy ion fusion has an attractive development path. A single accelerator driver can provide beams to different reactor chambers, allowing studies of reactor and target performance. Such a research facility could evolve into a Demonstration Power Plant without building a new accelerator driver.
- The U.S. clearly has the lead in inertial confinement fusion. A very active, well-funded program exists in Osaka, Japan, and the rf linac heavy ion approach is investigated in a substantial program in Germany.

2.2. PANEL RECOMMENDATIONS

2.2.1. Overview

In 1990, the Fusion Policy Advisory Committee (FPAC) recommended that heavy ion fusion be developed as a fusion energy alternative. The Induction Linac Systems Experiments (ILSE) were identified as the next logical step in that development program. Significant reductions in the ILSE Total Estimated Cost (TEC) have occurred as a result of design changes (4 versus 16 beams, etc.), reductions in the cost of metglass, and the availability of suitable, existing space and facilities at Lawrence Berkeley Laboratory (LBL). At the present time, LBL estimates that ILSE could be completed in three years if adequate funding were available. A conceptual design report for an ILSE construction start in FY95 will be submitted to DOE in March, 1993, and LBL anticipates a TEC in FY92 dollars of about $32M, which forms the basis for the panel's assessment.

The panel considered three budget cases: $5M, $10M, and $17M annual funding at constant level-of-effort (FY92 dollars), with a time horizon of about five years. It should be emphasized that in all budget cases, a *balanced* program is recommended that includes an experimental and analytical program for supporting IFE technologies, as well as an accelerator development and beam physics program.

In the ''reference'' ($17M) case, highest priority is assigned to the start and completion of the ILSE project, with $14M/year identified for ILSE and accelerator research and $3M/year identified for supporting technology and system studies. The $14M for the accelerator development and physics program includes ILSE PACE and OPEX funds, and theory, modelling and supporting experimental activities. At this level, ILSE will be completed and operational within four years. ILSE will provide an integrated demonstration of induction linac technology and the beam physics required to provide the data base for scaling to a heavy ion driver.

In the ''middle'' ($10M) case, $8M/year is identified for accelerator development and the supporting physics program. In this case, it is *not* possible to complete the integrated demonstration project ILSE, although a significant set of large-scale accelerator experiments could be completed, thereby providing an increased understanding of key technical issues. The theory, modelling and supporting experiments are reduced in this case, and up to $2M/year is identified for supporting technology and system studies.

In the ''low'' ($5M) case, with an allocation of $4.5M/year for accelerator research, the panel believes there is *no* credible program for the development of a heavy ion fusion energy option. In this case, advocates of the heavy ion program should enter discussions with other elements of DOE that may be more receptive to the development of heavy ion drivers. The base accelerator and physics program in this case continues the core accelerator research activities but does not provide any significant advances in large-scale accelerator demonstrations. At this budget level, the panel recommends that the funding be focussed on the retention and utilization of the core competencies and capabilities needed for the future development of heavy ion accelerators. Also in this case, it is recommended that $0.5M/year be applied to supporting technology and system studies.[3]

[3] Some members of the panel (Abdou, Dean, Meier and Majmabadi) believe that the budget for reactor studies and supporting IFE technologies should not be less than 20% of the total, including the low budget case.

In the remainder of Sec. 2.2, we provide a more detailed summary of panel recommendations in beam physics and accelerator development (Sec. 2.2.2), and system studies and supporting IFE technologies (Sec. 2.2.3).

2.2.2. Beam Physics and Accelerator Development

We summarize here the principal elements of the accelerator development and physics program recommended by the panel in the three budget cases.

Reference ($17M) Case

Lawrence Berkeley Laboratory (LBL) and Lawrence Livermore National Laboratory (LLNL) with participation by industry propose to build the Induction Linac Systems Experiments (ILSE), the next logical step towards the eventual goal of a heavy ion induction accelerator powerful enough to implode or "drive" inertial fusion targets. The Reference case at $17M/year would allow completion of the ILSE project in less than four years. This budget also includes $3M/year for research in system studies and supporting IFE reactor technologies in the high-priority areas identified in Sec. 2.2.3.

ILSE, although much smaller than a driver, would be the first experiment at full driver scale in several important parameters: most notably, line charge density and beam cross section. Many accelerator components and beam manipulations needed for a heavy ion driver would be tested on ILSE. The ILSE accelerator and the associated research program would permit experimental study of those beam manipulations required for an IFE driver which have not been tested sufficiently in previous experiments, and would constitute an important step in heavy ion driver technology.

ILSE Experimental Objectives: The guiding figure of merit for ILSE is adequate beam quality for extrapolation to driver parameters. This is to be done with space-charge-dominated beams similar to those of a driver, and with accelerator components similar to those of a driver. The primary differences between ILSE and a conservative induction linac driver are in the several features of scale summarized below. Many driver designs have lower kinetic energy, fewer lattice periods and fewer pulsers.

FEATURE	ILSE	DRIVER
Number of beams	4 merged to 1	64 merged to 16
Initial pulse duration	1 μs	37 μs
Total lattice periods	40	2000
Total pulsers	100	100,000
Final energy	10 MeV	10,000 MeV

From a physics stand-point, the square-root of the number of periods and number of pulsers is a good measure of scale. Using this measure, ILSE is roughly one-tenth scale of a driver. In addition to the 40 lattice periods shown for ILSE in the table, there will be an additional 100 lattice periods for the experimental hardware. The following are several noteworthy features of ILSE:

Source-Injector. Both ILSE and a driver would start with injected beams of about 2 MeV and line charge density of 0.25μC/m.

Beam Merging. Beam merging in a heavy ion driver at an energy of 50–100 MeV results in optimum economic advantage. In ILSE, using a lighter ion to result in similar-velocity ions, the equivalent merging experiment would be done at about 4.5 MeV.

Magnetic Focussing. Magnetic quadrupoles would be used for most of the length of a driver. Issues of aberration-generated emittance growth in a magnetic transport system would be studied for a space-charge-dominated beam in ILSE for the first time.

Longitudinal Compression. Drift-compression current amplification is needed to increase the beam power. It is necessary to compress in a way in which longitudinal space charge cancels the velocity tilt, thus avoiding chromatic problems in final transport. ILSE will be able to simulate various compression factors at different currents.

Beam Bending. Most driver scenarios make use of beam bending, although in some configurations it is possible to illuminate the target from only one side. Simulations have shown that beam bending is possible, resulting in only minor increases in emittance, if care is taken in matching the beam into the bending system. ILSE will allow experimental confirmation of these predictions.

Final Focussing. Final focussing in the reactor chamber must achieve a sufficiently small (~3mm) spot on the target. The high perveance of the ILSE beam will allow experiments that are more demanding in terms of space-charge effects than those of the driver. Experiments with and without neutralization, under various background conditions, will be possible.

Recirculation. Conceptual studies of recirculating beam induction accelerators have shown the potential of a substantial cost savings. ILSE will provide the first opportunity to experimentally investigate a heavy ion recirculating induction accelerator.

Longitudinal Instabilities. A driver is predicted to be unstable for growth of longitudinal bunches at long wavelengths. The growth rate is slow enough that a feed-forward control system should be adequate for complete

Table I. Levels of Effort and Activity Areas in the Reference Budget Case

	FY 95	FY 96	FY 97	FY 98	FY 99	Total
ILSE Construction (PACE and OPEX)	→	→	→	→		$36M
ILSE experiments					→	$9M
Accelerator theory and supporting experiments	→	→	→	→	→	$25M
System studies and supporting IFE technologies	→	→	→	→	→	$15M
Total	$17M	$17M	$17M	$17M	$17M	$85M

Table II. Levels of Effort and Activity Areas in the Middle Budget Case

	FY 95	FY 96	FY 97	FY 98	FY 99	Total
Multi-beam injector	→	→	→			$4M
Matching	→	→	→	→		$2M
Acceleration/longitudinal experiments	→	→	→	→		$7M
Combining				→	→	$2M
Magnetic transport				→	→	$2M
Buildings, alignment, vacuum, controls	→	→	→	→	→	$3M
Accelerator theory and supporting experiments	→	→	→	→	→	$20M
System studies and supporting IFE technologies	→	→	→	→	→	$10M
Total	$10M	$10M	$10M	$10M	$10M	$50M

stabilization. For the ILSE linac, there is negligible predicted growth. However the properties of the stable waves can be investigated, including bunch end reflections and correction by special pulsers. The longer transport distances available in an ILSE ring would allow the study of instabilities with measurable growth.

Steering and Alignment. ILSE will permit the examination of the practical tradeoffs between steering and alignment.

The principal program elements, recommended levels of effort summed over 5 years, and approximate schedule of activities for the Reference budget case are given in Table I. In addition, an assessment of the technical status and requirements is presented in Sec. 3.1.

Middle ($10M) Case

In the Middle ($10M) case, it is *not* possible to complete the integrated demonstration project ILSE, although a significant set of large-scale accelerator experiments could be completed. The accelerator theory, numerical modelling and supporting experimental activities are reduced in this case, relative to the Reference case, and up to $2M/year is identified for system studies and supporting reactor technologies.

The emphasis in the Middle case should be on tests of the low-energy part of what is in the ILSE plan. This would include matching experiments at a lower energy than is desired; it would also include magnetic transport experiments, but without acceleration. A major loss to the program in this case is that experiments with recirculation would not be affordable so that there would be no data to support the large cost savings that are expected for a driver using recirculation. In this budget case the important experiments on beam bending, compression and final focus would be removed from the five-year program.

In the Middle case, the panel recommends an accelerator development and physics program with the following principal elements:

- Multi-beam injector research using driver-scale cesium and potassium beams at the 2 to 3 MeV level.
- Multi-beam matching experiments.
- Multi-beam acceleration and longitudinal control using electrostatic focussing. These tests require acceleration to about 5 MeV.
- Beam-merging experiments.
- Magnetic transport experiments without acceleration.

These experiments would allow the study of some, but not all of the beam manipulations required in an induction driver. Important manipulations that would not be studied include:

- Acceleration in a magnetic transport system.
- Longitudinal drift compression.
- Bending of driver-scale beams.
- Recirculation.
- Large-scale final focussing experiments.

The principal elements, recommended levels of effort summed over five years, and the approximate schedule of activities for the Middle budget case are given in Table II.

To summarize, the accelerator development and physics program in this budget case would provide some

Table III. Levels of Effort and Activity Areas in the Low Budget Case

	FY 95	FY 96	FY 97	FY 98	FY 99	Total cost
Theory	→	→	→	→	→	$8.75M
Combiner/merge	→	→				$1.0M
Final focus/transport	→	→				$2.5M
Cavity impedence	→	→				$.5M
Magnetic transport	→	→	→			$3.0M
Ring/bend				→	→	$4.0M
Module Development	→	→	→	→	→	$1.25M
Diagnostics	→	→	→	→	→	$2.5M
System studies and supporting IFE technologies	→	→	→	→	→	$2.5M
Total	$5M	$5M	$5M	$5M	$5M	$25M

of the results of the ILSE program, but it leaves unanswered important questions, such as the viability of recirculation.

Low ($5M) Case

The Low budget case ($5M/year) is a significant reduction from historical IFE funding levels and permits progress on only a subgroup of identified critical issues with components reduced considerably from the scale of a heavy ion driver. Specific program elements, recommended levels of effort summed over five years, and approximate schedule of activities for the Low budget case are summarized below and in Table III. In the Low budget case, it should be emphasized that no progress is made in the first six activity areas listed in Table II for the Middle budget case.

The activities in Table III can be summarized as follows:

Beam Physics

- Driver theory, modelling and computations.
- Final focus/neutralized transport experiments.
- Magnetic transport experiments.
- Bend experiments.
- Small ring experiments.
- Beam-merging experiment with MBE.
- Cavity impedance research.

Development

- Modules-pulsers, insulators, ferromagnetic materials, and smart switches.
- System studies and reactor technologies.

As a final point, the theory and supporting R&D budgets for the "middle" and "reference" budget cases are similar to those in the "low" budget case. The exception is that the identified magnetic transport experiments are moved to the large-scale-experiments category in the middle budget case. Table IV provides the *average* annual cost for each activity.

2.2.3. System Studies and Supporting IFE Reactor Technologies

The technical feasibility of IFE requires development of certain key reactor technologies in addition to the accelerator, including high-repetition-rate chambers, automated target production, and target injection and tracking systems. The degree of success in developing these technologies will determine the choice and optimization of the driver design and the overall attractiveness (economics, safety, etc.) of IFE. Timely development of certain key technologies requires that an experimental and theoretical IFE reactor studies and technology program be supported in parallel with the driver development program.

In particular, the IFE technology program should focus on the areas discussed below and listed in Table V. The major headings are in order of overall priority and the sub-items are prioritized within each category. The entire list of items, however, is not necessarily in a uniformly descending order of importance. The items listed in this table are discussed in more detail in Sec. 3.2.

Chamber Environment and Interface with Driver. Protection of the first wall and re-establishment of the chamber environment between shots are feasibility issues for IFE. The highest-priority item is to develop the capability to accurately predict the repetition-rate limits of fusion chambers by developing analytical models and benchmarking these codes with experiments. Scale-model experiments to demonstrate chamber flow conditions and investigate chamber-driver interface issues are also recommended. This work must be closely coupled to efforts on modelling beam propagation and focussing.

Materials, Blankets, and Shields. This is an area where IFE should be able to benefit from the technology development being carried out for magnetic fusion. Areas of common interest include the development of low activation materials, including neutron damage and corrosion effects, blanket and shield design, environmental and safety studies, and the development of remote maintenance systems. Experiments addressing the feasibility

Table IV. Supporting Accelerator R&D

	Low ($M)	Middle ($M)	Reference ($M)
Theory/modelling	1.75	1.50	2.0
Focussing, neutralization, channel transport experiments	0.5	0.5	0.5
Magnetic transport experiments	0.6	0.1	0.6
Small ring/bend	0.8	0.8	0.8
Beam merging experiments	0.2	0.2	0.2
Cavity impedence research	0.1	0.1	0.1
Technology development: modules, pulsers, insulators, ferromagnetics, smart switches	0.25	0.25	0.5
Diagnostics	0.3	0.3	0.3
Large-scale experiments	0	0.3	0
Total	4.5	4.0	5.0

Table V. IFE Technology Studies and Experiments

1. Chamber Environment and Interface with Driver – Modelling and Experiments
- 1.1. Vaporization/Condensation (code development, experiments to benchmark codes, simulation experiments)
- 1.2. First Wall/Blanket Scale Models (scale models of fluid blankets, wetted walls, flow through porous materials)
- 1.3. Chamber/Driver Interface (numerical simulation and experiments on vapor flow, vacuum pumping)
- 1.4. Dissociation/Recombination for FLiBe and PbLi (chemical dynamics, experiments)

2. Reactor Materials, Blankets, and Shields – Analysis and Experiments
- 2.1. Corrosion Experiments/Material Compatibility Studies
- 2.2. Pulsed Neutron Damage/Activation of Reactor Materials

3. IFE Technology Development Studies
- 3.1. Development Plan for IFE
- 3.2. Systems Studies (subsystem design optimization, parameter trade studies, sensitivity analysis, overall cost/performance modelling)
- 3.3. Innovative Chamber Design (direct conversion, higher repetition-rate chambers, etc.)
- 3.4. Environmental and Safety Aspects (radioactive materials confinement and recycle, material selection, etc.)
- 3.5. Remote maintenance

4. Target Systems – Analysis and Experiments
- 4.1. Target Injection and Tracking
- 4.2. Mass production Techniques and Costs

of material issues unique to IFE designs should be addressed, and some effort on understanding pulsed neutron damage effects is needed.

IFE Technology Development Studies. A continuing activity in system modelling and analysis for drivers, chambers, experimental facilities, and power plants should be pursued in order to assess the impact of the experimental results on system performance and guide future research. Some effort on innovative reactor and chamber designs that are significantly different from those envisioned at present should also be pursued.

Target Systems. Target injection and tracking is a critical issue for IFE. Experiments to demonstrate the performance of injectors and trackers are recommended in the high budget case. Technologies for automated and inexpensive fabrication of high-quality targets do not exist. A major technology development program is not warranted until the target design is nearly finalized. Some work to address the anticipated cost of automated production and to develop technologies that are not dependent on the specifics of the target design is recommended in the high budget case.

Table VI. System Studies and IFE Reactor Technology Funding

Budget case	$5 M	$10 M	$17 M	FPAC[a] $30–40 M
System studies & IFE technology	$0.5 M	$2 M	$3 M	$10 M
Chamber environment and interface	X	X	X	X
Materials, blankets, shields	X	X	X	X
IFE development studies		X	X	X
Target systems			X	X

[a] FPAC total excludes recommended funding for KrF and light ion drivers.

For the system studies and supporting IFE reactor technology areas identified above, Table VI indicates the annual expenditures and the categories in which studies and experiments should be carried out in the three budget cases considered by the panel. Additional details regarding priorities and milestones are presented in Sec. 3.2. In Table VI an X indicates that at least some, but not necessarily all, of the items in the corresponding category should be pursued. This is only an estimate of what might be done. Actual costs cannot be assessed until tasks are defined in more detail and proposals to do the work are solicited. It is entirely possible that a lower priority study could be funded before a higher priority study, if the higher priority work could not be done within the budget. The last column in Table VI is the FPAC recommendation, for comparison.

Finally, beyond the five-year time horizon of this report, it should be emphasized that a significant growth in the total IFE budget (above the $17M case considered here), including an increase in supporting IFE technology areas, is required in order to proceed in a timely manner with an Intermediate Driver Facility.

3. TECHNICAL STATUS AND REQUIREMENTS

3.1. Beam Physics and Accelerator Development

3.1.1. Introduction and Background

Beginning with the 1976 international workshop on heavy ion fusion held in Berkeley, there were three different classes of accelerator systems considered for heavy ion fusion:

- System of synchrotrons (using fairly low-energy linac injectors).
- System of storage rings fed by a high-energy linac of the same energy as the final beam energy.
- Single-pass induction linac system.

The synchrotron was the first approach to be eliminated in a deliberate effort to down-select as early as possible. The drawback to the synchrotron is that the need for high current requires that the injection energy must be very close to the final energy.

The remaining two systems were studied in parallel in the U.S. for several years. The storage ring approach was the subject of work at Argonne (Ron Martin) and Brookhaven (Al Maschke), whereas the induction linac approach was the subject of work at Lawrence Berkeley Laboratory (Denis Keefe). After a few years, during which support was provided by both the high energy physics program and the inertial confinement fusion program, it was decided to establish the Heavy Ion Fusion Accelerator Research (HIFAR) program in Basic Energy Sciences in the Office of Energy Research. As part of this transfer, it was deemed mandatory to concentrate the available funds on one approach. The induction linac approach was selected with realization that the choice was not justified fully by technical arguments. A combination of technical and programmatic issues were considered in making the decision, and the following is a brief summary of those issues:

- The rf linac/storage ring approach was being studied both in Europe and in Japan. Thus, by focussing on the induction linac, the U.S. assured that the worldwide effort would cover both of the most promising approaches.
- The induction linac approach is conceptually simpler, because it is a single-pass system having few beam manipulations.
- In a number of reviews (including, for example, the 1979 Argonne Workshop) the emittance budget for the rf approach appeared marginal.
- The most serious technical obstacle faced by the induction linac approach is the limited current that can be transported. Results from simulations and later from the Single Beam Test Experiment (SBTE) at LBL showed that the current that could be transported in a strong focussing system is very close to the absolute limit at which the space-charge forces are as strong as the focussing forces.
- The invention of multiple-beam techniques, eventually demonstrated on the Multiple Beam

Experiment (MBE-4) at LBL, showed that there were economically attractive approaches to heavy ion fusion using the induction linac approach.
- The entry cost for the induction linac approach is concentrated in the front end of the accelerator where most of the key issues must be faced immediately. This is in contrast to the situation for the rf approach where the key issues concern the maximum current that can be stored and manipulated in storage rings. To test the rf approach, a very large, expensive rf linac is needed to provide an injector. Therefore, it was concluded that the U.S. should develop the induction linac approach with a series of relatively low-cost facilities: SBTE, MBE-4, ILSE, and finally an Intermediate Driver Facility (IDF).

Therefore, the principal programmatic argument in favor of the induction linac approach was the lower cost of doing key experiments. This is due to the simplicity of the single-pass system as compared to a large number of high-current storage rings. The principal physics arguments in favor of the induction linac approach were the added margin in the emittance budget and the success in transporting high currents in a strong-focussing system.

It is the panel's conclusion that these arguments in favor of U.S. focus on the induction linac approach to heavy ion fusion as embodied in the Induction Linac Systems Experiments (ILSE) remain valid today, particularly in view of the European and Japanese emphasis on the complementary approach based on rf linacs/storage rings.

After reviewing the documentation and rationale for ILSE provided by LBL and LLNL, the panel consensus regarding the beam physics and accelerator technology is that a very good team has been assembled for the project, the proposed program makes sound technical sense and is an essential step in the heavy ion fusion development plan and the related engineering development of ILSE will have a significant impact in other R&D areas requiring intense beams of heavy ions. To summarize the main conclusions:

- The ILSE project is an essential step for heavy ion fusion and should be given high priority. The program has been well formulated and is likely to have spin-offs in other areas of national importance. Because this is the only integrated induction linac program, preservation and nurturing of this capability is important for future U.S. technological competitiveness.
- The ILSE project complements the work on rf linacs/storage rings underway in Europe and Japan. The decision by the U.S. to pursue induction linac technology made sense when the decision was made and remains valid today. International collaboration on heavy ion fusion should be encouraged at the working level, with benefits expected from the exchange of ideas, technology development, and the tools required for calculations, simulations and experimental measurements.
- Lawrence Berkeley Laboratory is an appropriate location for ILSE to be built and operated. It has the technically qualified staff, and appears to be highly motivated to provide the required space and infrastructure to execute the project. Support from LBL management was evident from participation at the reviews.

3.1.2. Status and Requirements

To establish an experimental basis for induction accelerators, in 1988 a series of experiments were proposed known as the Induction Linac Systems Experiments (ILSE). In 1992, an update to the original proposal was made to reflect recent advances in accelerator science and technology. ILSE is the next logical step toward the eventual goal of a heavy ion induction linac powerful enough to implode or "drive" inertial confinement fusion targets. ILSE will be at full driver scale in several important parameters, most notably line charge density (a function of beam size), which was not explored in earlier experiments. Many other accelerator components and beam manipulations needed for an inertial fusion energy driver will be tested in ILSE, at full or partial scale. The goal of the ILSE program is to address all remaining beam dynamics issues, thus providing a solid data base for further progress toward a heavy ion driver for energy applications.

The following design criteria have been adopted for ILSE:

- Full driver scale in beam size, line charge density and emittance.
- Test all induction driver manipulations.
- Incorporate enough betatron and beam-plasma periods to provide sensitive, statistically meaningful tests of emittance growth.
- Provide a large enough advance in technology to proceed to the Intermediate Driver Facility without an additional step.

If successful, ILSE would accomplish the following important objectives:

- Provide the basis for choosing the optimal type of heavy ion accelerator.
- Test all induction accelerator subsystems at the relevant scale.
- Represent a significant step in driver technology.

Table VII provides a summary of driver issues for the induction linac by comparing ILSE goals with driver requirements for the various components. The importance of ILSE and the impacts it will have for future driver systems are evident from the table.

Electrostatic Focussing Accelerator Section

The first stage of acceleration in a heavy ion inertial fusion driver is expected to consist of multiple parallel beams which will then be combined in successive stages. A series of linear induction accelerator modules, each containing several electrostatic quadrupoles for parallel beam channels, offers a cost-effective solution. The earlier SBTE and MBE-4 experiments at LBL have already demonstrated that the basic technology is in hand and that the beam transport characteristics are understood to a large degree, and that this technology is appropriate for the task of accelerating low-energy space-charge-dominated heavy ion beams. Results obtained with SBTE on transporting pulses of 20 mA currents of 150 keV Cs^+ ions with electric quadrupole lenses, demonstrated impressive transverse stability of a space-charge-dominated transport system up to a space-charge force of 99% of the focussing force. The MBE-4 experiment, which accelerated the beam modestly, demonstrated that the transverse emittance did not grow during acceleration if the beam was aligned and matched. The longitudinal phase space showed a small increase with acceleration, which was understood for that experiment in terms of the 2.5% random voltage error of the induction units.

A number of important questions about this first stage of acceleration remain to be addressed. These include:

- Requirements for, and implementation and maintenance of quadrupole alignments. Significant emittance growth was observed for non-aligned beams (offset about 10% of aperture, i.e., about 3 mm for an ILSE quadrupole). The requirements for quadrupole alignment in ILSE are ± 100 μm in order that the beam centroid be restricted to ± 1.0 mm.
- Test the transverse and longitudinal performance at the same line-charge density as that in an eventual driver (0.25 μC/m per beam). This should allow tests of unexpected induced-charge and intra-beam effects.
- Study of the effects of random induction voltage errors on the longitudinal heating and beamlet synchronization in the combining stage.
- Quantitative study of the merging of multiple beams. This aspect is at present the least understood quantitatively, although qualitative agreement with simulations exists. The combined beam should be observed far enough past the combiner stage to demonstrate full merging.

All of these tests can be performed in the arrangement proposed in the ILSE project.

Magnetically Focussing Accelerator Section

A major portion of the ILSE project is the magnetically focussed accelerator section (5 MeV–10 MeV). A single beam with line charge density of 1.0 μC/m is accelerated, with transverse confinement provided by 40 magnetic quadrupoles. Although this portion of the project is intended primarily to supply the beam to subsequent experiments, several significant dynamics issues are addressed. No demonstration of magnetic transport of space-charge-dominated heavy ions beams has been demonstrated to date. The situation here is somewhat different than that encountered with electrostatic focussing, primarily because background electrons are not swept clear of the channel by strong electric quadrupole fields. Instead, electrons released close to the beam are drawn in by its high positive potential (up to 10 kV) and may degrade beam quality to an unknown extent by an erratic local lensing effect. Second, magnetic quadrupoles of large aspect ratio are employed, similar to those used at low energy in some conceptual driver designs and in the final transport at high energy. The type and magnitude of aberrations from these magnets is quite different from those of electrostatic quadrupoles, and their evaluation and elimination has been an ongoing element in heavy ion fusion theory and simulation. It is very desirable that an experimental test of the behavior of space-charge-dominated beams in large-aperture magnetic quadrupole transport be made at an early stage of the ILSE experiments, and possibly in small-scale precursor experiments.

Power Supplies for Induction Accelerator Cells

The induction cell is used to accelerate continually and compress the ion beam up to the energy and current required by the target. The induction accelerator cell can be thought of as an electrical transformer (approximately 1:1). The primary is loaded with metglass core and is energized by an external power source that consists of a dc power supply and a switched pulse forming network.

Table VII. Summary of Induction Driver Issues

Component	Issue	Driver requirement[a]	ILSE goal
Ion Source	adequate current emittance life	0.4 Amp $\varepsilon_n \leq 1.0\ \pi$ mm-mr 10^8 shots	0.4A C_s^+, .8A (K^+) 1.0 π mm-mr (K^+) 0.5 π mm-mr C_s^+ 10^7 shots
Injector	Hold 2 MV w.o. breakdown aberration control voltage control	2.0 MV $\Delta\varepsilon_n \leq 1.0\ \pi$ mm-mr $\pm$ 0.2%	2.0 MV 2.0 π mm-mr (K^+) $\pm$ 0.2%
Electrostatically focussed accelerator (100 MeV Driver, 5 MeV ILSE)	alignment/steering with velocity tilt quadrupole aberrations transverse stability/image effects beam halo	align ~ 100 μm steer ~ 1 m m $\Delta\ \varepsilon_n \leq 1.0\ \pi$ mm-mr eliminate by steering and electrode design control scrape-off	100 μm 1 mm $\Delta\ \varepsilon_n$ negligible eliminate by design experiment with scrape-off
Combiner/Merge	increased line charge density control chromatic effects emittance increase	0.25 μC/m → 1.0 μC/m tilt ≈ ± 2% $\Delta\varepsilon_n \leq 4\ \pi$ mm-mr	0.25 μC/m → 1.0 μC/m tilt ≈ ± 7% $\Delta\varepsilon_n \leq 8\ \pi$ mm-mr (K^+)
Magnetically Focussed Accelerator (10 GeV Driver, 10 MeV ILSE)	compression momentum spread longitudinal instability aberrations in magnetic quadrupoles electron cloud effect on dynamics control of pulse ends with voltage ears	25 m → 10 m $\Delta p/p \leq 5 \times 10^{-4}$ stabilize by design and feedforward control $\Delta\varepsilon_n 1.0\ \pi$ mm-mr negligible or controlable effect equilibrium pulse length as predicted, longitudinal emitance growth less than ~0.5 volt-s	3 m → 2 m $\Delta p/p \leq 0.01$ experiment with waves on beam $\Delta\ \varepsilon_n$ measurable examine experimentally equilibrium as predicted
Longitudinal Compression	Shaped current profile with amplification by factor of ten removal of tilt by beams longitudinal space charge field potential longitudinal emittance increase	final current profile meets target requirements final tilt less than ± 0.005 $\Delta\ \varepsilon < 0.25\ \pi$ volt-sec	Compression by factor of two, experiments on shape control final tilt less than ± 0.01 $\Delta\ \varepsilon \leq 0.02\ \pi$ volt-sec
Bending	control of chromatic aberrations	transverse jitter less than ~1.0 mm $\Delta\ \varepsilon_n \leq \pi$ mm-mr	transverse jitter less than ~1.0 mm $\Delta\ \varepsilon_n \leq 1.0\ \pi$ mm-mr
Final Focus	Geometric and chromatic aberrations	$\Delta\ \varepsilon_n \leq 1.0\ \pi$ mm-mr spot radius ≤ 3.0 mm final momentum spread less than ± 0.005	$\Delta\ \varepsilon_n \leq 1.0\ \pi$ mm-mr (full current) spot radius ≤ 3 mm for scaled, low current experiment momentum spread less than ± 0.01
Recirculator and Storage Rings	Vacuum Stability injection and extraction	10^{-10} torr feedback control 10 μs kickers	10^{-7} – 10^{-8} torr low growth experiment experiment with fast kickers

[a] For simplicity, this column refers to an example of a linear driver. Similar, but not identical requirements are found for recirculating induction drivers. Not all components are used in all designs, e.g., not all designs use beam combining.

The ion beam completes the circuit of the secondary, acquiring the energy associated with the dB/dt voltage at the cell gap. The switched pulse forming network must be repetitively pulsed at 1 Hz (ILSE) up to 10 Hz (IFE driver). The acceleration schedule for an IFE driver will require careful tailoring of the voltage waveform at each cell gap to provide energy gain, current multiplication and longitudinal focussing. Longitudinal focussing and current multiplication with a space-charge-dominated beam are physics areas to be studied on ILSE. The main issues to consider for the induction cell power supplies are efficiency, circuit protection, switching, and power dissipation for continuous operation.

The current required to energize (1000 J/m^3) the metglass primary is about 5 kA. The total current required from the switched pulse forming network for a 10 kA ion beam (typical for the final stages of an IFE driver) is 15 kA, giving an induction cell efficiency of 67% (assuming a transformer voltage ratio of 1:1). To fully utilize the entire flux swing of the core, the core is reset just prior to the acceleration pulse. This requires 5% of the magnetizing current. Assuming an 85% to 90% efficient, regulated power supply, the overall efficiency for an induction cell with a 10 kA beam is approximately 50%. Note that for ILSE, which runs at 1–4 A of beam current, the efficiency is considerably less. In the past, a terminating resistor was placed at the cell gap in parallel with the beam to protect the switch pulse forming network circuitry in the event of beam loss. Such terminators are not planned for the 10 kA sections of an IFE driver. The circuitry will have the required protection in the event of beam loss. The terminators are planned for ILSE, and will result in about a 20% loss in energy which could otherwise be delivered to the ion beam.

The high-power switches currently planned for ILSE are thyratrons. The switches are essentially the only part of the induction cell power source that require replacement. They will perform adequately at the 15 kA maximum current and the 1 Hz repetition rate. However, use of thyratrons will limit the voltage for each core to about 30 kV. The optimum switch for an IFE driver has not been developed. Spark gaps have the advantage that they can operate at higher voltage, but they do not have the requisite repetitive pulse capability. The higher voltage operations would result in fewer induction cells and an associated reduction in overall accelerator complexity and cost. It is recommended that some effort be placed in the development of high-power switches capable of continuous 10 Hz repetition rate and lifetimes exceeding 10^4 hours.

Because the duty cycle for the induction cell power supplies is so low (tens of microseconds at a few times a second), power dissipation at 1 Hz in ILSE is not considered an issue. Cooling may have to be added at higher repetition rates, and it is recommended that the cooling issue be considered in engineering design studies. The 10 Hz repetition rate is not an issue for the cores or switches, assuming thyratrons are used. The atomic vapor laser isotope separation program at LLNL has operated cores similar to ILSE (but with small diameter) in a pulsed mode for 10^{10} pulses, and thyratrons have been successfully operated for more than 10^4 hours.

Choice of Ion Species

There are several criteria in addition to high mass number that an ion suitable for heavy ion fusion possess. These include:

- Available in quantity from a reliable, low-emittance ion source.
- Available in nature as a single stable isotope without mass separation.
- Relatively low cross-sections for ion-ion collision charge exchange.
- Should not contaminate the accelerator, nor cause a significant increase in pressure.

In the Heavy Ion Fusion Systems Assessment study, ions of mass number A ~ 200 and charge state Q = 3 were found to be economically preferred to ions with Q = 1. This finding was at least partially a surprise since it implied that the very high beam-intensity requirement was not driving the cost so much as was the high kinetic-energy requirement. Although singly-charged ions are usually called for in most studies, the economic attractiveness of Q = 2 or 3 has been recognized in a number of heavy ion fusion reactor scenarios.

It is probable that the environment in a fusion reactor chamber will require consideration of charge and current neutralization. The currents implied by beams of ions with Q = 3 definitely require neutralization. Although a number of neutralization schemes have been proposed, neutralization has never been seriously studied. It is especially interesting to consider what neutralization transport experiments would be possible with a beam from ILSE.

There have been studies of ion sources that have a significant fraction of the beam at a higher charge state than Q = 1. All appear to result in a spectrum of charge states, and at the very least, all such sources have a very high current that has to be charge-separated very quickly without damaging the emittance of the beam. The last requirement, for charge separation, appears to be so formidable that such high-charge-state ion sources should only be considered as a last resort.

Fortunately, it appears that at least one (nearly) ideal species is available. Most of the experiments in heavy ion fusion have been performed with beams of cesium. Cesium is available as a single isotope (100% A = 133), and when emitted the ions have a closed atomic shell, which reduces the charge-exchange cross section. The mass of cesium is high enough that the difference between the ranges of cesium and ions with A ~ 200 is relatively unimportant. A small improvement in emittance, for example, resulting in a somewhat smaller target spot can compensate for the slightly longer range. The range-energy curves (e.g., page 8 of Hofmann's article in Appendix D of this report) show how close the range of 10 GeV uranium is to that of 10 GeV xenon (A = 136), and thus also to cesium.

The one deleterious aspect of cesium is its reputation for contaminating insulators and other parts of high-voltage components in an accelerator. Recent experience with improved commercial cesium dispensers shows promise that, with care and with proper concern during design, the contamination problem can be contained.

There has always been interest in using a noble gas source for heavy ions. As noted, xenon would have essentially the same range as does cesium. There are several drawbacks to a gas source that perhaps could be overcome. These include:

- Gas discharge sources in general have a higher effective temperature than do thermionic sources. This may result in larger transverse emittance.
- While the transverse emittance may be controlled by the source design, it is usually necessary to include one or more grids. The presence of the grids in a strong electric field frequently causes even more increase in emittance than the discharge itself caused.
- Some gas inevitably passes down the accelerator where it can cause loss of the beam through ionizing collisions with the beam. This can be controlled with differential pumping, but certainly adds complications.
- It may be difficult to obtain a single charge state and certainly in most cases there is more than one stable isotope.

To researchers familiar with the use of proton or alpha-particle rf accelerators, two points of difference between such facilities and an induction linac for heavy ion fusion should be noted. These are:

- The emittance of the ion source in most rf accelerators is not a limiting condition because of the growth of emittance that occurs during rf bunching. The induction linac designer attempts to preserve as much of the initial brightness of the source as possible until subsequent beam manipulations, such as beam combining or splitting, require emittance dilution.
- The vacuum requirements for a heavy ion beam are more severe than for a comparable fully-stripped light ion beam.

Other ions are possible for heavy ion fusion, and bismuth, mercury, uranium and others have been considered. Certainly more is known about uranium ion sources than about many other types.

We now turn to consideration of the ion choice for ILSE. The species of ion for ILSE has been variously specified as argon, neon, sodium and, most recently, potassium (A = 39). A good thermionic emitter for potassium appears to be nearing successful demonstration at LBL.

The advantage of the lighter ion species for ILSE is that scaled experiments approximating the currents and velocities typical of the full-scale driver can be made with affordable lengths of induction linac structure using ions only a factor of three to five times lighter than desired for a full-scale heavy ion driver. The substitution of a lighter ion for ILSE can be justified so long as it does not overly burden the program with source development issues, and also does not risk a significant physics complication that would not be important ultimately. At least for cesium, there has been enough experience in the heavy ion fusion program to allow confident planning for future facilities. In contrast to the successes with thermionic sources for cesium, and more recently for potassium, there have also been a number of other ion sources tested with less success.

Vacuum System Considerations

The primary driver for the ILSE beam line vacuum requirements is the minimization of either stripping (ionization) or charge pickup (recombination) resulting from collisions between the beam ions and background gas. The vacuum system design must also be compatible with the severe axial packing constraints and not induce mechanical vibrations that can lead to defocussing.

A change in the charge state of a beam ion will likely result in beam current loss because the focussing system is "tuned" to a particular charge. For cross-sections on the order of 10^{-16} cm^2, a uniform base pressure of $\sim 10^{-6}$ Torr is required in the ILSE accelerator, bend, and drift-compression lines to keep the current loss below 1 to 2% (see ILSE Conceptual Engineering Design, LBL PUB-5219, March, 1989). Loss of beam to physical structures in the beamline (e.g. focussing elements) can result in the introduction of contaminants (an "expanding cloud") and a local increase in pressure in the region of the primary ion beam. This is not considered to be a problem for ILSE. The combination of pumping speed along with contaminant diffusion and subsequent condensation effectively removes the desorbed material from the system in ~100 ms, long before the next ion beam pulse arrives (the steady-state contamination level that would result after a long period of accelerator operation is estimated to be acceptable). Moreover, the spacings between the structures in the beam line and the ion beam responsible for the contamination are large enough that the 1-μs beam passes the region of local pressure increase before it has a chance to interact with the expanding cloud. This may *not* be the case for a driver during the injection phase, because the beam pulse duration is projected to be as long as 20 μs. In general, the sections of the accelerator that present the most problems for the vacuum system are those where the beam energy is relatively low (higher cross section for interaction with the contaminants) and the beam time scale is relatively long (more time for the expanding cloud to reach the ion beam), i.e., the injector and electrostatically-focussed acceleration sections. In these sections of ILSE, a base pressure as low as 10^{-8} Torr may be required. An ion whose charge state is relatively stable (closed shell electronic structure) is preferred because it will have a lower ionization cross section.

The picture described above is relatively self-consistent, and there is some experimental data base to support it. Also, a base pressure, during operation, of 10^{-7} Torr was obtained on MBE-4, after several days of operation (lower current than ILSE). Nevertheless, it is recommended that the data base be continually increased, especially regarding the processes governing the contaminant cloud formation, constituency, and expansion rate, and in the nature of the interaction of the cloud with the ion beam.

Using outgassing data from the March, 1989 Conceptual Design Study, the minimum pumping speed (neglecting conductance) required to maintain 10^{-6} Torr in the accelerator, bend, and drift-compression chambers for ILSE is 100 Torr-ℓ/s. This should be readily attainable. If the same exercise is carried out for the ILSE injector and matching sections, then the required minimum pumping speed to maintain 10^{-8} Torr increases to 10^5 Torr-ℓ/s ($\times 10^2$ decrease in pressure and $\times$ 10 increase in estimated outgassing rate). This pumping speed will be very difficult to attain, and cooling of the injector may be required. Installation of cooling to the beam line will have an impact on the design and cost of the injector, and it is strongly recommended that this issue be reviewed and evaluated more closely.

The design of the vacuum system for ILSE is a continuing effort. The design outlined in the March, 1989 Conceptual Engineering Design Study (LBL Pub-5219) has been replaced. The new system features a vacuum manifold that runs parallel to the beamline. This new design makes better use of the limited axial access, allows flexibility in bringing different sections of the accelerator to air pressure separately, maximizes the conductance, and may be less expensive.

Beam Halo Considerations

The term "halo" is used to refer to the outer regions of the ion beam radial profile. If this region has a large enough radial extent, then interaction with physical structures in the beamline (e.g., focussing elements), and associated beam current loss resulting from contaminant interaction with the ion beam (see "vacuum system consideration") can result.

The net focussing force in the halo region is thought to be relatively large because of the relative proximity of the focussing elements and locally low beam density. Thus, the beam radial profile is thought to be flat for the 5 to 10 cm beam diameter, with strong radial gradients existing over only 1 to 2 mm. In the beam combiner section of ILSE, scrapers are proposed to define the beam diameter. At the present time, it is thought that these scrapers may have to be heated to high temperature to keep the surface free of absorbed material and thus minimize contaminant cloud formation. Also, extra pumping is planned in the region of the scrapers. This technique could be repeated in other sections of the accelerator, if required, to reduce the extent of the halo. Applying this technique to the high-energy sections of a driver will require an investigation of possible activation in this area.

Experimental and theoretical investigations should be carried out to characterize the halo extent and identify processes that govern its formation.

Radiation from Beam Loss in a Driver

The radiation dose from beam loss in an heavy ion fusion driver begins to be a consideration above T/A = 10 MeV, where the Coulomb barrier is overcome. For a ^{209}Bi driver, this corresponds to the 2 GeV point, which, in most scenarios, is downstream of the transition from the electric focus section to the magnetic focus section.

Though the peak current in a driver would be in the kiloampere range, the average current is expected to be about 4 mA. For comparison, Los Alamos Meson Physics Facility (LAMPF) is an 800 MeV proton linear accelerator with an average current of 1 mA. Therefore, there is a factor of four more current in a heavy ion fusion driver than at LAMPF, and it is assumed that the fractional beam loss above 2 GeV in a heavy ion fusion driver (0.1%) will be about twice as large as at LAMPF for T ≥ 100 MeV. It may be instructive to note that on

Table VIII. Neutron Yields for ^{209}Bi, Compared to Protons, Striking Copper[5]

^{209}Bi+Cu E-lab (MeV)	E/A (MeV)	^{209}Bi+Cu total neutrons (n/s/nA)	^{209}Bi+Cu n-dose @ 0 degrees. (mrem/hr/nA)	neutron production from protons striking Cu (n/s/nA) @ energy E/A
2090	10	2.3×10^7	182	5×10^6
4180	20.1	2.6×10^8	1911	
6270	30.1	7.5×10^8	4834	5×10^7
8360	40.2	1.5×10^9	8183	
10450	50.2	2.6×10^9	1724	1.5×10^8
	100			1×10^9
	250			7×10^9
	1000			45×10^{10}

a per-beam-particle loss basis, the neutron production from beam loss near the high energy end of a 10 GeV ^{209}Bi heavy ion fusion driver would be comparable to that of 100–200 MeV protons.

To estimate the radiation environment along a particle accelerator, it is important to know where the beam loss occurs—quite often most of the beam loss is not distributed uniformly along the accelerator, but is concentrated in a few regions of the lattice. At LAMPF, most of the 0.04% current loss occurs near the transition from the Alvarez section to the side-coupled cavity section (100 MeV). In a linear accelerator driver, most of the severe beam manipulations will be performed at kinetic energies that are below the Coulomb barrier.

Calculations of dose rates for two driver scenarios were investigated: a 10 GeV, 4 mA (average) ^{209}Bi accelerator, and a 4 GeV, 10 mA (average) ^{133}Cs accelerator. The beam halo was assumed to be striking copper. Some of the results for ^{209}Bi are reproduced in Table VIII, and are compared with protons lost in copper.

Beam Propagation in the Reactor Chamber

Heavy ion beams must propagate inside the reactor chamber over distances of several meters from the final focussing lens to the target. Here we briefly summarize the strategy for selection of a transport mode, describe the various categories of transport modes, and then give the status of each of these modes for heavy ion fusion.

The strategy for selection of a transport mode is to simultaneously satisfy four different constraints:

- The beam parameters should be chosen to minimize space charge and other effects: this favors high β, high A, and low Q (where $\beta = v/c$, v is the ion velocity, A is the atomic number, and Q is the ion charge state).
- Accelerator considerations can constrain the beam parameters; e.g., Q = 1 minimizes the longitudinal instability for induction linacs, whereas Q = 2 might occur for certain non-Liouvillian-stacking schemes for the rf accelerator approach.
- The reactor type will determine the environment through which the beam must propagate; this includes the type(s) of gas, the gas pressure, the cavity clearing time, and a host of other reactor-related issues.
- Economic considerations may eventually influence some of the beam parameters; e.g., for Q = 2 or 3, the accelerator becomes shorter and less costly. A lighter Q = 1 ion beam would behave the same way in the accelerator and would result in a small penalty in target range down to about $A \geq 60$.

With these constraints in mind, many transport modes have been proposed. All propagation modes studied to date can be grouped into seven categories:

- Ballistic transport with a bare beam.
- Ballistic transport with transversely-available electrons.
- Ballistic transport with axially-available electrons.
- Ballistic transport with co-moving electrons.
- Ballistic transport in gas or plasma.
- Self-pinched transport.
- Transport in channels.

For the first five categories, the beam is ballistically focussed from the final lens to the target. For the last two categories, the beam is first ballistically focussed to a small radius ($\leq r_t$), and then transported at small radius to the target. In principle, any of the seven modes could be used for heavy ion beam transport; in practice, each of these modes must be carefully assessed and evaluated.

In order of increasing pressure in the reactor chamber, the status of the various propagation modes is as follows:

- **Ballistic transport in hard vacuum ($\leq 10^{-4}$ Torr) for Q = 1 beams.** "Guaranteed to work" but requires N beams, where N is large enough that space-charge-spreading effects on each beam are acceptable. Requires a dry wall cavity, and cavity clearing is an issue.
- **Ballistic transport in moderate vacuum (10^{-4} Torr − 10^{-3} Torr) for Q = 1 beams.** "Guaranteed to work." At 10^{-3} Torr, some liquid "wall" schemes are allowed. Beam stripping and plasma effects are just beginning. This mode of propagation remains the first choice.
- **Ballistic transport with Q = 2, 3 at moderate pressure ($\geq 10^{-3}$ Torr).** In this regime, beam stripping occurs but charge-neutralization effects also occur. Considerably more research is required to establish the feasibility of charge neutralizing beams with Q = 2, 3. This may also include the use of axially-available electrons, transversely-available electrons, and/or co-moving electrons.
- **Ballistic transport in the "1 Torr window" (10^{-1} Torr − few Torr).** This regime offers some reactor wall protection, and pumping problems are less severe than for the lower pressure cases. This regime is complicated by plasma effects, knock-on electrons, filamentation instability, and multiple scattering. Considerable theoretical work was done for heavy ion fusion in this regime a decade ago. Now this regime is routinely used for light ion transport, and light ion research complements heavy ion research in this area. Further heavy ion research in this area is merited.
- **Preformed-channel transport (1 Torr − 10's Torr).** This regime offers smaller holes in the reactor chamber and higher allowed gas pressures. Wall-confined Z-discharge channel transport works well for light ion beams, and has been studied and demonstrated at the Naval Research Laboratory (NRL) and Sandia National Laboratories (SNL) for many years. Beams of 100's of kA of 1 MeV protons have been transported distances up to 5 meters at high efficiency using a channel current $\leq$50 kA in a channel with radius $\geq$1 cm.

  For a heavy ion fusion reactor scenario, two problems must be addressed. (1) Laser-created channels require a high discharge drive voltage, which produces an electrical breakdown problem. This problem must be solved in order for laser-created discharge channels to be a viable option for any ion fusion reactor scheme. (2) The spot-size radius for heavy ion fusion targets as discussed in this report is $\leq$0.3 cm. It presently appears that the channel radius will be limited to a radius $\gtrsim$0.5 cm because of hydroexpansion and radiative heat transfer. Research should be carried out to investigate this limit and establish if channels are a viable option for these small spot-size-radius targets. For a different class of heavy ion fusion targets that have a spot-size radius $\gtrsim$0.5 cm (similar to light ion fusion targets that have a spot-size radius of 1.0 cm), channels should indeed be a viable option.
- **Self-pinched transport (~0.1 Torr − 10's Torr).** This regime is ultimately very attractive since it uses small holes in the reactor chamber and requires no electrical discharge. The concept is similar to channel transport, but now the net beam current acts as the channel current. There are many variations; e.g., gas only, preionized plasma channels, annular plasma channels, etc. Present simulation results for the "gas only" case at LBL, LLNL, and NRL indicate that the gas breakdown is too good, and that the net current is too low to confine the beam. However simulations at NRL using a preformed plasma channel indicate higher net currents, albeit for examples with large-radius beams (>1 cm). Two problems need to be addressed: (1) Can the gas-produced breakdown eventually be understood well enough and possibly modified to produce sufficiently large net currents? (2) Can the hydroexpansion problem be overcome so self-pinched transport at small radius ($\leq$0.3 cm) becomes possible? Research to address these heavy ion fusion issues is merited because of the potentially high advantages of this transport mode.

Synergy of Research on Heavy Ion and Light Ion Transport

Research on heavy ion fusion transport has been performed at LBL, LLNL, NRL, and SNL. Current research interests at LBL and LLNL are to examine propagation in moderate vacuum (~10^{-3} Torr), study neutralization for higher-charge-state beams (Q = 2, 3) at higher pressures, and investigate the effects of intensity-dependent deflection of beamlets in a beam bundle with partial neutralization. There is a continuing interest at LBL, LLNL, and NRL to investigate channels and self-pinched propagation.

Research on light ion fusion has been performed at SNL, NRL, Cornell University, Mission Research Corporation, and the University of Wisconsin. Present light ion research is on ballistic transport in gas in the 1-Torr regime, detailed studies of gas breakdown and conductivity growth, and initial work on self-pinched propagation for light ion fusion. In addition, a considerable amount of work on wall-confined channels and wire-guided transport has been completed.

Heavy ion fusion beams with Q = 1 at low pressure ($<10^{-3}$ Torr) propagate as bare beams in vacuum, and are subject to space-charge spreading; this regime is of unique interest to heavy ion fusion. At all higher pressures ($>10^{-3}$ Torr), the beam strips and the electrical current can greatly exceed the particle current. At these higher pressures (especially for the 1-Torr regime, channel transport, and self-pinched transport), heavy ion beams begin to resemble light ion beams and they must be neutralized. It is for these regimes that heavy ion transport research should benefit from light ion transport research, and vice-versa.

There is presently good communication and cooperation between researchers on heavy ion transport and light ion transport, and this synergism should continue to be nurtured.

Considerable insight into heavy ion transport can be gained from theoretical studies, and possibly from small-scale experiments. Recommended research areas include:

- **Analytical and numerical studies**
  Ballistic transport in moderate vacuum (10^{-3} Torr) for Q = 1.
  Ballistic transport for Q = 2, 3 at $>10^{-3}$ Torr.
  Study of charge-neutralizing schemes.
  Ballistic transport at "1 Torr".
  Preformed channels (especially electrical breakdown problems and small-radius limits).
  Self-pinched propagation (especially small-radius limits).
- **Small-scale experiments**
  Charge-neutralization experiments.
  Small-radius channel demonstration experiments.
  Reactor environment studies (vapor pressures, particulate matter, cavity clearing, etc.).

3.2. SYSTEM STUDIES AND SUPPORTING IFE REACTOR TECHNOLOGIES

3.2.1. Introduction and Background

An important aspect of the panel recommendations in Sec. 2 is that a balanced program in IFE be established that includes both reactor technology studies and experiments as well as driver development and the associated physics program. In the past, IFE technology research has been limited largely to reactor studies with almost all of the reactor design parameters based upon analytical, rather than experimental studies. As a result, many uncertainties exist in the performance and operation of present IFE reactor conceptual designs. The impacts of these uncertainties vary in magnitude, and some of the uncertainties are sufficiently large that the technical feasibility of the reactor is at stake. This will likely remain the case as long as untested analytical estimates of complex phenomena are used to predict reactor parameters without an experimental data base to benchmark the analytical estimates.

The technical feasibility of IFE requires development of certain key reactor technologies in addition to the accelerator, including high-repetition-rate chambers, automated target production, and target injection and tracking systems. The degree of success in developing these technologies will determine the choice and optimization of the driver design and the overall attractiveness (economics, safety, etc.) of IFE. Timely development of certain key technologies requires that an experimental and theoretical IFE reactor studies and technology program be supported in parallel with the driver development program.

By way of background, it is important to note that since 1971 there have been forty-nine IFE power reactor design studies. Eleven of these have been driven by heavy ion beams. Heavy ion fusion reactor studies have been funded by Germany, Japan, the DOE's ICF program, and the Office of Fusion Energy and have resulted in conceptual designs for heavy ion fusion power plants that have attractive environmental, safety, and economic features. Most recently, OFE sponsored two industrial and university teams to study both heavy ion and laser driven reactors. The final reports of these studies have not been released by DOE. Key parameters in the design of IFE reactors are the target gain and the driver efficiency. The relatively high efficiency of heavy ion beam accelerators, both rf and induction, make them a good match to predicted target gain curves. As a result, the costs for heavy-ion-beam driven power plants are estimated to be lower than those driven by lasers.

The major parameters of the last four heavy ion fusion design studies are summarized in Table IX. These four design studies have taken different approaches to the driver. HIBALL-II used an rf linac with five transfer, ten stacking, and ten bunching rings to produce twenty beams. HYLIFE-II employed a recirculator induction linac, which uses the same induction cores many times to produce four beams. Prometheus-H used a one-beam

Table IX. Major Parameters of Four Heavy Ion IFE Reactor Studies

Parameter: Type of accelerator	HIBALL-II (1984): RF Linac	HYLIFE-II (1991): Recirculating Induction Accelerator	Prometheus-H (1992): Induction Linac	OSIRIS (1992): Induction Linac
Beam Energy (MJ)	5	5	7	5
Net power (MW)	946 × 4	1,083	1,000	1,000
Driver Efficiency	27%	20%	20%	28%
Illumination	Cyl. Symmetric	1-sided	2-sided	2-sided
Target Gain	80	70	103	87
Repetition rate (Hz)	5 per Cavity	8.2	3.5	4.6
Gross thermal eff.	42%	46%	43%	45%
Breeding material	$Pb_{83}Li_{17}$	FLiBe	Li_2O	FliBe
Structural material	Ferritic Steel	Hastelloy or Stainless Steel	SiC Composite	C/C Composite

induction accelerator pulsed sequentially to feed fourteen storage rings. Osiris used an induction linac with lower ion mass and voltage to produce twelve beams. All designs use some form of liquid protection of the first wall of the reactor.

In addition to the key parameters of target gain and the driver efficiency and cost, other critical design features include: (1) the emittance requirement of the beams to irradiate a sufficiently small spot on the target, (2) beam propagation in the reactor cavity environment, (3) re-establishment of the reactor cavity environment between shots, (4) containment of the microexplosions, (5) target fabrication, (6) target delivery, and (7) radiation damage to materials and, in particular, to the final beam focussing element.

Although these reactor studies have proposed solutions to key feasibility issues, there is still great uncertainty in many parameters, such as the time to reestablish the reactor cavity environment between shots. Almost all of the reactor design parameters are based upon analytical, rather than experimental evidence. Furthermore, the difference between viable and nonviable design concepts lies within the bounds of uncertainty and will likely remain there so long as untested analytical estimates of complex phenomena such as three-dimensional multi-phase hydrodynamics are used to predict reactor chamber behavior without the benefit of experimental data. With this level of predictive capability in most parts of the reactor design, design studies have emphasized diverse solutions to design problems rather than fine-tuning one particular approach.

3.2.2. Status and Requirements

Reactor studies have highlighted that the technical feasibility of IFE requires solutions to key technological challenges. It is unlikely that major IFE initiatives (such as the Intermediate Driver facility, IDF) would be approved unless there is high confidence that these key technical areas are being resolved or can be resolved.

Therefore, an experimental and theoretical program for IFE reactor technologies should be established in parallel with the driver development program in any budget case. This program should focus on the areas listed in Table X. The major headings are in order of overall priority and the sub-items are prioritized within each category. The entire list of items, however, is not necessarily in a uniformly descending order of importance.

Below we summarize the issues, status, and technical efforts that should be carried out for each of the major areas listed in Table X. We also give some of the important milestones that could be achieved and the overall payoff if these areas of research are implemented.

Category 1—Chamber Environment and Interface with Driver

Technical Status. Most heavy-ion IFE reactors use chamber designs with flowing (liquid or granular) first surfaces to deal with the extremely high heat and particle loads. The wall must survive this environment and the deposited energy must be recovered for conversion to electricity. In between shots (~0.1-s duration), the reactor chamber must be cleared of the debris from the microexplosion, and the needed environment for beam propagation must be reestablished. Concepts include liquid curtains and jets, coolant flow through porous fabrics or structures, liquid-metal films, and flowing granular material. Gas-protected, dry-wall chamber designs would also be possible if beam propagation in the range of 1 Torr proves to be feasible. (See discussion in Sec. 3.1.2 on beam propagation in the reactor chamber.) Be-

Table X. IFE Technology Studies and Experiments

1. Chamber Environment and Interface with Driver – Modeling and Experiments	
1.1.	Vaporization/Condensation (code development, experiments to benchmark codes, simulation experiments)
1.2.	First Wall/Blanket Scale Models (scale models of fluid blankets, wetted walls, flow through porous materials)
1.3.	Chamber/Driver Interface (numerical simulation and experiments on vapor flow, vacuum pumping)
1.4.	Dissociation/Recombination for FLiBe and PbLi (chemical dynamics, experiments)
2. Reactor Materials, Blankets, and Shields – Analysis and Experiments	
2.1.	Corrosion Experiments/Material Compatibility Studies
2.2.	Pulsed Neutron Damage/Activation of Reactor Materials
3. IFE Technology Development Studies	
3.1.	Development Plan for IFE
3.2.	Systems Studies (subsystem design optimization, parameter trade studies, sensitivity analysis, oveall cost/performance modelling)
3.3	Innovative Chamber Design (direct conversion, higher repetition-rate chambers, etc.)
3.4.	Environmental and Safety Aspects (radioactive materials confinement and recycle material selection, etc.)
3.5.	Remote Maintenance
4. Target Systems — Analysis and Experiments	
4.1.	Target Injection and Tracking
4.2.	Mass Production Techniques and Costs

cause of the lack of a data base, there are major uncertainties in these designs, including establishment of the liquid protection, effects of the blast, flow around geometric perturbations (*e.g.* beam penetrations, vacuum chamber, target injection and tracking), protection of inverted surfaces, and prevention of dry spots on solid material behind the liquid.

The interconnection of the chamber environment and driver should be emphasized. The liquid protection of the chamber must be compatible with the constraints imposed by beam propagation and focussing. The ability to reestablish the cavity environment in between shots is uncertain. A few kilograms of material are vaporized (and dissociated in the case of materials like PbLi and FLiBe) with each pulse, which temporarily raises the chamber pressure. If the pressure in the chamber (or in the beam ports near the chamber) is too high, it may not be possible to propagate the beams and focus to the small spot sizes required to achieve high target gain. The vaporized material must condense and recombine and/or be pumped out of the chamber between shots. The time required to return to an acceptable vapor pressure sets the maximum repetition-rate for the chamber. If the chamber can not be pulsed on the order of 1–10 Hz, IFE may not be feasible. While sophisticated models have been used for the analyses of the first walls and for estimates of repetition-rates, these models suffer from the lack of a data base.

For the heavy ion driver, there is a direct path from the chamber to the driver beam lines, and the flow of radioactive material (tritium, activated target and chamber materials) must be reduced to an acceptable level during both normal operating conditions and during a failure of the confinement systems. Under normal operating conditions, material ejected or diffusing back through the beam lines will be recovered through vacuum pumping systems along the beam lines. In accidents, gate valves are proposed to isolate the chamber from the driver.

Priorities. The topics listed in Category 1 of Table X address these key issues with experiments and simulations needed to benchmark and improve predictive capabilities. The highest priority item is to improve the vaporization and condensation modelling. The second item is to experimentally demonstrate that the proposed flow characteristics can be established for representative chamber concepts. The third item focuses on vapor flow up the beam line and the ability to maintain the required vacuum condition in the accelerator. Item 1.4 deals with the issue of dissociation and recombination. This work is necessary to prove the feasibility of using materials like PbLi, FLiBe, and Li_2O as the first surface material. It is ranked lower than the basic vaporization/condensation work, since alternate single element materials such as Li, Pb or C could be used if recombination results in unacceptably low repetition rates.

Milestones:

1.1. Develop predictive capability for vaporization and condensation and demonstrate its accuracy experimentally.
1.2. Demonstrate that chamber flow characteristics can be achieved for selected chamber concepts.
1.3. Using simulations and scale model experiments, show that the vapor pressure in the beam line can be maintained at an acceptably low pressure and that the flow of tritium up the beam line can be controlled.
1.4. Develop predictive capability for dissociation and recombination and demonstrate its accuracy experimentally.

Payoff. Accomplishment of these milestones would establish the feasibility of repetition-rated chambers for IFE, particularly a flowing first wall design, which is a technical feasibility issue for heavy-ion fusion.

Category 2—Reactor Materials, Blankets, and Shields

Technical Status. Recent chamber designs have emphasized the use of low-activation materials. Some of these materials are the same as being proposed for magnetic fusion energy (MFE) reactor designs, and IFE will benefit from development and testing of these materials. Some of the material combinations in IFE designs have not been thoroughly analyzed or tested for compatibility. The radiation environment complicates the technical issues. For example, the radiative dissociation of FLiBe raises concern about the corrosion of carbon by free fluorine in the Osiris chamber. The effect of target materials that are deposited in the fluids used to protect chamber structures also raises concerns about material compatibility.

While designs with liquid first wall and blankets minimize the amount of structural material, the fundamental material issues for IFE are similar to those of MFE (material behavior under bombardment by 14-MeV neutrons, need for low-activation materials). Utilization of liquid first wall and blanket and accessibility of the IFE chamber for component replacement (as compared with tokamaks), however, may allow use of structural material with a shorter fluence life time for an economic IFE reactor. Whether or not the pulsed nature of the IFE source enhances or diminishes radiation damage effects to materials is an unresolved issue. Radiation damage testing for materials and conditions relevant to IFE chamber designs should be part of the overall Office of Fusion Energy materials development program. While a separately funded effort on neutron damage work is not recommended, some small-scale analytical and experimental effort may be useful for understanding pulsed damage effects.

The functions of the blanket (breeding tritium) and shield (protection from radiation) are similar to those of an MFE reactor. The IFE reactor studies have extensively utilized the data base and experience from MFE research in blanket and shield design.

Priorities. Both of the items listed in Category 2 are feasibility issues for specific chamber designs and material combinations. They are not, however, overall feasibility issues for IFE, because other materials are generally available that could be substituted if the selected materials prove to be unworkable. Such substitution is often at the expense of some attractive feature of the design. For example, the use of steel instead of carbon or SiC materials will lead to higher activation and a lower safety rating.

While there are differences between detailed designs of blankets and shields for an IFE reactor compared to MFE, the data bases from MFE (even though sparse) have and can be used for IFE reactor designs. IFE specific R&D may be needed later when the detailed design and proper material choices have been identified.

Milestones:

2.1. Measure the compatibility temperature limits of FLiBe, Pb and PbLi with low activation structures such as carbon, SiC, and vanadium alloys.
2.2 Investigate pulsed neutron damage through modelling and experiments. Measure critical neutron activation cross-sections.

Payoff. Increase the technical feasibility of using low activation materials.

Category 3—IFE Technology Development Studies

Technical Status. As discussed in Section 3.2.1, there have been many conceptual design studies for commercial IFE power plants. Systems codes have also been written and used to investigate plant performance and economics as a function of key design variables. Studies have also been conducted to determine the sensitivity of the results to various assumptions (e.g., target gain, repetition-rate limits, etc.). Over the years, these systems studies have been useful in defining the likely operating space for IFE power plants and pointing out the areas of technology development that have the highest leverage for improving the system cost and performance. They have also been used to explore the large design space for heavy ion drivers and have lead to innovations that reduce projected costs. As new information is developed on target physics and driver technology, it will be important to assess the impact on overall system performance of the eventual end-product, a commercial power plant.

Priorities. At this time, it is appropriate to give higher priority to studies that focus on near-term activities and facilities. We believe that the highest priority is to establish a comprehensive, well-conceived development plan for IFE, a plan that clearly shows the objectives of each phase and the technology development required to proceed to the next phase. The second priority covers the broad area of systems studies. These studies should focus on issues or analyses that impact the design of near-term facilities, such as the intermediate driver facility, the integrated test facility, and the demonstration power plant. Because there is no chamber concept without unresolved feasibility issues, it is important to continue to study innovative chamber designs as backups to the current concepts. The areas of environmental and safety and remote maintenance are listed for completeness, but they are given lower priority because they are areas in which IFE must rely heavily on the work done in MFE reactor designs.

Milestones:

3.1. Complete IFE development plan.
3.2. System modelling and design optimization for drivers (Intermediate Driver Facility, Linac, Recirculator).
System modelling and analysis of the Integrated Test Facility and Demo.
3.3. Innovative chamber design studies.

Payoffs:

3.1. Clear plan for IFE development.
3.2. Optimized facility designs, comparison of optimized linacs and recirculators, tools to help guide research.
3.3. Design diverse, fall-back concepts.

Category 4—Target Systems

Technical Status. The IFE approach requires ignition of targets at a rate of 5–10 Hz for a 1000 MWe power plant. Over the course of a year, up to 250 million targets (assuming an 80% capacity factor) will be required. It is clear that totally automated target production at a high rate must be developed. Furthermore, this production process must have high reliability, high quality control, and low capital and operating costs. Development of such a target fabrication process is a feasibility issue for IFE. Targets that are produced for Defense Programs may be inappropriate for energy applications, because Defense Programs applications are very specialized, and one-of-a-kind, expensive targets are affordable in the context of these experiments. Mass production of inexpensive targets is only an issue for energy applications.

Industry and the National Laboratories have the capability to make very small DT-filled capsules of the same type and to the quality specifications that are required for future IFE reactors. These capsules, however, are made one-by-one and involve many man-hours of effort each. Concepts and techniques have been identified for mass production of high-quality capsules, but there has been essentially no technology development directed toward mass production techniques. Technologies and approaches to make larger capsules, characteristic of energy applications, must also be developed.

Targets must be injected into the chamber at a rate of 1 to 10 Hz. Targets should be accelerated at a rate of 10's to 100's of g's to achieve final velocities of about 100 m/s or more. Targets must survive (i.e., maintain required quality specifications) the acceleration and transit to the center of the chamber. The target injection and tracking systems must be protected from the damaging effects of the fusion energy pulse with distance and/or shielding. The injector must be highly reliable and position the targets accurately in time and space. The tracker must supply targeting information to the driver early enough to allow for beam steering and pointing.

Preliminary conceptual designs have been developed for target injection and tracking systems, but none has been built and tested. While frozen hydrogen has been accelerated to typical IFE parameters, precision multi-layer fuel capsules have not. Calculations indicate that the hohlraum and plastic fuel capsule protect the cryogenic fuel from overheating during transit through the hot chamber. The effects of heating on the capsule surface finish requires further analysis and/or experimentation.

Priorities. Target production and injection are both feasibility issues for IFE. These technologies must be developed by OFE because mass production and target injection are not required for defense applications. It is probably too early to have a significant effort on either of these topics, but it is not too early to develop attractive credible concepts. There is high confidence that target injection and tracking could be demonstrated given the number of options for these subsystems and the technologies developed for defense systems. The survivability of a multilayer, cryogenic capsule, however, is uncertain. Small-scale experiments could demonstrate much of the injection and tracking technology even before the exact design for high gain target is finalized. Research on automated target production should be focussed on finding analog mass-production techniques that might be applicable to IFE. Development should be limited to aspects that are not dependent on the exact details of the target design (e.g., transport and handling technologies).

Milestones:

4.1. Assessment of target tracking capabilities and evaluation of options. Demonstration of subsystem performance (injector, tracker).

4.2. Assessment of mass production technologies in other industries (drugs, semiconductors, etc.). Development of some subsystem technologies.

Payoff. Progress in this area will improve the technical feasibility basis for these critical IFE technologies.

APPENDIX A. CHARGE TO PANEL AND MEETING CHRONOLOGY

The charge to FEAC Panel 7 is encompassed in the four articles of correspondence included in pages A2–A6 of this Appendix:

1. Letter from Happer to Conn (September 18, 1992).
2. Letter from Happer to Conn (October 13, 1992).
3. Letter from Conn to Davidson (October 22, 1992).
4. Memorandum from Davidson to FEAC Panel 7 (October 22, 1992).

Of particular note, in the area of driver development and next-generation experimental facilities, the principal focus of the panel's assessment is limited to heavy ions.

Dr. Robert W. Conn
Chairman, Fusion Energy
Advisory Committee
University of California, Los Angeles
Los Angeles, California 90024-1597

Friday, September 18, 1992

Dear Bob:

Through this letter I am requesting that the Fusion Energy Advisory Committee provide its views on the inertial fusion energy program of Energy Research.

The Fusion Policy Advisory Committee (FPAC) recommended, and the National Energy Strategy established, a development program for Inertial Fusion Energy (IFE) that would have the potential to lead to a Demonstration Power Plant by about 2025, in parallel with magnetic fusion development. The FPAC recommendation included relying on Defense Programs' Inertial Confinement Fusion for target physics information and ignition, developing energy-specific driver capability (primarily heavy ions with light ions and lasers as back-ups), and addressing reactor concept and technology development.

Since the time of these FPAC recommendations, fusion budgets have been cut and the possible future levels of fusion energy budgets have been better defined at levels significantly lower than FPAC envisioned. In addition, the plans for an inertial fusion ignition experiment within Defense Programs remain uncertain. Within these changed circumstances, I ask you to consider the nature and extent of an IFE program.

The options for IFE range from no activity (at least until after laboratory ignition within Defense Programs) to carrying out various forms of research that prepare for the longest-lead, energy-specific needs of a future inertial fusion energy option. Our initial strategy has been to emphasize heavy ion driver research to allow an IFE development path with potential to fit the National Energy Strategy schedule. Given the dependence of IFE on Defense Programs' activity and the present budget circumstance, it seems unrealistic to expect a specific schedule for IFE. However, it may be appropriate to pursue research that could reduce future development time. Is there a research program that complements the Defense Programs' Inertial Confinement Fusion activities, that does not require major new facilities in the near term, and that has both broad-scientific and energy-specific value?

I recognize that your views will depend on a number of factors, including your judgment as to the viability of laboratory inertial fusion, the probability that such a pulsed system could become a useful electrical energy source, the state of classification of inertial fusion, and the likelihood and extent of future international collaboration on IFE. Considering all factors you deem relevant, and considering that the total budget for fusion energy cannot be expected to grow significantly, what is the appropriate near-term activity in IFE?

Your response will have direct impact on FY 1995 planning. Thus, I will need your reply by April 1993.

Sincerely,
William Happer
Director
Office of Energy Research

Dr. Robert W. Conn
Chairman, Fusion Energy
Advisory Committee
University of California, Los Angeles
Los Angeles, California 90024-1597

October 13, 1992

Dear Bob:

During the September 23 meeting of the Fusion Energy Advisory Committee (FEAC), we discussed the charge on Inertial Fusion Energy (IFE) dated September 18, 1992. At issue is the nature and extent of an IFE program within the present constrained budget circumstance. Based on that discussion, this letter extends the charge.

I would like FEAC's advice on what the Inertial Fusion Energy activities within Energy Research should be for annual funding (in FY 1992 dollars) of $5M, $10M, and $15M.

Thank you for your willingness to take up this issue.

Sincerely,
William Happer
Director
Office of Energy Research

Dr. Ronald Davidson
Princeton Plasma Physics Laboratory
Post Office Box 451
Princeton, NJ 08543

Octber 22, 1992

Re: Charge to FEAC Panel 7
Dear Ron,

We have received a charge letter dated Sept. 18, 1992 from Will Happer regarding Inertial Fusion Energy (IFE) activities within the OFE. I'd like to ask you to chair a FEAC Panel 7 to address the issues raised in Will's letter and provide findings and conclusions for consideration by the full FEAC in making our recommendations to DOE. I know you have already made progress in putting together a list of people to serve on the Panel and we should finalize that list and get started as soon as possible. Please aim to make an interim report to FEAC at our next meeting, probably in late January, and then have a Panel Report ready for discussion in mid-March.

Will recently sent an addendum letter in which he asks that we address the issues raised in his letter of 9/18 for three possible IFE budget levels: $5M, $10M, and $15M. The key question put to us is, "Is there a research program that complements the Defense Program's Inertial Confinement Fusion activities, that does not require major new facilities in the near term, and that has both broad-scientific and energy-specific value?"

At the moment, the main IFE activity in OFE involves the heavy ion driver program. In the context of the charge and the different budget cases, I suggest in the driver area that the panel focus its attention to heavy ions, that you assess both the induction and RF linac approaches, and that you factor in the plans of others on the international scene. Overall, you should consider the relative balance between driver research and research in other key areas to IFE such as materials R&D, reactor and systems studies, and other areas you may identify. Please take into account how the IFE activities in OFE can leverage off related activities funded within either OFE or the Defense Program for ICF. Further, please consider the resources needed to insure that key milestones and demonstrable progress can be achieved over the next 5-year period. It will not help to recommend activities that will always fall short for budgetary rather than technical reasons.

Please keep me informed of the Panel's progress and let me know if there is any way I can help. Thanks to you and to all your Panel members for agreeing to take on this important task.

Sincerely,
Robert W. Conn
Chairman, FEAC

cc: A. Davies
D. Crandall

MEMORANDUM
TO: FEAC Panel 7 Members
FROM: Ronald C. Davidson
SUBJECT: Guidelines for FEAC Panel 7 on Inertial Fusion Energy
DATE: October 22, 1992

Thank you for agreeing to serve on FEAC Panel 7 on inertial fusion energy (IFE). I realize that you have busy schedules, and completion of the panel's activities by April, 1993 presents a significant challenge.

William Happer's September 18 charge letter and Robert Conn's October 22 guidance letter on this charge are attached. Based on these letters and several useful discussions with leaders of the inertial fusion community, I suggest the following guidelines as the intended scope of our panel's review and analysis.

1. Consistent with previous recommendations by the Fusion Policy Advisory Committee (FPAC)

and the National Academy of Science (NAS) panel on inertial fusion, the principal focus of FEAC Panel 7's review and planning activities for next-generation experimental facilities in IFE will be limited to heavy ions.
2. The panel will consider the three budget cases: \$5M, \$10M, and \$15M annual funding at constant level-of-effort, with a time horizon of about 5 years.
3. While limiting the analysis of next-generation experimental facilities to heavy ions, the panel will assess both the induction and RF linac approaches, and factor European plans into its considerations as well.
4. Finally, the panel will identify high-priority areas in fusion materials and technology, taking into account how IFE can benefit from related activities funded by the Office of Fusion Energy or by Defense Programs. The panel will also assess the priority of systems studies for various driver options in the different budget cases.

Thanks again for agreeing to serve on FEAC Panel 7. Because many of you will be at the November APS Division of Plasma Physics meeting in Seattle, we will have our first panel meeting on Wednesday, November 18, from 9:30 a.m. to 5:00 p.m. At least part of the presentation agenda will be tutorial in nature to bring the panel up-to-date on the current status of IFE, including experimental developments and reactor studies status.

Dolores Lawson from my office will be in contact with you regarding the meeting location.

cc: FEAC Members

APPENDIX B. FUSION ENERGY ADVISORY COMMITTEE

Advice and Recommendations to the U.S. Department of Energy[1]

Members of FEAC
Robert W. Conn, Chairman
David E. Baldwin
Klaus H. Berkner
Floyd L. Culler
Ronald C. Davidson
Stephen O. Dean
John P. Holdren
Robert L. McCrory, Jr.
Norman F. Ness
David O. Overskei
Ronald R. Parker
Richard E. Siemon
Barrett H. Ripin
Marshall N. Rosenbluth
John Sheffield
Peter Staudhammer
Harold Weitzner

Dr. William Happer
Director
Office of Energy Research
U.S. Department of Energy
Washington, D.C.

May 4, 1993

Dear Will:

In your letter to me dated September 18, 1992, you requested that the Fusion Energy Advisory Committee (FEAC) provide its views on the inertial fusion energy (IFE) program of Energy Research. The letter provided background and questions that were the context for our deliberations. In a supplemental letter dated October 13, 1992, you also requested that FEAC's advice be given assuming three possible annual funding levels (in FY1992 dollars), \$5M, \$10M, and \$15M. The FEAC met on April 15 and 16, 1993 to consider your charge regarding IFE and to formulate our advice.

Following receipt of your letters, FEAC formed Panel 7, chaired by Prof. Ron Davidson of Princeton University. The Panel included eighteen people, five FEAC members and thirteen other people who helped enormously as a result of their technical expertise and experience. The Panel looked carefully at the IFE program in Energy Research, provided FEAC with a comprehensive report, and provided an explicit set of findings and recommendations. We extend our thanks to the Panel for its extensive work and help.

FEAC accepts the report of Panel 7 and accepts and endorses the findings and recommendations given in the report. The scope of the Panel's review and analysis adhered to the following guidelines:

1. The principal focus of the Panel's review and planning activities for next-generation experimental facilities in IFE was limited to heavy ions.
2. The Panel considered the three budget cases: \$5M, \$10M, and \$17M annual funding at constant level-of-effort (FY1992 dollars), for a time period of about five years.
3. The Panel assessed both the induction and RF linac approaches, and factored European RF linac plans into its considerations. However, it is important to emphasize that the Panel's tech-

[1] In response to the charge letter of September 18, 1992.

nical assessment was limited to heavy ion drivers for IFE and that the findings and recommendations of the Panel and FEAC were formulated in this isolated context.

4. Neither the Panel nor FEAC evaluated the relative status and prospects for IFE as compared with magnetic fusion energy. Nor were comparisons made of the relative technical merits of fusion by heavy ion drivers and fusion by specific magnetic confinement geometries such as tokamaks or stellarators. Finally, neither the Panel nor FEAC reevaluated the relative merit of heavy ions as compared to other potential drivers, such as KrF, light ions, or diode-pumped lasers.
5. The Panel did identify high priority areas in system studies and supporting IFE technologies, taking into account how IFE can benefit from related activities funded by the Office of Fusion Energy (OFE) and by Defense Programs.

A principal finding is that the Department of Energy (DOE) has not established an IFE program that resembles the one envisioned by the FPAC, chaired by Dr. Guy Stever for the Department in 1990. A further principal finding is that the Induction Linac Systems Experiment (ILSE) has high technical merit and is an essential proof-of-principle experiment in demonstrating the induction linac as a heavy ion driver.

Turning now to the recommendations, in all budget cases the Panel and FEAC recommend a balanced program that includes an experimental and analytical program for supporting IFE technologies, as well as an accelerator development and beam physics program.

In the "reference" ($17M) case, highest priority is assigned to the start and completion of the ILSE project, with $14M/year identified for ILSE and accelerator research and $3M/year identified for supporting technology and system studies. The $14M for the accelerator development and physics program includes ILSE PACE and OPEX funds, and theory, modelling and supporting experimental activities. At this level, ILSE will be completed and operational within four years, providing an integrated demonstration of induction linac technology and the beam physics required to provide the data base for scaling to a heavy ion driver.

In the "middle" ($10M) case, $8M/year is identified for accelerator development and the supporting physics program. In this case, it is *not* reasonable to embark on the integrated demonstration project ILSE although a significant set of large-scale accelerator experiments could be completed, thereby providing an increased understanding of key technical issues. The theory, modelling and supporting experiments are reduced in this case, and $2M/year is identified for supporting technology and system studies.

In the "low" ($5M) case, there is *no* credible program for the development of a heavy ion fusion energy option. The base accelerator and physics program in this case continues some of the core accelerator research activities but does not provide any significant advances in large-scale accelerator demonstrations.

During our meeting of April 15 and 16, the Department informed FEAC that the proposed FY1994 budget for IFE in Energy Research is $4M, *i.e.*, less than the lowest case you asked us to consider. This caused the FEAC to reflect on the history of the IFE program in the Department and to formulate a suggestion.

In 1990 the FPAC recommended transferring the IFE program from the Office of Basic Energy Sciences to the Office of Fusion Energy. The FPAC recommended a budget profile sufficient to support the combined magnetic/inertial fusion energy program. Unfortunately, fusion funding since that time has failed to keep pace with the FPAC recommendations. In any case, DOE did not launch the ILSE project.

We recognize the great opportunity for fusion development afforded the DOE by a modest heavy-ion-driver ILSE program that leverages off the extensive target physics program being conducted by Defense Programs. Consequently, we urge the DOE to reexamine its many programs, both inside and outside of Energy Research, with the view to embark more realistically on a heavy-ion IFE program. Such a program would have ILSE as a centerpiece and be done in coordination with the program to demonstrate ignition and gain by Defense Programs.

Sincerely,
Robert W. Conn
Chairman, on behalf of the
Fusion Energy Advisory Committee

REFERENCES

1. Report by the Fusion Policy Advisory Committee, DOE/S-0081, September, 1990.
2. *Heavy-Ion-Driven Inertial Fusion*, JSR-77-41, February, 1978; *Ion Propagation in Reactors*, JSN-79-19, January, 1980; *Heavy Ion Fusion*, JSR-82-302, January, 1983; and *Heavy Ion Fusion III*, JSR-86-302, March, 1987.
3. *Review of the Department of Energy's Inertial Confinement Fusion Program*, Happer Committee, March, 1986; and *Second Review of the Department of Energy's Inertial Confinement Fusion Program*, Koonin Committee, September, 1990.
4. Heavy Ion Fusion Systems Assessment, D. K. Dudziak et al., eds., LA-11141-MS, December, 1987.