Snowmass Fusion Summer Study (July 11-23, 1999)
Inertial Fusion Concepts Working Group

Final Reports of the Subgroups

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Subgroup 1: Targets

(Max Tabak, Jill Dahlburg, Rick Olson)

Targets Summary (Max Tabak)

The target physics subgroup discussed the following three questions: Question 1A: What are the key scientific issues for validating each target concept and how can they be resolved? Question 1B: How can existing (and new?) facilities be used to test each concept? Question 1C: i) What IFE target physics issues will not be resolved on NIF? ii) What is required to get to high yield?; and iii) What is the significance to IFE of experimentally demonstrating high yield / high gain ? During the discussions, the third question actually turned into a debate concerning the related question of whether or not a single-shot high-yield facility is necessary prior to the ETF.

For Question 1A, three inertial fusion concepts were discussed: indirect drive, direct drive and the emerging concept, fast ignition. Also discussed was the emerging concept, magnetized target fusion. Each concept was sketched, difficulties were described, and research programs were laid out. The established concepts, direct and indirect drive with lasers, have benefited from decades of study and have established through detailed comparisons between experiment and theory a first principles understanding of many of their critical scientific issues: materials properties, hydrodynamic stability and symmetry control. In other areas, such as electron transport or laser-plasma instabilities, there is an adequate empirical basis to proceed, but a complete first principles understanding may be absent. In the design of targets driven by z-pinches or heavy ion beams much of this understanding carries over. Fast ignition using a short pulse laser beam, while promising significantly higher target gains and more relaxed implosion requirements than other inertial fusion concepts, has the greatest physics uncertainties, particularly in the areas of laser light and hot electron transport. Magnetized target fusion is a batch burn concept that uses dense walls to implode a preheated plasma and magnetic fields to reduce thermal conduction losses.

For Question 1B, the use of a number of existing or planned facilities to validate these concepts was discussed. Apart from doing physics experiments (Rayleigh-Taylor instability, material properties and others), the National Ignition Facility (NIF) will be the integration-validation test for direct and indirect drive and possibly for fast ignition. The Nike laser at the Naval Research Laboratory has the smoothest beams of any fusion laser. These smooth beams can be used to study the Rayleigh-Taylor instability in planar geometry. The Omega laser at the University of Rochester, a Nova scale laser, can be used to study direct-drive and indirect-drive implosions in NIF configurations, addressing a variety of physics issues. The Z-machine at Sandia National Laboratories can be used to study z-pinch implosion physics, NIF foot physics, radiation flow for z-pinch driven ignition schemes and even magnetized target fusion. Magnetized target fusion can also be studied at ATLAS, to be constructed by Los Alamos National Laboratory, and at Shiva-Star at the Air Force Research Laboratory. Heavy ion accelerators like that at GSI in Germany and the proposed HIF IRE can study heavy ion deposition physics and responses in heated plasmas. Fast Ignition can be studied on the Vulcan laser (50 J, 50 terawatt) at Rutherford-Appleton Laboratory, at Gekko (50J now-500 J) at ILE, Osaka as well as other facilities in the United States, Germany and France. An ignition demonstration would require tens of kilojoules of pulsed compressed light, together with a NIF-scale driver. A goal of the Fast Ignition effort is to justify this expenditure on the NIF.

For Question 1C, the approach to energy was discussed. Although pursuing ignition on the NIF is a DOE DP funded activity, it is critical to the IFE mission. Ignition on the NIF will validate much implosion and thermonuclear burn physics, but a balanced program involving DOE OFES is still required in target physics. Energy conversion issues specific to other drivers like ion beams or z-pinches can't be studied on the NIF. Fast Ignition research is currently outside the DP program. The mainline direct and indirect laser schemes to be tested on the NIF are inconsistent with liquid wall protection schemes. New target designs are needed. The current NIF laser indirect drive point design does not lead to adequate gain with affordable lasers.

Is a separate high-yield facility necessary before an Engineering Test Facility (ETF) is built and what are possibilities for it? New designs may demonstrate high yield on the NIF as constituted or with some upgrade. A $1-2 B z-pinch could achieve high yield, as might a heavy ion driver (but a cost was not discussed). Ultimately, we need to demonstrate high gain before the DEMO energy conversion unit is built, but 25 MJ yields are adequate to test engineering features in an ETF.

Following are summaries of the three sessions on Targets.

Question 1A: What are the key scientific issues for validating each target concept and how can they be resolved?

Session Leader: **Max Tabak**

Speakers to initiate discussions:

Indirect Drive	John Lindl
Direct Drive	Jill Dahlburg
Fast Ignitor	Michael Key
Magnetized Targets	Irv Lindemuth
Other Concepts	Friedwardt Winterberg

Session Summary (Max Tabak)

<u>Indirect Drive</u>

In indirect drive, the most studied inertial fusion scheme, energy from an outside source such as laser light, an ion beam or the kinetic energy in z-pinch is converted into x-rays. These x-rays then transport from the location where they are created to the implosion capsule where they are absorbed by the ablator. The reaction to the expansion of the heated ablator material then drives the capsule implosion. Ignition relies on the formation of a hotspot (with scale that of an alpha particle range) which accumulates much of the energy of the implosion. Burn then propagates to the high-density main fuel where the bulk of the yield is produced.

This scheme allows the separation of capsule implosion physics from driver coupling physics; so ignition on the NIF would validate implosion capsule designs for other drivers. In particular, thermonuclear burn physics, adiabat control through control of the temporal history of the radiation temperature, and hydrodynamic stability of the implosion would be validated on the NIF. Models of radiation transport can also be validated with laser facilities.

There are driver specific issues, however. For laser drivers, the laser-plasma interaction is a critical issue. Although this coupling physics is not completely understood, the work during the NOVA Technical Contract and more recently shows that laser-plasma instabilities can be adequately controlled through beam smoothing. Because projected laser efficiencies are typically 10% or less, target gain is a critical issue. The efficiency-gain product should exceed 8-10 for adequate cost of electricity. The current baseline indirect-drive laser targets have insufficient gain. However, preliminary calculations of new designs with improved coupling efficiency from hohlraum to capsule show that indirect drive with lasers should not be ruled out at this time.

Current heavy ion target designs, although sophisticated, have more than adequate gain in integrated ion-beam deposition/radiation-hydrodynamics/thermonuclear burn calculations (130 at 3MJ) given driver efficiencies in the 25-40% range. Capsule stability is thought to be acceptable, based on single mode growth factor calculations. The growth factors calculated are less than or equal to those calculated for the NIF point design where very detailed 2D/3D multimode calculations have been performed. Similar calculations are required for the heavy ion designs. The detailed deposition profile for ion beams and the hydrodynamic response of the converter to the deposited energy affect the locations of radiation generation and hence the illumination symmetry on the capsule. However, by varying converter properties in the hohlraum the capsule design can accommodate various deposition profiles. There is an ongoing European program to measure and understand heavy ion stopping powers in hot matter. Also, preheat of the capsule may be caused by radiative relaxation of the atomic states of the in–flight ions or by the nuclear fragmentation of the incident ions. These effects are believed not to be critical based on measured nuclear fragmentation cross sections and calculated atomic relaxation rates. The sensitivity to beam pointing and power balance can be addressed with 2D/3D radiation-hydrodynamic codes.

There are currently three schemes to drive capsules with x-rays produced by z-pinches. Two of these schemes involve producing radiation in primary hohlraums and then transporting the radiation to a secondary hohlraum that holds the implosion capsule. For these designs, the major issues are the coupling efficiency from the primary hohlraum to the implosion capsule and the symmetry and temporal history of the radiation driving the capsule. The third z-pinch design, the so-called dynamic hohlraum, involves imploding a z-pinch wire array upon foam that surrounds the implosion capsule. This design has much higher coupling efficiency than the prior two. The issues here are the stability of the wire array, its effect on the symmetry of the radiation field and the temporal history of the intensity of the radiation. These issues can be resolved by a combination of 2D/3D MHD calculations and experiments with z-pinches.

Some target design issues involve interactions with reactor design and target fabrication requirements. For instance, the hohlraum materials chosen must be easy to recycle, minimize the induced radioactivity and have high opacity to x-rays. The target must also be inexpensive to fabricate. Green light is less stressing for laser design than blue light, but it is not a favored option for target design/plasma physics reasons. Can the new beam smoothing options coupled with lower intensity target designs make this an acceptable option? Current indirect-drive laser illumination schemes place beams over 2π steradians. This is not consistent with current liquid first-wall power plant concepts. New target designs are needed to remedy this. On the other hand, heavy ion targets are limited only by the packing requirements of the final magnetic focussing elements in the reactor wall. Relaxing the beam spot requirement is a major challenge for heavy ion target design.

<u>Direct Drive</u>

The primary advantages of direct-drive laser fusion are (1) simplicity of the target, (2) excellent coupling efficiency (demonstrated to be greater than 80%) because it avoids the energy conversion phase of indirect drive, and (3) like all IFE concepts, the driver is removed from the target chamber. It shares many critical issues with indirect drive: efficient coupling, keeping fuel on a low adiabat, demonstrating implosion symmetry, and demonstrating sufficient target stability. Although direct drive is normally done with lasers, there are proposed efficient designs that use ion beams to directly illuminate a capsule. However, the hydrodynamic stability properties of these designs are questionable. 2D/3D hydrodynamic calculations coupled with future experiments on an IRE would be required to settle the issue. For now, direct drive is primarily a laser concept.

Of the direct-drive issues the most stressing is hydrodynamic stability. Most schemes raise the ablator adiabat to increase ablation stabilization. A recent design uses radiation produced in an outer high-Z layer to engineer a tailored adiabat that is RT stable at the ablation front (high-adiabat) and yet maintains cold (low-adiabat) ignition-appropriate conditions in the inner fuel region. 1-D calculations for this design produce gain 130 (when zooming is used) at 1.3 MJ, raising the gain curve a factor of three from earlier designs. However, no integrated 2-D multimode calculations have been carried through to burn for this design. Current calculations also do not include the effects of magnetic fields. Ultimately some 3-D hydrodynamic calculations will be needed as well as planar and convergent Rayleigh-Taylor experiments.

Experiments are ongoing at the University of Rochester and NRL leading to hoped-for validation of NIF direct-drive designs. The current experiments will provide equation of state and opacity data, beam energy balance limits and Rayleigh-Taylor growth rates to benchmark the computer codes.

Direct drive may require somewhat better DT ice and ablator finishes than does indirect drive. There is an ongoing target fabrication effort to meet these requirements. Direct-drive target designs usually require power plant chamber perforations spread over 4π steradians, so current direct-drive targets use dry-wall or wetted-wall power plant concepts. However, target designs that use less than 4π steradians would be useful. In one recent publication, the cone angle for uniform illumination is less than 55 degrees. Individual laser beams must be aimed to 25-micron accuracy in order to achieve good symmetry without sacrificing coupling efficiency (Note: It is possible to relax the pointing accuracy by overfilling the beams. This does reduce coupling efficiency). If the final optics are placed at 25 meters to protect them from x-ray and neutron damage, this translates to a 1 microradian pointing requirement.

Fast Ignitor

Fast ignition relies on a somewhat different ignition scheme from conventional direct or indirect drive. Instead of igniting in a hotspot in the center of the fuel formed during the implosion, a fast-ignited capsule will be ignited by a short pulse laser on the capsule surface after the fuel has stagnated. The implosion can be accomplished with lasers, ion beams or z-pinches. Because ignition occurs after implosion, hydrodynamic instabilities can't quench the burn. Because the Fast Ignitor's compressed state has lower density than that of the conventional implosion, symmetry requirements can be relaxed somewhat. The nominal gain curve for the Fast Ignitor is a factor 5-10 above the conventional gain curves. This higher gain can be traded for fuels with low tritium loading or smaller driver energy. The resistance to mix implies relaxed target fabrication requirements. It may also be possible to relax some of the cryogenic requirements. If it works, the integrated IFE story becomes stronger. Unfortunately, there is no integrated calculation or adequate validation experiment at this time.

The major issue for the Fast Ignitor is coupling the ignition energy from the short pulse laser to the high-density ignition region. This issue is comprised of three others: transport of laser light close to the assembled fuel, coupling of laser light to hot electrons (or possibly ions) at critical density and transport of hot electrons from the critical density to the ignition region. Assembling the compressed fuel ablatively creates an overdense plasma with scale dimension comparable to the initial capsule radius. Ponderomotively boring holes through a long plasma to conduct the Fast Ignitor beam may prove difficult. Non-spherical implosion designs may reduce the scale of the coronal plasma where the ignitor beam would enter and simplify this problem. These implosion calculations can reliably be performed with existing codes. PIC codes predict laser-electron coupling efficiencies between 40% and 90%. Efficiencies above 40% have been measured in some experiments. Transport of the hot electrons between the critical surface and the ignition region has quite rich physics with many possible plasma instabilities. The forward currents are 10^4-10^5 Alfven currents, so magnetic fields and current and charge neutralization should be important. Magnetic fields, depending on the simulation technique, between 10's and 100's of megagauss are predicted. This physics must be investigated with a research program that supports laboratory experiments together with a 3D parallel PIC code and with a hybrid code that can deal with high background electron densities. The experiments should study holeboring through overdense plasmas, electron transport through highly compressed matter and aspherical implosions.

Near term experiments can be carried out with a single Petawatt class laser beam coupled with a high-energy long-pulse beam for plasma formation. If positive conclusions follow from this concept exploration, an ignition demonstration at NIF can be envisaged. This would require converting up to 10% of the NIF beams to short pulse ignitor beams and using the remaining beams for fuel compression. A bottom line economic question that affects the technology is: how much ignitor energy will be required to make the concept robust?

Magnetized Targets

Magnetized target fusion is an emerging concept between magnetic confinement and inertial confinement. In this approach, a preheated plasma with an embedded magnetic field is squeezed by a liner implosion to ignition conditions. The magnetic field reduces the thermal conduction losses while the liner confines the plasma and supplies the energy required to heat it. The magnetic field allows lower implosion velocities and hence driver powers than IFE while the inertial confinement of the fuel allows lower stored magnetic field energy than MFE.

There are several issues. This is a batch burn concept. It was unclear how to refuel the target after ignition was obtained. Will the Q be big enough for IFE? There have been no MHD calculations demonstrating a target with Q large enough for an energy mission. The tools are available to do this calculation and it should be done. A small amount of high-Z pollutant injected into the plasma will radiatively cool the plasma and kill ignition. Are there designs that minimize mix and still have adequate Q?

The development cost for this concept is low because there is little capital expenditure for experiments. The experiments can be conducted on existing facilities.

Question 1B: How can existing (and new?) facilities be used to test each concept?

Session Leader: **Jill Dahlburg**

Speakers to initiate discussions:

NIF	John Lindl
Omega	Richard Town
NIKE	Jill Dahlburg
Z	Rick Olson
GSI	Max Tabak
Liner Drivers	Irv Lindemuth
Petawatt (PW) laser for Fast Ignitor	Mike Key

Session Summary (Jill Dahlburg)

Following are summaries of the key points of each talk and associated issues.

NIF

KEY POINT: The NIF will enable integration experiments which include: gain energetics; pulse shape and compression; hydrodynamic stability and impact on direct drive; symmetry for indirect drive; and ignition and burn.

Q: What is the metric for success?

A: Target gain.

Information obtained from NIF experiments will carry over to:
(a) heavy ions (e.g., capsule physics, symmetry control, and hohlraum energetics);
(b) direct drive (e.g., hydrodynamic stability (imprint and target fabrication)); and
(c) maybe even be able to test the fast ignitor concept.

OMEGA

KEY POINT: The OMEGA laser facility at the University of Rochester's Laboratory of Laser Energetics addresses critical direct-drive and indirect-drive physics issues.

The OMEGA laser is a 60-beam glass laser system capable of delivering up to 30 kJ in a variety of pulse shapes of relevance to direct-drive and indirect-drive target designs. Achieving a high degree of illumination uniformity is crucial for the successful implosion of direct-drive IFE targets. Long-wavelength (low l-mode) perturbations are seeded by beam to beam variations. Short-wavelength (high l-mode) variations are seeded by structure within individual beams. To control the high l-mode structure, OMEGA uses 2D SSD. The current implementation of 2D SSD has a UV bandwidth of 0.3 THz with 3 color cycles. In FY2000, the bandwidth will be increased to 1 THz with 1 color cycle. A further reduction of sqrt(2) in the instantaneous non-uniformity will be achieved when polarization smoothing is also added in FY2000. Control of low l-mode requires power balance and accurate beam pointing. OMEGA will demonstrate power balance of 3-4% in a 400-psec window during FY2000 and routinely achieve pointing accuracy of 10 microns rms.

Although originally conceived as a direct-drive implosion facility, OMEGA has proven to be an extremely flexible system capable of performing direct-drive planar foil studies and indirect-drive hohlraum experiments. For example, the OMEGA laser was the first facility to be able to control the low-order mode asymmetries (P2 and P4) in indirect-drive capsules by means of beam phasing on multiple beam cones. In planar beam geometry, experiments have been performed to study laser imprint and the Rayleigh-Taylor (RT) instability. With the completion of a planar cryogenic handling system in 2001, OMEGA will be capable of extending its EOS studies and RT growth measurements to cryogenic deuterium.

By the end of 1999, the cryogenic handling system for direct-drive implosion experiments will be installed. This facility will enable layering studies (using IR heating) of deuterium and DT ice in spherical capsules which are representative of IFE targets. During 2000, deuterium cryogenic implosion experiments will be undertaken with thin wall (~ 1 micron) plastic shells. This will be followed by DT cryogenic experiments in 2001. These targets will be energy-scaled versions of those proposed for ignition experiments on the NIF. These experiments will integrate all aspects of the direct-drive IFE implosion design apart from ignition and burn propagation, and offer a severe test of the predictive design codes used for IFE target studies.

NIKE

KEY POINT: Nike is a flexible, uniform laser that is addressing outstanding physics issues that determine the success of a direct drive ICF pellet.

Nike is a 2-3KJ laser capable of the most uniform target illumination of all high-energy lasers suitable for fusion. The large bandwidths (3 THz) and advanced beam smoothing available with Nike allow better than 0.2 percent effective time-averaged illumination uniformity when overlapping 40 beams on planar targets. Nike experiments examine laser imprint, hydrodynamic instability, equations of state (EOS) for ICF materials, and other physics issues related to ICF. Nike provides the temporal laser pulse shapes needed to simulate the low isentrope compression and acceleration of pellet shells needed for high gain implosions. Peak intensities of up to $2x10^{14}$ W/cm^2 are available for planar-target acceleration experiments. The planar geometry allows superior diagnostic access and allows acceleration of targets whose thickness approaches that of high gain target shells with modest laser energy. The Nike diagnostic suite includes high resolution, single line crystal x-ray imagers that are used to detect the lateral mass flow due to hydrodynamic instability in laser-accelerated targets.

Nike experiments are fielded to address the design criteria for high pellet gain, with particular emphasis on control of the target isentrope and inhibition of the Rayleigh-Taylor instability. In initial work, very low levels of laser imprint, equivalent to better than 100 Angstroms surface finish, were inferred from plastic targets accelerated with the Nike uniform illumination. Recent work has concentrated on examining the underlying physics of advanced target designs where the ablator is preheated but the fuel remains cold. This work includes hydrodynamic instability measurements with x-ray preheated plastic and deuterium-loaded foam targets; EOS measurements of candidate materials including foams and deuterium loaded foams; and emission measurements of x-ray producing layers in targets that preheat the ablator and that may also ameliorate laser imprint.

Z

KEY POINT: The large volume, long pulselength hohlraums together with an extensive suite of x-ray and shock diagnostics on Z offer the opportunity to study a number of key physics issues relevant to indirect-drive ICF target concepts.

The Z pulsed-power facility is presently capable of providing hohlraum drives with pulselengths ranging from ~3 ns to ~15 ns in length and peak hohlraum x-ray input powers of up to ~15 TW in small (~6 mm diameter) hohlraums and ~30 TW in large (~17 mm diameter) hohlraums. Hohlraum temperatures on Z range from ~80 eV in long-pulse, large hohlraums to ~150 eV in short-pulse, small hohlraums. The Z diagnostic suite includes XRD arrays, transmission-grating spectrometers, PCD arrays, soft x-ray framing cameras, laser velocity interferometry, and a laser active shock breakout system. A laser backlighter system will also be available on Z beginning in about 2001.

The ~80-150 eV x-ray driven hohlraums on Z provide a platform for studying a number of the key physics issues of indirect-drive ICF targets. These include: hohlraum energetics, hohlraum wall opacity, wall motion in filled hohlraums, hohlraum hole closure, capsule ablator EOS, DT EOS, shock propagation in capsule ablator materials, and ablator burnthrough. In addition, a number of issues that are specific to z-pinch driven indirect-drive ICF concepts can also be studied with the Z facility. These include z-pinch implosion energetics and reproducibility, temporal shaping of the x-ray drive, x-ray transport and symmetrization, and capsule preheat.

GSI

KEY POINT: GSI provides a capability to measure changes in ion packet energy as those packets are propagated through laser-produced plasmas. It can provide stopping power data relevant to heavy ion fusion.

The plasmas are produced with a 100 J on-site laser (1 kJ in the future), which heats foils. Ion beams are passed through the expanding plasma. Ion packet energy modification can be inferred from measured changes in ion packet arrival times.

Magnetized Target Fusion (MTF) Liner Facilities

KEY POINT: Because of existing and near-term pulsed power facilities (e.g., ShivaStar at AFRL and Atlas at LANL), liner-driven MTF can be explored without any major capital investment.

Magnetized Target Fusion (MTF) was presented as an unexplored path to fusion that is a blend of MFE and IFE in the sense that the magnetization of the fuel reduces thermal losses (a la MFE) and the predominant heating mechanism is compressional heating by an imploding pusher (a la IFE). The optimal time and density scales for magnetized targets are intermediate between MFE and IFE. Operation at the intermediate density allows MTF systems to be much smaller than MFE systems and to require much lower power and intensity from the drive than IFE systems. Although any implosion driver can be considered as an implosion driver candidate for magnetized targets, MTF advocates have chosen magnetically-driven liners as the lowest cost path to evaluating the principles of MTF and demonstrating a burning plasma.

A recent OFES-funded liner experiment on ShivaStar demonstrated liner performance suitable for significantly compressing a field-reversed configuration. The 30 cm long liner had an initial radius of 5 cm. Radiographs and other diagnostics indicated that the liner achieved a kinetic energy of 1.4 MJ, with excellent symmetry at a radial convergence of 12. The Atlas facility, operational in 2001, will be able to drive MTF liners to more than 10 MJ at MTF-relevant velocities.

Addition to NIF (Petawatt laser) for Fast Ignitor

KEY POINT: Most of the laser technology needed to convert NIF beams to fast igniter beams has been demonstrated in the Petawatt beamline at NOVA. A full-scale high-gain fast ignition demonstration at NIF could be carried out if about 10% of the NIF beams were used for ignition and the rest for fuel compression.

Prior to any full-scale test, basic science studies are needed to establish the feasibility of transporting energy efficiently from igniter laser beams to the ignition spark. Such experiments can be carried out with a single Petawatt beam line coupled with a high-energy plasma-forming beam line. This is technically possible either at NIF or in a separate facility such as SPIRE (a continuation of the Nova-Petawatt program).

Transmission grating compressors are needed for the igniter beams to deliver more energy in longer pulses and this technology is currently being developed along with other diffractive optics for NIF. Current technologies for beam quality by adaptive optics and prepulse control are adequate for fast ignition.

Question 1C: (i) What IFE target physics issues will not be resolved on NIF?
(ii) What is required to get to high yield?
(iii) What is the significance to IFE of experimentally demonstrating high yield/high gain?

Session Leader: **Rick Olson**

Speakers to initiate discussions:

Indirect-drive target issues not resolved on NIF	Max Tabak
Direct-drive target issues not resolved on NIF	Richard Town
What's required to get to high yield (ZX, X-1)	Rick Olson
What's required to get to high yield (NIF Upgrade)	Mark Herrmann
High-yield/high-gain demonstration not needed	John Lindl
High-yield/high-gain demonstration needed	Keith Matzen

Session Summary (Rick Olson)

Max Tabak and Richard Town led discussions concerning the target physics issues that would not be addressed on NIF. Max initiated discussions on four indirect drive issues that either cannot (because it's not possible) or will not (because they're not in the plan) be investigated on NIF. The indirect-drive issues are: 1) two-sided illumination where a small solid angle is subtended by laser beams; 2) laser illumination with green light (there was some disagreement on this); 3) physics issues specific to other drivers (e.g., ion deposition); and 4) indirect-drive implosion coupled to fast ignition. Richard led the discussions concerning direct-drive target issues that would not be resolved on NIF. He began by stating that "90% of direct-drive issues can be examined on NIF". The remaining 10% that cannot be resolved on NIF include: 1) high-yield implosions; 2) high rep rate and target deployment suitable for energy application; and 3) target chamber and final optics material issues. Although there was much group discussion concerning past and potential future experiments on Omega, NIKE, and NIF, the overall conclusions concerning what could not be done in either pre-NIF or NIF experiments remained unchanged from the basic points originally listed by Max and Richard.

Rick Olson, John Lindl, and Mark Hermann led the discussions concerning the second question -- What is required to get to high yield on either the ZX/X1 or the NIF/NIF-upgrade paths? Rick believes that the ZX/X1 path to high yield would require a combination of a ~10 year R&D program and a ~$1B facility. The R&D program would involve experiments (on the existing Z and an intermediate facility called ZX) in the areas of pulsed power, hohlraum energetics, pulse shaping, and symmetry. For IFE, research in the areas of rep-rate, standoff, and reactor chamber concepts would also be required. To indicate the level of extrapolation that the ZX/X1 path would involve, Rick made the comparison that, in terms of A_wT^4 (which is proportional to power into a hohlraum), Z is similar to Nova in input power, but also has more energy (longer pulselength). There seemed to be agreement (on the part of SNL and LLNL) that the ZX/X1 path is feasible but not assured. It was pointed out during Rick's presentation that LLNL has also calculated yields of ~400-1000 MJ using the X1 power pulse as input. John Lindl described a potential technique for high-yield target experiments on NIF.

This involves a recently developed "advanced-coupling target" employing lower laser power, longer pulse shapes, new wall material mixtures, and larger capsule/hohlraum size with improved coupling efficiency. John described a recent unoptimized, 2D integrated calculation done by Larry Suter indicating ~600 kJ absorbed in a capsule with a ~70 MJ yield. John indicated that straightforward improvements upon Larry's calculation will increase the calculated yield to ~150 MJ. His "guess" for an upper limit on high yield calculations utilizing NIF laser input is ~400 MJ. This is preliminary work in progress. John stated that high yield in NIF is "by no means assured". An item worth noting about the related discussions involves the question of whether or not a new NIF target chamber (~$100M) would be required for high-yield experiments. Apparently, it is possible that a limited number of high-yield experiments could be done in the existing NIF chamber. In a more general approach to the topic of "What's required for high yield?" Mark Hermann gave a presentation on results from capsule calculations ranging from 20 MJ to > GJ with the peak drive temperature chosen for 40% ignition margin. His basic conclusion is that bigger is easier - lower peak drive temperature is required for the same margin or, if we use a big capsule with 300 eV, it can be very robust.

The third question in this session turned into a debate concerning whether or not a single-shot high-yield facility is necessary and/or useful prior to the ETF. John Lindl stated that no new high-yield/high-gain facility is required prior to the ETF for either target physics or the development path reasons. Keith Matzen maintained that high-yield/high-gain in a single-shot facility is needed for IFE and should be positioned on the roadmap at a time prior to the ETF. John's main points can be summarized as follows: 1) ignition and burn propagation physics is scale-size invariant; 2) differences between ion and laser targets can be tested in nonfusion experiments; 3) ETF requires ~25 MJ capsules (hence does not require high-yield capsules); 4) multiple chambers could allow high-yield tests in the ETF; and 5) high yield might be possible on NIF (as discussed previously). Keith presented a different point of view. He made the following points: 1) the DOE/DP has a high-yield mission need and might provide a ~$1B single-shot high-yield facility; 2) the step from NIF to ETF is "enormous"; 3) the high-yield step adds value for IFE target design; 4) the high-yield step adds value for IFE chamber design; 5) the high-yield step reduces risk for ETF; and 6) the incremental cost to DOE/OFES would be small if DOE/DP funds the facility. There was a significant amount of discussion of the high-yield question throughout the entire session (even before John and Keith began their discussions), indicating a range of viewpoints on the issue. Jill Dahlburg and Rick Olson have a rather extensive set of notes from the session, indicating some of the various positions taken by the attendees (who represented nine different research institutions).

<u>**Subgroup 2: Drivers and Standoff**</u>

(Steve Payne, John Sethian, John Barnard, Rick Spielman)

Drivers and Standoff Summary (Steve Payne)

The Drivers and Standoff Subgroup discussed questions relating to (1) individual driver characteristics, (2) standoff issues, (3) and what is required for a convincing IRE scenario for each driver candidate. Throughout these discussions, five driver candidates were considered. As mentioned earlier, the mainline IFE driver candidates (which are at the PoP level) are heavy ions, KrF lasers, and DPSSL's; the other candidates (which are at the CE level) are z-pinches and light ions. MTF was explicitly discussed, but not considered to be directly in the IFE category.

The five driver candidates are briefly illustrated in Table 4, and their key characteristics are listed in Table 5. The U.S. heavy ion driver is an induction linear accelerator that creates a high current (10's to 100's of kA) beam of multi-GeV heavy ions. The KrF laser uses electron-beam pumping of a gas mixture to produce a UV laser beam (248 nm), whereas the DPSSL uses diode arrays to pump a solid-state medium to produce an IR laser beam that is frequency-tripled into the UV (350 nm), analogous to NIF technology. The z-pinch uses a very high-current pulsed-power driver (20 MA on Z) to pinch a wire array on axis to make an intense x-ray source. A light-ion driver uses a high-current light-ion diode to produce a high-current (~MA) ion beam at moderate energy (10's of MeV). A summary of current values of parameters (brightness, uniformity, pulse shaping, efficiency, durability, rep-rate, cost) is given in Table 5.

Standoff issues refer to interface issues between the driver and the target, as summarized in Table 6. For heavy ions, the mainline approach uses ballistic transport with a quadrupole magnet array for final focus, with a standoff distance of the order of many meters. Other options include neutralized transport, and channel transport. For the UV lasers, the final optic may be a grazing incidence metal mirror (KrF or DPPSL), or a hot fused silica wedge or grating (DPPSL). For a z-pinch, a recyclable transmission line (RTL) concept is being considered. For light ions, transport may be neutralized ballistic transport with a lens system, or any of several forms of channel transport. Every standoff scenario needs further study.

Results of the IRE discussions are roughly summarized in Table 7. In this Table, the weakest link is the "E" category, which requires further physics/engineering exploration. In particular, note that the key issues are neutralized and channel transport for HIF, durability for KrF (survivability of pumping foil), cost of diodes (DPPSL), durability for z-pinches (ability to recycle the RTL), and durability (ion source performance and reliability) and final transport for light ions.

An overall driver summary is given in Table 8. The results were agreed upon only after extensive discussions (!). In each case, the bar shown was quantized to only three levels (small, medium, or large). Very roughly, this Table shows the various strengths and weaknesses of the various drivers. Our IFE development plan, current research approaches, and IRE development studies will sort out the potential of each driver to meet the requirements for a successful IFE system.

Following are summaries of the three sessions on Drivers and Standoff.

Table 4. Five driver options are being considered for IFE.

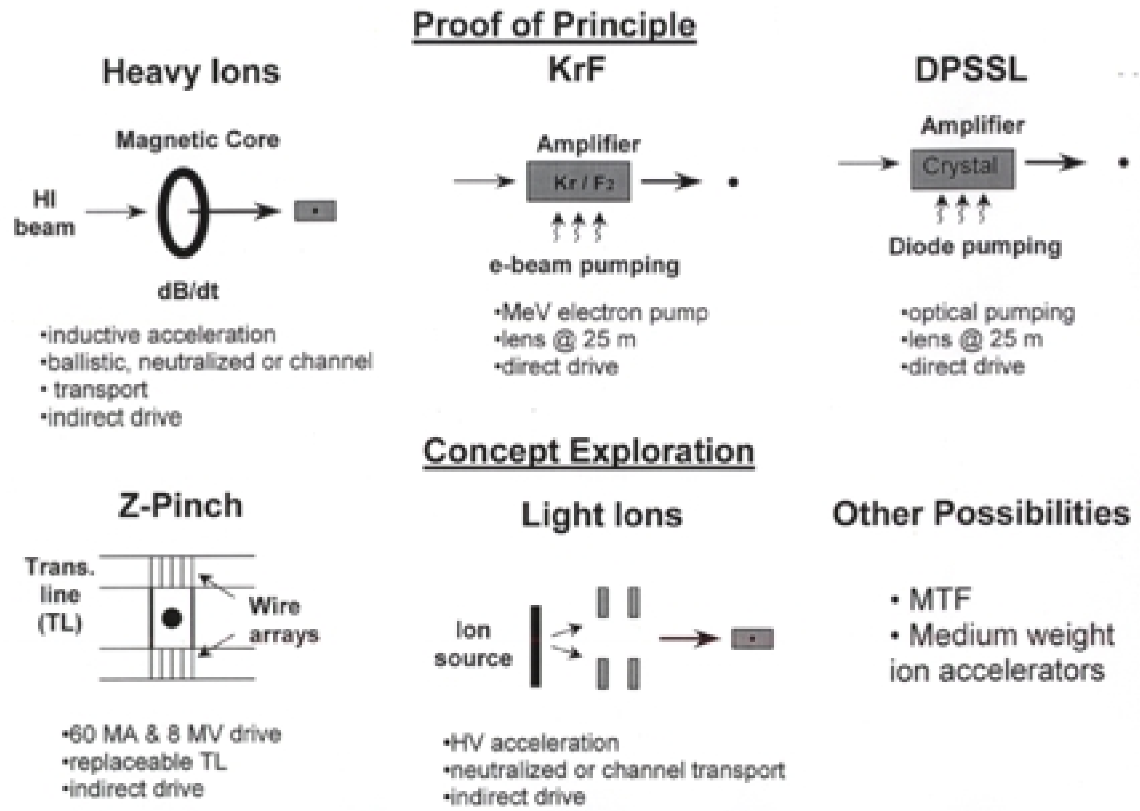


Table 5. Status and potential of IFE drivers.

Drivers	Brightness	Uniformity	Shaping	Efficiency
Heavy Ions	Ion source brightness suitable	x-ray smoothing	Velocity tilts and/or separate beams for foot and main pulses	45% for Kr, 32% for Pb; deduced from e-linacs and core loss measurements
KrF	3×10^{17} W/cm^2 str.; 10x requirement	0.2% meas. for beam; meets spec.	Pulse stacking ; meets spec.	7% by component validation
DPSSL	3×10^{18} W/cm^2 str.; 100x requirement	0.04% calc.; 0.2% needed on target	10^4:1 demonstrated; meets spec.	10% by component validation
Z-pinch	x-rays from wire array drive hohlraum	% -level demonstrated	% -level demonstrated	15% (wall plug to x-rays) demonstrated
Light Ions	10% of IFE; second-stage diode needed	x-ray smoothing	Velocity tilts and/or separate beams for foot and main pulses	64% demonstrated

Table 5. Continued.

Drivers	Durability	Rep-rate	Cost
Heavy ion	10^8 shots; based on Astron and improved source	10 Hz	$150/J for Kr; $230/J for Pb; vendor estimated
KrF	10^2 shots currently; 10^5 shots in Phase 1	100 Hz in literature	$225/J; extrapolated costs
DPSSL	10^8 shots for diodes demonstrated	10 Hz in small test bed; meets spec.	$400/J; assumes 5c/W diodes, large extrapolation
Z-pinch	Single shot now; 10^2 shot burst mode with replaceable trans. line for IRE	Single shot now; 0.1 Hz with replaceable trans. line	$30/J of x-rays demonstrated
Light ion	10^4 shots; many issues to resolve	Single shot now; ultra-pure carbon anode needed	$150/J demonstrated

Table 6. Standoff issues and how they are being addressed.

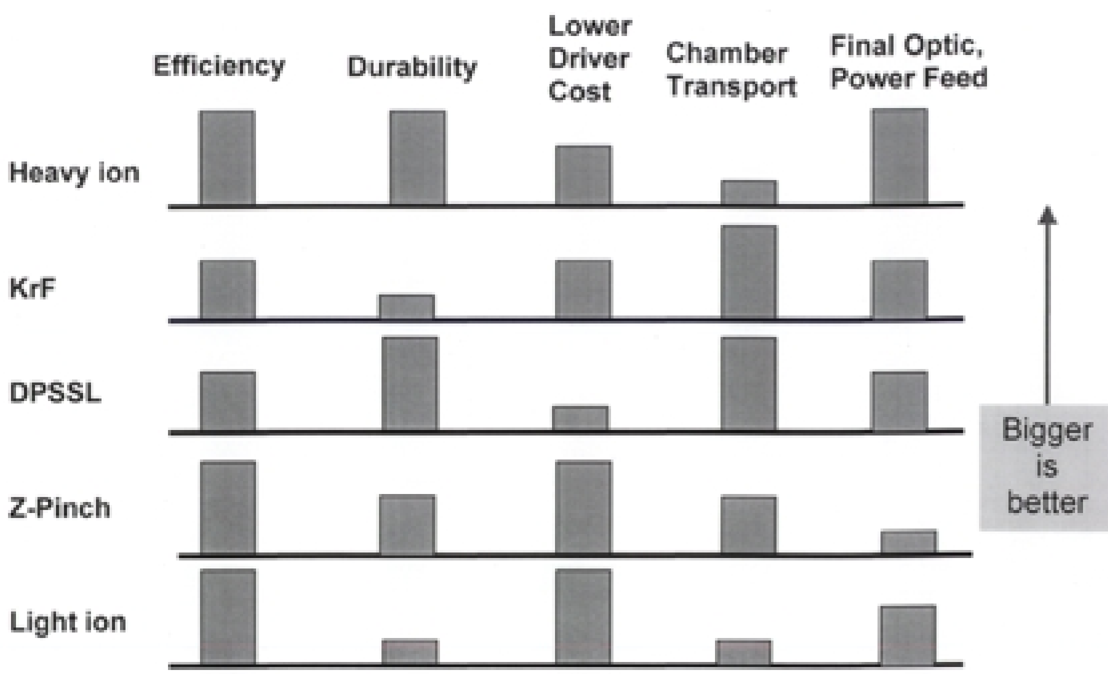
Drivers	Final Optic or Power Feed Lifetime	Power Transport Efficiency; Focusability
Heavy Ions	Design superconducting final optic based on data and neutronics	Assess neutralization and channeling
KrF	Metal mirror and heated silica studied at low-to-moderate dose studied	100% transport at <0.5 Torr of Kr to reduce x-rays
DPSSL	More data needed	Assess gas-breakdown and target heating issues
Z-Pinch	Develop replaceable transmission line	67% transport through present TL X-rays from wire array drive hohlraum
Light Ions	Assess/manage irradiation of lens	Assess neutralization and channeling

Table 7. Status of IRE concepts.

(Key: I = integrate, V = validate, E = explore)

Drivers	Brightness and Uniformity	Focusability & Chamber Transport	Durability	Driver Cost
Heavy Ions	V	V (ballistic transport); E (neutralized & channeling)	I	I
KrF	I	I	E	I
DPSSL	I	I	I	E
Z-Pinch	V	I	E	I
Light Ions	V	V (neutralized); E (channeling)	E	I

Table 8. Driver options for IFE have a variety of strengths and weaknesses.



Question 2A: How can the source brightness, beam uniformity, pulse shaping accuracy, efficiency, reliability, repetition rate, and cost of each driver concept be improved?

Session Leader: **John Sethian**
Speakers to initiate discussions:

HIF	John Barnard
LIF	Mike Cuneo
KrF	John Sethian
Z-pinch	Rick Spielman
Other Concepts	Koichi Kasaya

Session Summary (John Sethian)

We heard five excellent talks discussing the main driver concepts for IFE: heavy ions, light ions, KrF lasers, Diode Pumped Solid State Lasers (DPPSL's), and the z-pinch. All addressed the posed questions to one degree or another. We also had one auxiliary equally fine talk on Medium Ion Sources. The discussions were lively, probing and generally polite. A general consensus was impossible to reach, primarily because each advocate steadfastly (and properly) believes his or her driver is the most promising approach. However a few points were agreed upon:

All of the candidate drivers have promise. All of them have distinct advantages and distinct challenges. Of the five, the heavy ions and two lasers are the most advanced. They have well-defined program plans, with clear cut metrics and goals that must be met for IFE. The z-pinch is a copious source of x-rays, but is in the concept exploration phase with respect to inertial fusion energy, and faces challenging issues that must be addressed conceptually before a program can be formulated. The light ion work is presently on hold due to problems with the source, but a new type of source may make these a viable candidate. Nevertheless, given the relatively immaturity of even the most developed of these concepts it seems inappropriate to totally exclude any of them.

A synopsis of each driver talk, and the related discussion, are reported below. We caution, however, in taking this as the sole basis for ranking one driver over another. In fact, the drivers need to be explored in the context of a complete Inertial Fusion Energy system. This requires a broad based science and technology program, with the explicit goal of validating critical technologies. The program must look at all the issues for each driver, the target gain, chamber, target fabrication, target injection, and ultimately, the cost of electricity.

<u>Heavy Ions</u>

Three different examples of heavy ion drivers were given, based on "bottoms up" systems codes. (A preferred configuration for a heavy ion accelerator - ion species, charge state, voltage and total energy, has not yet been chosen.) In a highlighted case, the driver energy is 6 MJ, uses 4 GeV, 200 amu (+1 charge state) ions, and has a peak ion current of 4.1 kA in each of 32 main pulse beams out of 48 beams. Heavy ion driver costs are projected to be in the range $ 0.64 to $1.3 B (about $200/Joule). This is based on systems studies, vendor estimates based on anticipated technology advances, and economies of scale. The typical cost reductions required for the different components, from the present technology to an IFE system, is within an order of magnitude. The exception is the superconducting magnet arrays, whose cost reduction is more uncertain because they are still in the design phase. The estimated costs of the magnet arrays, however, do reflect the current price of low-temperature superconductors and are based on experience with costs of actual accelerator superconducting magnets. The cost of a heavy ion accelerator can be improved by reducing the target energy requirements, reducing the length of the accelerator, or reducing the cost per unit length. The latter can be done by improving the unit costs or decreasing the diameter of the arrays and cores. Many programs are underway with vendors to reduce the cost further.

The efficiency of a heavy ion driver is anticipated to be 30-45 %. This is based on systems analysis of induction accelerators, which include a variety of energy loss mechanisms. The pulsed power for these machines was estimated to be 75% efficient, and core losses were based on measurements of core samples and actual cores driving resistive loads. A model of beam dynamics and transport was also incorporated into the systems code. The high efficiency of ion drivers is realized with several existing electron beam induction accelerators (for example, ATA was quoted to have an efficiency of "tens of percent"). Existing heavy ion induction accelerators have low efficiencies (about a few percent) because they are low current; however, as the current increases, the power driving a full-scale core does not increase substantially, so the accelerator efficiency is consequently expected to increase.

The beam brightness can be considered a measure of the phase space density, and for heavy ions the phase space density at the source (achieved in scaled experiments) should be 1000 times larger than what is required at the target. So the beam brightness should be adequate, but the flux capabilities are very low. Ion source research and development will be necessary to meet the flux and lifetime requirements. For example, the energy flux of the plasma lens experiment at GSI (with an Ar^{18+} beam) is ~ 2×10^{10} W/cm^2, about a factor of 1000 lower than the 7×10^{13} W/cm^2 needed per beam in one HIF design. On the other hand, the collider at RHIC will reach a peak energy flux of 7×10^{14} W/cm^2 and the SLC electron-positron collider has a peak flux of 10^{21} W/cm^2, so some aspects of accelerator technology have already reached driver scale. The new requirement is high current along with high energy.

Requirements for the beam uniformity or pulse shaping of a heavy ion driver have not been determined, but are not expected to be an issue due to radiation smoothing. Beam centroid errors may be more stringent but still can be met; 2D target simulations allow +/- 200 μm pointing errors, and preliminary tracking experiments indicate these are achievable.

Pulse-shaping requirements have also have not been finalized, but they are also not expected to be a problem. Two methods are proposed to achieve the proper foot/main pulse shape; using separate sets of beams for the foot and main pulse, or using velocity tilts to vary the energy. Optimally, a combination of both methods will probably be used. More simulations to verify these approaches need to be carried out.

Heavy Ion accelerators should meet the required rep-rate and lifetime, based on experience with electron linacs. It was pointed out that research accelerators such as LANSCE have availability exceeding 85% during scheduled operating runs.

Light Ions

Presently, light ion fusion development is on hold due to the lack of a sufficient ion source. Nevertheless, when the work was halted, the work had progressed to the point that only “3 factors of 3” were needed in parameter improvement for light ions to meet the anticipated requirements for a high-yield driver. Specifically, an ion energy of 12 MeV was reached, with 30 MeV needed; current densities of 0.5 kA/cm^2 were reached, with 1-2 $kA.cm^2$ needed, and a 15 nsec long pulse was achieved, with 40 nsec needed. These three parameters were achieved simultaneously on PBFA II. It is also necessary to decrease the ion beam divergence; 22 milliradians was achieved in single-stage diode, meeting the transverse particle energy requirement for fusion. A total divergence of 6-12 milliradians is needed; it is proposed to achieve this range in a post acceleration step at constant emittance. Subsequent work on the SABRE accelerator has demonstrated current densities that scale to fusion requirements at the necessary pulselength of 40 ns. When the light ion program was placed on hold, beam production on SABRE had progressed to within a factor of 2 to 4 of injector stage requirements, without an optimal source.

The main stumbling block to achieving a viable light ion driver is the realization of a robust, pure, ion source with the required brightness. Past efforts concentrated on lithium ions, which proved unsuitable primarily because of impurity issues. The most promising candidate is now believed to be a 50 MeV Carbon ion source. One reason for this is that the main impurity in the previous ion sources were carbon ions anyway. An 80% pure carbon source was also demonstrated on SABRE.

Other issues regarding the driver (pulse shaping, efficiency, reliability, rep-rate and cost) have not been fully considered because of the fundamental question of a suitable source. Pulse-shaping would be accomplished with velocity tilts and/or separate beams for the foot and main pulses, as in HIF. A 60-70% ion production efficiency has been demonstrated in many previous experiments. For an initial demonstration, it is estimated that the source should have a lifetime of 10^6 shots (2 weeks at 1 Hz), and that the cost of a rep-rate machine about the size of Hermes III (the potential driver technology - albeit single shot) is about $80M for one (of 12) modules.

Diode-Pumped Solid State Lasers (DPPSL)

The Mercury Laser (100 J/10Hz/10% efficiency) under development at LLNL will be a test bed to develop DPPSLs for fusion energy. DPPSL’s have already meet the repetition rate required for IFE (up to 25 Hz in small apertures), and they should meet the durability requirements- current technology with DPPSL's show laser diode pump bars at about 100 W/cm @

10^8 pulses, with 200 W/cm @ 10^{10} pulses required. It is believed that advanced development of the pump diodes and optics will achieve the necessary lifetime, and a viable development path to achieve these was presented. The efficiency of DPPSL is expected to be 10% and could be as high as 20%. These are "stem-to-stern" efficiency estimates, based on all the components in the system and include cooling and beam transport to target. The present projected aggregate efficiency of all the components, tested individually, is 9%, assuming shaped pulses but excluding cooling or beam transport. The 10% figure represents the baseline goal for Mercury. The 20% figure assumes more advanced development.

The cost of a DPPSL is driven by the cost of the pump diodes. In Mercury (year 2001) the cost of the diodes is expected to be $3.00/peak Watt. That number is needed to drop to $0.50 /peak Watt for the IRE (2010), and to $0.05/peak watt for an IFE system (2030). The estimates for cost reduction are based on systems studies of diode plant manufacturing, anticipated technology advances, and economies of scale. The diode manufacturing facility is assumed to produce one fusion power plant worth of diodes per year. As DPSSLs are a growing commercial industry, these cost reduction numbers should be reasonable.

DPPSL's easily meet the brightness requirements, by about two orders of magnitude or more. They also have the high contrast (10^4:1) needed for pulse shaping, and it appears that this is not an issue. However target designers can always come up with very strange pulse shapes (e.g., an exponential transition from foot to main pulse) that may present a challenge.

The present spatial uniformity of the DPPSL needs to be improved, but it is not known by how much. For example, although the present high-gain target design under development assumes the laser is very uniform throughout the entire pulse, it may be that high-beam uniformity is only required during the early foot. Nevertheless, a theoretically viable approach has been proposed, based on 2D-SSD, and sculpting the laser sprectrum, and potentially four-color operation, to achieve very uniform beams throughout the pulse—as low as 0.03% RMS at 1 nsec, in modes 20-300 is projected. However, this smoothing, if achievable, ignores the modes < 20 which SSD cannot smooth as well, and comes at the expense of a very large number of beams, which may effect the cost, efficiency and durability. The Mercury laser will provide the necessary test bed to perform a proper integrated demonstration of this technology.

<u>Krypton Fluoride Laser (KrF)</u>

NRL is building the Electra KrF Laser (700 J/5 Hz/30 cm aperture) to develop the technologies required for IFE. The requirements for an IFE KrF laser were derived from power plant studies and the high-gain target design. The present Nike amplifier (5 kJ/ 38 kJ e-beam) suggests that scaling the architecture (ISI beam smoothing, angular multiplexing and double-sided e-beam pumping) to a IFE-sized laser (30-50 kJ, with eight 38 kJ e-beams), should be a reasonable extension of existing technology. The challenge is to build one with the needed rep-rate, durability, efficiency and cost.

The cost requirements are estimated to be $225/laser Joule, of that the pulsed power costing $5.00/electron beam Joule ($70/laser Joule). It appears the pulsed power costs can be met, based on systems studies, vendor estimates based on anticipated technology advances, and economies of scale, but this needs to be demonstrated. The pulsed power system will be all solid state and will probably feature some form of magnetic compression as used in the Sandia RHEPP accelerator. The cost of the other laser components needs to be refined, but based on several studies (Sombrero, LANL, and Ignition facility) the overall system costs seems reasonable.

All the components of a KrF system need to be developed for durability, but the two most limiting components are the hibachi foil (which separates the laser gas at ~ 1 atmosphere from the diode at vacuum) and the amplifier optical window. Both last several hundred shots on Nike, and both need to have lifetimes exceeding 10^8. It is anticipated that a long-life hibachi can be built using a helium cooled double foil arrangement as tested by AVCO. The window will require an optics development program.

KrF has demonstrated extremely high beam spatial uniformity: 1.2% non-uniformity per beam. This should be adequate for IFE. Based on other excimer lasers, this uniformity is expected to hold for a rep-rated system. KrF brightness is an order of magnitude higher than required for direct drive. Pulse shaping is not an issue, within the same "target designer" constraints as a DPSSL. One of the advantages of a KrF system is that the pulse shaping, zooming, and beam smoothing can be carried at low energy in a single front end which feeds the entire laser.

The present projected efficiency of a KrF laser is about 7%. This is adequate for IFE, based on the Sombrero Power Plant studies, but leaves little head room. The efficiency estimates are based on systems studies of the advanced pulsed power (80%), experiments with a high transparency hibachi developed at Los Alamos (80%), the estimated efficiency of the ancillary components such as gas recirculator (95%), the demonstrated intrinsic efficiency of KrF test cells, de-rated by 20% for fill factor (12%), and beam transport to target (90%). Needless to say, efficiency is one of the prime areas that will be addressed with Electra.

<u>Z-pinches</u>

Z Pinches make lots of x-rays; 1.9 MJ and 200 TW, efficiently and at relatively low cost ($30/Joule $_{\text{x-ray}}$). The Sandia Z machine is an outstanding technical achievement, and the question is now whether or not the concept can be turned into a viable approach for fusion energy. This system is just now starting to be evaluated, and with no power plant concept to define the requirements, it would be difficult to answer the specific questions of this topic. Nevertheless, several points can be made regarding a z-pinch driver: first, z-pinches are scalable to large drive energies (up to 60 MA is considered) which will lead to large fusion yields. Hence the rep-rate, in principle, can be low (assuming other power plant issues allow this). Second, the efficiency of this system (from wall plug to x-ray energy out) has been demonstrated (single shot) to be about 15%. It is not unreasonable to assume that future pulsed power developments can improve this two-fold. Third, pulse power has historically been inexpensive compared to other drivers, and, it is not unreasonable to assume cost reductions as the technology is improved. Fourth, the technology to rep-rate a pulsed power system has been demonstrated with the RHEPP machine at Sandia.

Whether all these attributes can be maintained as they are integrated into a fusion power system needs to be addressed. For example: the efficiency of the whole system (wall plug to fusion energy, including cooling and ancillary components) needs to be taken into account. The target design may require pulse shaping that can affect the driver characteristics. And, it will take a significant engineering effort to get to a rep-rated multi-TW system. To go from the RHEPP technology to the initial driver designs requires a 4x increase in voltage (2.3 MV to 10 MV), and a 2000x increase in current (25 kA vs. 50 MA).

Other Concepts: Medium Weight Ions

This talk addressed one question for one driver, namely how can the source brightness be improved for a light ion driver. The source under consideration is a cryogenically cooled extraction ion diode. It has achieved 3-6 milliradians divergence with a nitrogen beam (there is some oxygen impurity), as compared to 15-60 milliradians for proton beams. This "Medium Ion Beam" (MIB) approach combines the low cost of light ions, with the high brightness of Heavy ions.

Question 2B: What are the key standoff issues for each driver scenario and how can they be addressed? (e.g., final optics for lasers, final transport and focus for laser beams, final focus magnetic lenses for heavy ion beams, final transport and focus for ion beams, power feed for rep-rated z-pinches,...)

Session Leader: **John Barnard**
Speakers to initiate discussions:

HIF and LIF	Craig Olson
DPSSL and KrF	Steve Payne and John Sethian
Z-pinch	Steve Slutz

Session Summary (John Barnard)

The success of Inertial Fusion Energy (IFE) depends on the ability to transport a succession of pulses of energy to a small volume in a short time to detonate a sequence of targets, without the resulting target explosion destroying the chamber or the permanent structures used in delivering the pulse. "Standoff issues" are those physics and engineering issues that are related to the delivery of the energy pulse through the chamber and to the protection of the permanent structures. Some commonalities exist between the standoff issues for the various driver concepts, and these are outlined in this brief introduction. In the following sections, we focus on the standoff issues unique to ion drivers (both heavy- and light- ions), then on laser beam issues (DPSSL's and KrF). Finally, the issues for the exploratory concepts (z-pinch and MTF) are described.

For ion and laser beams, the solid walls of the chamber must be protected from neutrons, X- and γ-rays, streaming gas and ions, and debris from the target explosion. In addition, the final focusing optics must be protected, since they are generally large, high precision, and costly components. In some designs, bending optics (which must also be protected) are used to introduce a jog in the laser or ion beam path. This jog permits a neutron and γ-ray dump to be inserted on a line-of-sight to (but further from) the target, reducing further transport of γ's and neutrons up the ion or laser beam line. Shutters are often provided just outside the chamber to limit much of the projectile debris and gas flow from the target explosion. The density of vapor or gas in the chamber must be chosen to be consistent with propagation of the beam at high intensity.

For the z-pinch concept and some Magnetized Target Fusion concepts, it is required to have conductors deliver the energy pulse to the target; therefore, a cost effective way of replacing the power feeds must be developed. In addition, the higher yields of these latter options must be considered in the chamber design.

HIF and LIF

The main standoff issues facing ion drivers are (1) the choice and validation of beam propagation mode in the chamber (that results in a sufficiently small and well-pointed spot at the target), (2) beam instabilities, and (3), for heavy ions, configuration of the final magnet assembly and shielding of the magnet. Because of the relatively small total beam solid angle and narrow cone angles required by a two-sided indirect drive target, flowing thick liquid walls (e.g. Flibe, LiPb, LiSn, or Li) provide an attractive means of protecting the solid chamber wall from neutron, γ-rays and X-rays from the target explosion, but other wall options (dry-wall and liquid-wetted) are available for ions (and have been described in system studies). The other chamber options are discussed in greater detail in the section on IFE chambers; here we will generally assume thick-liquid Flibe walls to discuss ion beam standoff issues.

There are a number of propagation modes that are being considered for transport of the ion beam through the chamber. They may be broadly divided into unneutralized ballistic transport, neutralized ballistic transport, and channel transport.

Unneutralized transport may be considered for chamber pressures less than $\sim 10^{-4}$ Torr, where generation of free electrons is sufficiently low. This pressure is in the lower end of the range contemplated for Flibe liquid walled chambers. Unneutralized transport is the mode of operation of most accelerators in operation today that require small focal spots, such as colliders. However, the currents required for heavy ion fusion are much larger so space charge effects become important. Unneutralized propagation is possible even, e.g., for the case of a target that requires 4 MJ of 4 GeV, mass 200 ions, provided the number of beams is increased to 480 (up from the original design of 48, where 90% charge-neutralization was required). For a beamlet focusing half-angle $\theta = 0.01$ rad, the total solid angle obtained by this number of beams would be 1.2% of 4π steradians. Some current chamber designs prefer fewer beams, so targets which allow larger ion energies, or neutralized propagation modes, are favored. The issues associated with unneutralized ballistic focus would be few, however, if neutralized modes prove to be unsuccessful. One issue is the degree of stripping of the beam by the residual gas and the subsequent defocusing of the beam from space charge. Operating at the lower end of possible Flibe gas pressures (< 10^{-4} Torr) reduces this effect. A second issue is the degree to which photoionization by the target X-rays (generated as a result of target heating by the prepulse) ionizes the surrounding gas and the beams. Since this occurs near the target and will likely provide partial beam neutralization, the effect on focusability could be beneficial. Both effects have been simulated but require examination over a wider parameter range in fully-integrated simulations.

For neutralized ballistic transport, there are a number of options for providing electrons to neutralize the beam, and minimizing the effects of space charge: pre-ionization of the gas through which the beam propagates; co-injection of electrons; passage of the beam through a disposable foil or gas puff; or beam induced ionization of the gas. The light ion fusion program has experimentally achieved 99.98% neutralization by passage of the beam through a foil, confirmed in calculations by the hybrid electromagnetic code IPROP, so the more modest neutralization fractions (90-99%) proposed for heavy ion fusion do not appear to be problematic. Neutralization fractions of ~90% have been simulated using the electromagnetic code BICrz, (assuming a preionized surrounding cylindrical column exists) and have achieved nearly emittance-limited spot sizes. These simulations, however, neglected some electron sources (e.g. chamber walls, nearby Flibe, target emission and photoionization); the code improvements to include these sources are in progress. Ionization methods including whistler mode wave heating will be experimentally investigated in the near term.

The final option, at higher risk, is that of channel transport whereby azimuthal magnetic fields provide strong focusing of the beam. The magnetic fields are generated by either a plasma discharge producing a longitudinal current (a "pre-formed channel" [~10-100 Torr]); a wire carrying a current ("wire-guided"); or "self-pinched" transport (whereby the fields from a highly-stripped, but space-charge neutralized ion beam produce the self-focusing magnetic field [at ~5-30 mTorr]). The main advantage of channel transport options are that the ion beams may be combined in a small number of entrance holes (reducing the total beam solid angle thus minimizing neutron and γ-ray leakage from the chamber). Also, the focal distance to the entrance hole can be much less than the chamber radius, easing beam brightness requirements. For preformed channels, creating and maintaining a stable channel, and establishing return current paths which, in some cases, can be geometrically orthogonal to the beam current path, are the key scientific issues. For self-pinched transport, recent experiments at NRL with high-current proton beams have demonstrated this mode, in the pressure regime predicted by IPROP, for the first time.

Instabilities may also be a concern. For unneutralized ballistic transport, the known beam instabilities are not expected to be of concern. However, as the neutralization fraction increases, in the neutralized ballistic and channel transport modes, filamentation, resistive hose, and the electron-ion two stream must be considered. The linear growth rates for these modes have been calculated. Simulation studies using BICrz have not detected any instabilities in the partially-neutralized regimes thus far simulated (with ~90% neutralization fractions), but the code is axisymmetric. Channel transport modes have more complicated physics and the effects of instabilities are still being explored. Filamentation has been observed in experiments at NRL with proton beams in certain pressure regimes. The use of high-current (~100 kA) proton beams to model stripped heavy ion beams was advocated.

In addition to instabilities, other physics questions such as those regarding the interaction of multiple beams, or the degree to which the longitudinal velocity tilt can be removed at the stagnation point, just before the beam passes the final optics, need to be addressed via both simulations and experiment.

For the mainline ballistic focus, the final focus quadrupole and bending magnets do not materially intersect the beam path. For efficiency reasons, low T_c superconducting magnets (e.g., using NbTi cable at 4^o K) are the baseline case for final focusing and bending magnets. However, low T_c magnets can tolerate only 1.0 mJ/cm^3 of heating before a quench (reversion to normal conducting) can occur. Shielding must therefore be provided to prevent scattered neutrons and γ-rays from intersecting and heating the coils of the magnets. Both longitudinal shielding (between the magnet and the target) and radial shielding (between the beamline and the magnetic coils) can be used. Simulations using neutron and γ-ray transport codes have shown that in simple examples enough shielding can be provided to prevent magnet quenching. The exact geometry of the final focus magnets is still being designed. How to compactly configure the quadrupoles as close as possible to the chamber and to each other, with adequate longitudinal and radial shielding, is an optimization question which is still being addressed. Other types of magnets such as high T_c and even pulsed normal conducting magnets (for the final few magnets in the beamline) could be used, should low T_c superconductors prove to be unattractive. If high T_c magnets work and are economical, they will become the main approach rather than a backup.

Other issues include the control of gas flow up the beamlines. A combination of shutters and strong differential pumping is envisioned to prevent debris and gas from propagating down the beamline, adversely affecting beam propagation.

The questions posed in the previous sections will be addressed through a number of existing and upcoming experiments, together with sophisticated simulations. Scaled final focus experiments at LBNL have demonstrated that emittance-limited spot radii are obtainable from space-charge dominated beams for unneutralized ballistic transport, and neutralized experiments using a grid are planned. The planned High Current Experiment (1 A) will allow similar studies at line charge densities comparable to those in a driver (but at larger perveance). The NRL machine, Gamble II, has tested, and may test further, aspects of neutralized and channel transport modes using proton beams. The Integrated Research Experiments will enable definitive studies of several propagation modes and neutralization concepts at perveances and line charge densities near to or larger than in a driver. Simulations using the codes BIC, IPROP, and the latter's descendant version LSP will be carried out with realistic models for electron generation, permitting confidence in the understanding and extension of IRE-level results (100s MeV) to driver-scale results (1-10 GeV).

DPPSL and KrF

As mentioned above, the chamber, final bending and focusing optics must be protected from x- and γ-rays, from gas pressure impulses, and shrapnel from the exploding hohlraum. The mainline DPSSL and KrF approaches to IFE use direct drive targets which require laser lines of sight to the target distributed approximately uniformly in solid angle. Liquid flows are therefore not favored for first wall protection and either dry walls or liquid wetted walls are the baseline designs.

If unprotected, the first wall would receive ~0.5-5 J/cm^2 x-ray fluence per shot, ablating ~0.1 to 1 μm per shot (depending on material) off the solid wall at a nominal 5 meter radius. For IFE, ablation must be limited to << 1 nm per shot. To avoid this ablation, the chamber would be filled with Kr or Xe gas at ~ 0.5 Torr, reducing the x-ray fluence by two orders of magnitude, and reducing the ablation rate to << 1 nm/shot as required. There are two constraints on the chamber gas density. Gas breakdown by the laser occurs if the laser intensity is > 10^{14} W/cm^2 at 1 Torr. Thus at 1 Torr, breakdown will not occur until the beams propagate to ~ 1 cm of the target (but would suffer breakdown on target ~4 x 10^{14} W/cm^2). Experiments with Nike at 10^{14} W/cm^2 have shown little difference between a 0.1 Torr gas fill and vacuum propagation; experiments at 0.5 Torr show some changes, but these may be instrumental. The other constraint on the chamber gas is set by heating of the cryogenic target, which calculations show will occur if the pressure is greater than ~0.5 Torr. Experiments to explore target survivability in chamber gas have been proposed using wind-tunnels, in the near term, at a university-scale. Determining the exact pressure range where breakdown and target heating are avoided and wall protection is afforded is still a research area. Also the effects of impurities in the residual gas on breakdown need further investigation. Finally, the ablation rate has been estimated using Nova x-ray results; these results may prove to be pessimistic as the x-ray spectrum from the direct-drive target explosion differs considerably from the indirect-drive target experiments.

A second option for wall protection is to use wetted walls (Pb) as in the Promethius design (1995). Breakdown occurs at a factor of two lower density than in Kr, so ~0.5 Torr would be the maximum vapor pressure allowed during the laser pulse. Calculated recovery times indicate that the vapor pressure can be reduced to ~0.1 Torr between shots, well below the breakdown limit. To protect the final optic in the wetted wall reactor design, a Kr or Xe gas puff in a tube between the reactor wall and the optic could be used to provide the shielding from x-rays. The fill time is ~10 msec and optical distortions have been experimentally shown to stabilize after ~50 msec.

The final (bending) optic requires some protection. If a ~0.5 Torr Kr or Xe gas fill is used to avoid first wall ablation, then at the final optic (~25 m from the target) the x-ray flux would be about 6 orders of magnitude lower than in the vacuum case. The dose rate in the final optic would be dominated by the line-of- sight neutrons. The final optic would bend the laser beam and allow residual line-of-sight neutrons and gamma rays to pass into a beam dump. There are several candidates for final optic: Grazing Incidence Metal Mirror (GIMM); hot fused silica prism or grating; also, other optical materials or liquid metal mirrors could prove useful. GIMM's have a laser damage threshold of 1 J/cm^2. GIMM's will accumulate ~3 displacements per atom (resulting in an acceptable 99% reflectivity for Aluminum GIMM's) after an exposure of 2.4 x 10^{12} Rads (corresponding to an exposure of 2 x 10^4 Rad/s for 4 years at a standoff distance of 25 m.) Thus, each GIMM would need to be replaced 7 to 8 times over the 30 year lifetime of the power plant. Additional work is needed on the optical damage threshold of GIMMS versus wavelength, and with neutron exposure.

The second option for an optical material is heated fused silica (SiO_2). This has a higher damage threshold (>10 J/cm^2) than GIMM's, although the effect of radiation on damage fluence needs further investigation. As the SiO_2 accumulates neutron and gamma-ray dosage over time the absorption coefficient increases because of defects. Experiments on the SPRIII nuclear reactor at Sandia National Laboratory have begun assessing the change of absorption coefficient as a function of radiation exposure. For the drive (3ω) radiation of a DPSSL (350 nm wavelength), the absorbtion coefficient was ~ few per cent after exposures of 320 kRad neutrons and 800 kRad γ-rays obtained in 8 shots. The IFE rate is 18 krad/s in neutrons and 3 kRad/s in γ-rays, so the test was equivalent to ~20 seconds of IFE reactor neutrons. Annealing tests at 350^o C, showed the absorption coefficient between 200 and 300 nm to be significantly reduced after a few hundred seconds, and at 350 nm to be reduced somewhat. Numerical models which assume 50 kRad/s of neutron dose for temperatures between 350 and 500 degrees C indicate that the absorption coefficient at 350 nm reaches a steady state (0.04 cm^{-1} for 500^o C). Thus, the self-annealing properties of the hot-fused silica could make an attractive solution to the final optic problem. Other materials such as KDP appear to be harder to neutrons than fused silica and therefore merit further investigation. However, this potential solution is only available to DPSSL's, since the absorptivity at the shorter wavelength of KrF would be too large, even with annealing. For DPSSL's, the long term effects of radiation on the damage threshold and absorption coefficient need study. Finally, the effects on final optic of residual debris from the target explosion that is not stopped by the shutter should be evaluated.

The final focusing optic in the beamline is located approximately 50 m from the target explosion. As a result of the final bending optic, the final focusing optic receives a radiation dose primarily from scattered radiation off of the bending optic. The contribution from radiation that penetrates the neutron dumps is small. The total radiation flux is ~20 times less than at the final bending optic, so that GIMM's or heated fused silica optics could again provide the solution.

Z-pinch

Z-pinches provide a straightforward way for converting stored electrical energy in capacitor banks into x-rays which can drive a hohlraum. For the IFE application the main conceptual problem is how to deliver the energy pulse to the z-pinch repetitively in an economically attractive manner. There have been three conceptual approaches to the power feed problem: (1) recyclable transmission lines (RTL's), (2) flux compression by high velocity projectiles, and (3) ion or electron beams.

The most promising approach appears to be the RTL. Several ways have been proposed to construct the RTL. Wire webs, or sheets of material could be used to provide smooth anode surfaces. The material could be produced from stainless steel (at ~$3/kg), plastic coated with Al (~$1/kg), or solid coolant (e.g., Flibe [a salt] with a thin conducting coating, or solid lithium). The cost of material limits the mass of the RTL. For 1 GJ of generated electricity, $19 (at $0.07/kwatt-hr) of revenue are generated, limiting RTL mass to a few kg if composed of steel (for example). However, magnetic pressure in the RTL will result in electrode motion during the pulse, which results in electrode kinetic energy and increased RTL inductance. As the RTL mass is increased the electrode motion is reduced. Thus, there is a tradeoff whereby low RTL mass reduces cost, but increases RTL motion and thus decreases efficiency, and increases recirculating power. Estimates indicate that yields of 1-10 GJ will be required, with shot frequencies less than ~1 Hz and standoff distances greater than 4 m. Yields can be reduced if some of the excess magnetic field energy can be reused, e.g. by recharging capacitors with the reflected wave, but details need to be worked out.

The second option considered envisions a conical projectile to compress a conical electrode, within which an initial current has been seeded flowing in a poloidal direction. The projectile reduces the area enclosed by the current increasing the flux and driving a voltage. Ten km/s projectiles have been demonstrated and would be envisioned for this application. The disadvantage of this concept is that the area of the projectile would be quite large (~500 m^2 for typical parameters). Also, large initial seed fields and some pulse compression would also be required.

The third option considered would use electron or ion beams to power the z-pinch. In essence this requires a "reverse diode" whereby a beam is absorbed on a grid creating the potential (~8 MV) to drive the current (~60 MA) which drives the z-pinch. It may be difficult to generate and propagate such a low impedance electron beam; the possibility of current neutralization and ion stripping make ion beams more attractive. There are several issues of inverse diode operation that need to be studied. Diodes may require an initial magnetic field to keep electrons from traveling across the gap, although, it is expected that once current is delivered to the gap the self-magnetic field will perform this task. Instability-induced electromagnetic fluctuations may allow electrons to cross the gap even in the presence of a strong magnetic field, which would lower the efficiency of converting beam energy into current. However, this process also has the beneficial effect of charge neutralizing the beam within the gap allowing the use of a larger gap. Finally, the anode will become a source of ions which will be accelerated across the gap, thus requiring a clean high-Z anode to reduce the parasitic current.

Clearly, IFE z-pinches are in the concept exploration phase. More work is needed on a self-consistent reactor conceptual design, as well as more concrete RTL designs in the favored approach. Experiments on existing SNL z-pinch machines would be useful in exploring some of the fundamental questions in this concept.

<u>MTF</u>

Magnetized Target Fusion operates in a density regime that is somewhere between MFE and IFE. However, some options for MTF have similarities with respect to the chamber and standoff issues for IFE. One concept analogous to IFE, requires the injection of a ~10 cm diameter, DT gas filled metal shell into an IFE-like chamber. A conducting helical Li wire connects the top and bottom of the shell, which are separated by an insulating ring. A current through the wire is generated using charged ion beams (one positively and one negatively charged, or possibly ion and electron beams) at the poles of the shell, which create a Field Reversed Configuration (FRC) magnetic field interior to the metal shell. This allows a lower compressed line density ρr than required for IFE, requiring a lower implosion velocity. The shell is imploded using particle, laser, or plasma beams that compress and ignite the fuel. The standoff issues associated with this concept may have commonalities with ion or laser driven fusion, as beams are candidates for both magnetic field generation and ablatively driven implosion of the shell. However, the regimes are quite different than IFE, in that pulse lengths are on the order of 1 to 10 μs and the beam energies are in the 10-50 MJ, with target yields in GJ range. The exact concept for the driver needs more development.

There are other options for MTF such as magnetic, or pneumatic pressure-driven implosions, and some options under consideration may use power feed options similar to those envisioned for z-pinches. As with z-pinches, self-consistent reactor concepts for MTF are in an early stage and need further development. Proof of principle experiments on high density FRCs using single shots and liner implosions are being considered to address basic feasibility issues of MTF.

Question 2C: What would convincingly demonstrate that each driver concept is a viable driver candidate for IFE? Specifically, what is a convincing Integrated Research Experiment (IRE) for each driver candidate?

Session Leader: **Rick Spielman**
Speakers to lead discussions:

HIF	Roger Bangerter
LiF	Mike Cuneo
DPSSL	Howard Powell
KrF	John Sethian
Z-pinch	Steve Slutz

Session Summary (Rick Spielman)

Definition of an IRE

The first thing that this question raised was the need to clarify (at least to the participants) the IFE road map. The participants pointed out the need for clear milestones and metrics for all levels of the road map. The suggestion was made that motion from one level of the road map to another should be based on universal performance metrics.

There were spirited and candid discussions on the area of metrics and milestones concerning how one defines key parameters such as cost and efficiency needed for an IRE. One real question is demonstrated vs. projected performance. Also, there was a difference of opinion on what level of performance an IRE needed to have. The DPSSL and KrF teams argued that an IRE should demonstrate all of the technology and physics of the driver by building a single module of a fusion driver. This would validate driver technology, transport performance, and cost. The Heavy Ion team argued that only scaled experiments are necessary and that an IRE need not have the parameters of a single module of a fusion driver only the results need be scaled to reactor driver parameters. A Heavy Ion IRE would have a lower voltage, a lower current, a different ion, and could not conduct full-scale transport experiments. The definition of an IRE needs to be settled prior to a decision on moving forward on the road map.

HIF IRE

HIF supporters described their roadmap to an IRE as based on experiments from a number of facilities around the world and from calculations. The HIF IRE is a facility to validate the metrics of HIF and to make engineering and physics improvements. It was also suggested that the HIF IRE be a flexible research tool. The proposed HIF IRE has the following proposed performance parameters: Kr^{+1} ions, 200-MeV energy, 1 kA current, a total beam energy of 30 kJ, and a 335 ns pulse length bunching to 5 ns. A summary of the issues presented is given below:

(1) Scaled beam experiments have been performed with brightness exceeding the requirements for a fusion driver. Other beam requirements are met with scaled dimensionless parameters.
(2) The ETF/DEMO driver requirements determine the IRE goals. This includes beam quality, cost, beam neutralization, etc.
(3) The cost goal of $150M for the IRE requires improvements in the state-of-the-art of accelerator technology.
(4) At a minimum the IRE must validate the expectation of beam coupling. Exploring other target issues is desirable.
    1. Beam target physics at $3x10^{12}$ W/cm^2
    2. Focussing experiments
    3. Beam dynamics
    4. HIF target concepts

<u>DPSSL IRE</u>

The DPSSL program optimism is based on recent laser technology development and direct-drive target experimental results. The DPPSL testbed "Mercury" was initiated with DP/LDRD funding at LLNL. With 100 J of energy, Mercury will be able to validate many of the laser physics and engineering assumptions that are being made today, during a Phase 1 (PoP) program.

Because of the extensive work in the area of Nd:glass laser technology the real issues that impact DPSSL's are those relating to the DPSSL components and amplifiers needed for high rep rate. Also the cost of DPSSL's are now at ~ $3.00 per W or 6x higher than needed for an IRE.

Mercury's goals are:

a. Demonstrate efficiency
b. Test gas cooled amplifiers
c. Test new laser crystals
d. Test rep rated architecture
e. Demonstrate beam quality
f. Demonstrate efficient frequency conversion

Mercury will not test full size apertures.

The IRE, if the Phase 1 goals are met, would address integrated performance, segmentation issues within a beamline, vendor development, beam transport, optics survivability, target tracking, and materials tests. Cost is the major issue for DPSSL's, but it is not unreasonable to expect reductions in cost as commercial applications of DPSSL's grow. The cost of a DPSSL IRE is estimated to be $50M - $100M, following a $40M Phase 1 (PoP) program.

<u>KrF Laser IRE</u>

The next step in the KrF laser program is the construction of a Phase 1 (PoP) laser called "Electra" by ~ CY 2003. This laser would be relatively small but would demonstrate most of the key technologies needed for the IRE. The Electra parameters are planned to be: 5 Hz rep rate, 30-cm aperture, and 700 J. The key Phase 1 issues are:

a. Rep rate
b. Durability
c. Beam quality
d. Cost
e. Efficiency
f. Continued IRE systems studies

The proposed IRE performance parameters are: 150-kJ energy, η ~ 6-7%, 5 Hz, $3x10^8$ shots (10^{10} lifetime), $225/J costs, with a total IRE cost of $50M - $100M. The key issues that must be successfully addressed before proceeding to an IRE are efficiency and lifetime.

Z-pinch IRE

Z pinches are a new concept for IFE. The immediate attraction of the concept is the low cost of the driver and the high efficiency of converting stored electrical energy to x rays (15%). Recyclable transmission line concepts have been proposed to solve the standoff issue; these were discussed in the Standoff Session and in the IFE Power Plants Session.

The z-pinch IFE concept is presently in the Concept Exploration Phase and would be expected to remain there for a few years. Note that z-pinch physics issues and ICF issues are being address through DP funding. Besides standoff, the major deliverable prior to moving toward a PoP Phase would be a comprehensive reactor system study. Phase 1 (PoP) deliverable would address rep rate in pulse power and stand off at the 0.1 Hz, 20-MA level.

LIF IRE

LIF is a long time IFE concept that has been unable to demonstrate adequate non-protonic beam intensity. Recent analyses have shown that this was primarily due to the lack of a pure ion source. Low-level Concept Exploration work has been proposed that would focus on the ion source issue. Subsequent Phase 1 work could be accomplished on existing Sandia pulsed power devices (RHEPP 1, RHEPP 2, HERMES III). The key metric for proceeding to Phase 1 would be the demonstration of a pure ion source. The advantages of efficiency, cost, and an attractive power plant scenario with standoff are the impetus for continuing the effort.

IRE Summary Comments

The presentations for the driver candidates gave their individual plans leading to an IRE. The laser presenters (DPSSL and KrF) suggested that they are now beyond the Concept Exploration phase and are ready to proceed with Phase 1 Proof-of-Principle (PoP) experiments. In the case of heavy ions, which are currently engaged in PoP development, the argument was made that the next step is an IRE. The other concepts, z-pinches and light ions, remain in the Concept Exploration phase.

Subgroup 3: Inertial Fusion Power Plant Concepts

Ken Schultz, Robert Peterson, Per Peterson

Inertial Fusion Power Plant Concepts Summary (Ken Schultz)

An IFE Power Plant concept is the integrated choice of a target, a driver, a reaction chamber, and a heat transport/power conversion system. The target options are direct or indirect drive, and the specific target designs are strongly driven by the physics requirements and the choice of driver, although target fabrication and injection issues, compatibility with the chamber design and environmental issues must also be considered. Options for the driver to heat and ignite the target are heavy ion beams, lasers, light ions and pulsed power sources such as z-pinches. Three major categories have been explored for chambers to contain the target explosions and convert the x-ray, debris and neutron energy from the explosion to heat: dry-wall designs, wetted-wall designs, and thick liquid-wall concepts. For each of these options a variety of material choices and configurations have been explored. Heat transport and power conversion systems that have been considered include flowing liquids (Flibe, LiPb, Li), flowing solids (Li_2O) and various coolants (He, H_20). Rankine (steam) and Brayton (gas turbine) power conversion cycles have been considered.

Each driver has a choice of target and chamber options, and the characteristics of the drivers appear well suited to selected options. The heavy ion beam driver is well-suited to indirect-drive targets and the thick liquid wall chamber concept, for example, the HILIFE-II design. The high efficiency of the heavy ion accelerator accommodates lower indirect-drive target gains, and the short standoff of the liquid chamber concepts eases beam focus requirements. Wetted-wall chambers like OSIRIS also match well with heavy ion beam drivers. Laser beam drivers like the KrF or solid state lasers are well suited to direct drive and dry-wall chamber designs like SOMBRERO. The higher gain of direct-drive targets eases concerns about low laser efficiencies, and the longer stand-off of lasers allows use of a larger, simple chamber with reduced concern about final optic protection. The wetted-wall chamber concept is also possible with laser beam drivers, as exemplified by the KOYO design. The “main line” IFE power plant concepts thus appear to be settling down to two: the heavy ion beam driver with indirect-drive targets and a thick liquid-wall chamber, and a laser beam driver with direct-drive targets and a dry-wall chamber, both with a wetted-wall chamber as a “back-up” option.

Several IFE “Exploratory Concepts” also exist that either have identified technical hurdles or that have been little studied, but should be kept in mind. Light ion beam drivers offer the potential for high efficiency and low cost, but have been unable to overcome ion source limitations. Ideas exist for ion sources (possibly with “middle weight” carbon ions) that may overcome this limitation. The wetted-wall chamber concept appears well-suited to light ion fusion. The “fast ignition” concept involves using “conventional” target implosion to compress a cold target to high density and a separate igniter beam of extreme intensity to initiate a propagating fusion burn in the compressed target. The physics of laser interaction with matter at these extreme conditions are little explored, but if fast ignition proves to be real, it offers the intriguing possibility of very high target gains (~500) for low input energy (~500 kJ), which could make possible both an improved fusion power plant product, and a lower cost development pathway. Depending on the target and driver configuration, fast ignition might use dry-wall, wetted-wall or liquid-wall chamber concepts. However, a key unexplored issue is delivering the fast ignitor beam in the chamber environment. The z-pinch has made tremendous progress in the past year and offers large x-ray energy with high efficiency and low cost. Concepts exist for using this energy as a driver for inertial fusion and, if successful, might be rep-rated to form the basis for an IFE power plant. This potential driver, and the related Magnetized Target Fusion concept which uses a liner to compress a magnetically confined plasma, could use a thick liquid-wall or possibly solid Li with voids and a density gradient for shock dissipation.

Clearly, there are several viable target options for IFE. The proper choice varies from driver to driver, and each driver could be coupled with several chamber options. The major technical issues for IFE target chambers can be divided into four areas: chamber dynamics, chamber materials, liquid hydraulics, and neutronics, safety, and environment. The Snowmass participants discussed these areas in depth, identifying the key technical issues. Many of the technical issues can be investigated in existing ICF or MFE facilities and programs, or in small-scale "university type" laboratory experiments, thus allowing progress in IFE chamber development to proceed with modest funding.

Issues exist for IFE target fabrication and injection that must be resolved for IFE to be a practical energy alternative. For indirect-drive HIF IFE, target fabrication is the main issue. Significant design and development work is needed on fabrication of the distributed radiator hohlraum/beryllium capsule target. For laser direct-drive IFE, target survival during injection is the main issue. Thermal protection of the capsule is essential and will require serious re-evaluation of the dry-wall target chamber concept.

IFE chambers and targets are key features of an IFE power plant. Numerous issues exist that must be resolved for IFE to be a practical energy alternative. However, numerous possible solutions also exist that appear attractive. It is essential that close coordination be established between the target designers, the chamber developers, the target fabricators, the target injection system designers, and the safety and environment worriers. The basic approach that is recommended is to take maximum advantage of the work that is being done by the ICF Program for the NIF. In parallel, we must carry out IFE design studies on selected issues and modest scale laboratory development activities to demonstrate and select the appropriate options. This effort is expected to result in the demonstration that a credible pathway exists to practical IFE chamber design and target fabrication and injection with a high probability of success. This information will contribute to the decision in about 2003, or later, of whether or not to proceed with an IFE IRE and if so, what technologies to use. These will then be applied to the IRE, demonstrating many of the chamber and target technologies needed for IFE.

Following are summaries of the three sessions on Inertial Fusion Power Plant Concepts.

Question 3A: What are the key IFE power plant concepts, advantages, and issues?

Session Leader: **Robert Peterson**
Speakers to initiate discussions:

HIF power plant concepts	Wayne Meier
LIF power plant concepts	Robert Peterson
DPSSL and KrF power plant concepts	Gerald Kulcinski
Z-pinch power plant concepts	Mark Derzon
MTF power plant concepts	Kurt Schoenberg

Session Summary (Robert Peterson)

This session addressed the question of what are the major design concepts, what are their advantages and key issues. There was some question as to the meaning of "key". One interpretation is issues that can invalidate the concept or effect its attractiveness as a power plant concept. This session was organized as a series of talks by advocates of different types of IFE power plants arranged by driver type, with ample time for discussion and questions. The discussions were generally constructive in pointing out issues and suggestions for how a concept could be improved. There were some members of the MFE community present. As a result of the presentations and discussions, a list of issues was defined. We have organized the issues and driver type into Table 9. Based on the discussions during the sessions some elements in this matrix are defined: others are not.

Wayne Meier presented a summary of Heavy Ion Fusion power plants, which consisted of one thick-liquid design and three wetted-wall designs. The advantages of thick liquid protection (HYLIFE-II) are the plant structure lifetime, the need for a greatly reduced materials program, the projected low cost of electricity and low tritium inventory. There are unresolved issues of liquid jet hydraulics, chamber dynamics, driver cost, Flibe dissociation, corrosion and cleanup, the lifetime of hardware, tritium control, and diagnostics. It is clear from this list that, even though HYLIFE-II is currently the best funded IFE power plant concept development effort, it has more issues than can be addressed in the current program. The attractive features of the wetted-wall concepts (HIBALL, OSIRIS, Prometheus-H) are lower pumping powers, rapid replacement of flow control devices, low activation, resistance to x-ray and debris damage, and the possibility of adaptability to laser fusion. Issues include fabricability of wetted structures, wetting mechanisms, flow around penetrations, rep-rate, maintenance and tritium recovery. The list of issues is substantial and there are currently no efforts on wetted wall concepts in the US. It was suggested that both thick-liquid and wetted-wall concepts could benefit from new data on PbLi, Flibe and SnLi.

Bob Peterson presented a summary of Light Ion power plants. Work on LIF has been placed on hold in the US because of ion source problems and the growing interest in z-pinches, although it could be revived with perhaps a different ion species. Beam transport issues were thought to be the most difficult issue in the LIBRA series of LIF power plants, so each was designed around a particular transport method: LIBRA used preformed channels; LIBRA-LiTE used neutralized ballistic; and LIBRA-SP used self-pinched channels. All three concepts are wetted walls and have similar chamber issues to

Table 9. IFE Power plant concepts.

Type	Plant Concept	Stand-off	Driver Cost	Driver Energy	Target Yield	Driver Eff.	Thermal Eff.	Materials
HIF	HYLIFE-II HIBALL OSIRIS Prometh.-H	HI transport	High Cost code	Low-Med.	Low – Med.	High	Med.	Flibe/SS PbLi/SiC Flibe/C Pb/SiC
LIF	LIBRA LIBRA-LiTE LIBRA-SP ADLIB UTLIF	LI transport	Low Expert costing	Med.	Med.	High	Med.	PbLi/SiC Li/SS PbLi/SS
Laser Fusion	SOLACE HYLIFE SOMBRERO Prometh.-L	Mirrors/ Lens Survival	Med. –High Cost code	1 – 4.5 MJ	150 - 1800	5% - 12 %	39% - 55 %	LiO_2/C Li/SS $LiAlO_2$/SiC PbLi/SiC
Z-Pinch	---	Recycled Trans. Line	Low	High	Very high	High	?	Li/SS
MTF	---	---	Low	High	Very high	High	?	Li
Type	Wall Protection	Materials Recycle	Target Inject.	Develop Cost	ES&H	Avail.	Unit Size	Maintain.
HIF	Thick liquid Wetted wall	---	pneuma tic	IRE ETF	Flibe Low T_2	---	2-4 GWe	Good
LIF	Wetted wall	---	pneuma tic	---	---	---	300-1000 MWe	Good
Laser Fusion	Thick liquid Gas Granular	---	pneuma tic	NIF IFE ETF	C High T_2	---	700-1000 MWe	Good
Z-Pinch	Thick liquid	---	With MITL	Z ZX X-1	---	---	---	---
MTF	Thick liquid	---	---	---	---	---	---	---

the wetted wall HIF concepts. The allowed gas density in the chamber is generally high in the LIF concepts so rep-rate issues are not as extreme. The unique issues of LIF power plants are beam generation and transport. The advantages of LIF are high efficiency, low-cost pulsed power, and the demonstrated rep-rate of ion drivers. There is currently no effort in the US on LIF power plants, but some of the ideas could be applied to other IFE.

Jerry Kulcinski summarized the state of laser fusion power plants. Because of the relatively low efficiency of KrF drivers, the higher-gain direct-drive targets were chosen over indirect-drive. This led plant designs away from thick-liquid chamber concepts. Fear of liquid condensation on laser optics led the designs to gas-protected walls. Gas protection involves the use of a gas that is dense and thick enough to stop the most penetrating ions and x-rays from reaching the target chamber wall. The SOMBRERO design uses 0.5 Torr of Xe gas in a 6.5 m radius chamber to stop 1.6 MeV C ions from the ablator of the target. A fireball is formed in the gas by the x-ray and ion energy deposition that radiates energy to the graphite wall over about 0.1 ms, a time that is long enough for conduction in the graphite to keep the temperature low enough to avoid erosion of the wall. The critical issues of this concept are the target emissions, the fireball behavior, the first wall heat conduction, tritium retention in the wall, and target injection through the gas. The advantages of gas protection are no vapors to condense on the laser optics and the ability to handle many penetrations. Prometheus-L is a wetted wall concept for lasers. Liquid metal grazing incidence mirrors would allow some vapor to be in the target chamber, though most laser designers would prefer that no vapor was present. Tritium retention is a major safety issue, but it was pointed out that high temperatures in the graphite of SOMBRERO would reduce the tritium retention. New two-sided illumination targets would lead to new chamber concepts. Finally magnetic protection of the wall was suggested as a way of reducing the chamber gas density.

Mark Derzon summarized the sate of z-pinch drive IFE power plants. Z-pinches have the major advantage of being tolerant of dirty chamber conditions. The concept, so far un-named, uses re-cycled Flibe and Al transmission lines to carry current to the target. This standoff issue is quite different from HIF, LIF and lasers in that there is no transport required through gas. The transmission lines and target are rapidly inserted into a Li pool with steel walls. The blast, which would be of high yield, is contained in the liquid, which is dumped into the basement after the shot. There it is fed into heat exchangers, tritium extraction and materials recycling equipment. The concept is new, so there are many issues yet to be resolved, but the fact that it does not require a pristine chamber environment avoids problems that are a constant worry in other concepts. Several suggestions were made for improvements to the concept, such as bubbles in the liquid to mitigate shocks. Z-pinch fusion could also have a less expensive development path because of the low cost of pulse power.

The final talk was by Kurt Schoenberg on magnetized target fusion. This talk was more on the promise of MTF than on a specific power plant concept. MTF combined some advantages of IFE and MFE. MFE can be explored on existing or soon to exist machines without the need for a dedicated facility. Two old power plant concepts for liners (FLR and Linus), traditional IFE chamber concepts, and the SNL z-pinch power plant concept may all be adaptable to MTF. There is a wide range of target yields that might be attractive for a power plant. Attractive power plants are possible at lower gain than usual for IFE. Target fabrication may also be easier.

In summary, there are several viable target chamber options for IFE. The proper choice varies from one driver type to another, and in fact each driver type could be made to work with multiple chamber options. There are many issues for each of the chamber options, because the IFE chamber technology program has been very small. It is hoped that a new IFE chamber technology program will be developed that will begin to address some of these issues systematically. A new technology program should balance resolution of issues on older concepts with development of new ones. Care should be taken to keep the three main concepts (thick liquid, wetted-wall, and gas-protected) in the development path. Magnetic protection and granular flows should also be kept in play. It has been many years since a new IFE power plant concept has been developed in the US. New technologies and new driver and target constraints have appeared in the mean time. Therefore, there should be some effort into updating old concepts and developing new concepts.

Question 3B: What are the key scientific issues for the fusion chamber (e.g., first wall protection, …) and what are the proposed solutions? What experiments could be done to test the relative merits of these solutions?

Session Leader: **Per Peterson**
Speakers to initiate discussions:

Chamber concepts summary	Mark Tillack
Chamber dynamics for IFE	Robert Peterson
Chamber materials for IFE	Everett Bloom
Liquid hydraulics	Per Peterson
Neutronics, activation, safety	Jeff Latkowski
Chamber development path	Wayne Meier

Session Summary (Per Peterson)

The IFE target chamber must provide the interface between the target, the drive, the blanket and the balance of plant. The chamber concept selection and design will have major leverage on the attractiveness of an inertial fusion energy power plant. Target chamber systems for inertial fusion energy (IFE) must:

- regenerate chamber conditions for target injection, driver beam propagation, and ignition at sufficiently high rates (i.e. 3 - 7 Hz);
- protect chamber structures for several to many years (ideally the life of the plant, ~30 yr.) or allow easy replacement of inexpensive modular components;
- extract fusion energy in a high-temperature coolant and produce tritium; and
- reduce the volume of radioactive waste generation and reduce possible release fractions low enough to meet no-public-evacuation standards.

Because the target chamber is a relatively small fraction of the total capital cost of an IFE power plant (9% – 12%), the target chamber influences the cost of electricity primarily through the driver-target coupling, controlling the required driver energy; through the plant availability and safety, and through controlling waste generation. Beyond making IFE technically and economically feasible, target-chamber research provides the potential for substantial leverage to reduce the IFE cost of electricity.

Driver standoff provides a major input for chamber technology selection. Because laser beams can be focused accurately at long distances and because laser final optics rely on standoff to control x-ray and debris damage, laser IFE chamber concepts have gravitated toward dry-wall designs, as shown in Fig. 2, which can produce minimal debris mobilization. Solid walls introduce issues related to neutron irradiation damage, which can be controlled by optimizing the chamber size, taking advantage of the reduction of neutron fluence obtained with the square of chamber radius, and by use of rapidly replaceable blanket structures and re-use of the blanket breeding material. Heavy ion drivers, light ion drivers, z-pinches, and magnetized target fusion (MTF) perform best when the standoff distance is minimized. This provides motivation to pursue thick-liquid chambers, where liquid jets can be located within tens of centimeters of targets to provide shielding of chamber structures (Fig. 2). The time required for gravity clearing of the chamber after a shot can pose a rep-rate limit, which can be circumvented by using oscillating flow streams to sweep the chamber, dynamically clearing it of droplets from the previous shot. For all of the driver options, wetted-wall chambers with flow-guiding structures provide an intermediate option, simplifying liquid hydraulics questions at the expense of higher neutron damage to the flow structures and, for lasers, at the expense of potential optics contamination from liquid evaporation.

The major technical issues for IFE target chambers can be divided into four technical subtopics: Chamber Dynamics, Chamber Materials, Liquid Hydraulics, and Neutronics, Safety and Environment. The Snowmass participants discussed these areas at depth, identifying the key technical issues summarized in Table 10. Many of the technical issues can be investigated in existing ICF or MFE facilities and programs, or in small scale, "university type" laboratory experiments, thus allowing progress in IFE chamber development to proceed with modest funding.

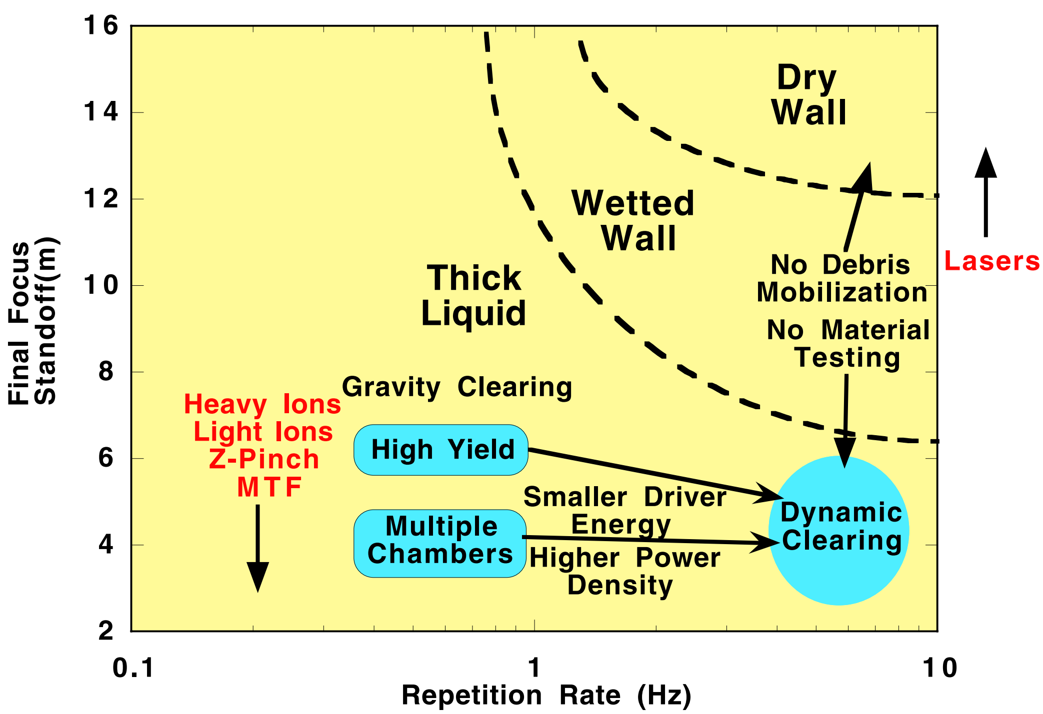


Figure 2. Driver stand-off characteristics will influence chamber selection.

Table 10. IFE Target Chamber Issues (Possible near-term approaches in parenthesis).

Research Area	Thick Liquid	Wetted Wall	Dry Wall
Chamber Dynamics	Target induced impulse loads to liquid Condensation of target and ablation debris by droplet sprays (Z-pinch, university experiments)		Direct-drive target emission Fireball re-radiation or magnetic diversion of target ions (Z-pinch experiments)
Chamber Materials	Corrosion, hohlraum material recovery from coolant No requirement for fusion neutron source	Fusion neutron effects on flow structures	Fusion neutron effects on structures (materials development parallels MFE efforts)
Liquid Hydraulics	Formation of free jets Pocket disruption and droplet clearing (water experiments with scaled impulse loads)	Liquid film formation and stability (small-scale experiments)	
Neutronics/ Safety/ Environment	3-D modeling of final focus neutron and gamma irradiation Hohlraum, coolant and structure materials activation Accident mobilization and off site dose minimization Waste minimization (mobilization experiments with liquid coolants)		

Question 3C: What are the issues in target fabrication, target characterization, target injection, target robustness (e.g., tolerances), and what is the path for addressing them?

Session Leader: **Ken Schultz**

Speakers to initiate discussions:

Target physics requirements	Max Tabak and Debra Callahan-Miller
Target fabrication issues	Warren Steckle
Target injection issues	Gottfried Besenbruch and Ron Petzoldt
Possible development paths	Ken Schultz

Session Summary (Ken Schultz)

The goal of these discussions was to consider the target fabrication and injection requirements for the power plant concepts being developed for both direct-drive and indirect-drive IFE, and to identify the pros, cons, issues and opportunities associated with each concept. We hope that the results of these discussions will contribute to the eventual selection of a limited subset of these target concepts and development of their fabrication and injection technologies for application to IFE.

This topic had strong interaction with the Targets Subgroup. This Session of the Inertial Fusion Power Plants Subgroup focused on what to do for IFE target fabrication and injection, and the companion afternoon IFE Target Technologies topic group focused its discussions on how to do IFE target fabrication and injection.

Description

At the heart of an inertial fusion explosion is a target that has been compressed and heated to fusion conditions by the incident driver energy beams. For direct drive, the target consists of a spherical capsule that contains the DT fuel. For indirect drive, the capsule is contained within a cylindrical or spherical metal container or “hohlraum” which converts the incident driver energy into x-rays to drive the capsule. The “Target Factory” at an inertial fusion power plant must produce about 1-2 x 10^8 targets each year, fill them with deuterium-tritium fuel, layer the fuel into a symmetric and smooth shell inside the capsule, and deliver the completed target to the target chamber at a rate of about 5 Hz. These fragile targets must be injected to the center of the target chamber, operating at a temperature of 500 - 1500°C and possibly with liquid walls, without mechanical damage from handling and acceleration, or thermal damage from the hot target chamber environment. Target fabrication must be done with extreme precision of manufacture, extreme reliability of delivery and at a manufacturing cost four orders of magnitude lower than current ICF target fabrication experience. Target injection must be done with precision, and reliability of delivery and without damaging the mechanically and thermally fragile targets. The choice of power plant concept, chamber design and protection scheme, and target design all impact the target fabrication and injection challenges. These challenges do appear to be achievable, but will require a serious — and successful — development program.

Target Physics Requirements

Debbie Callahan-Miller described the physics requirements, materials and design options, and current designs for indirect drive HIF targets. Both direct and indirect drive targets were also discussed thoroughly during the IFE Targets subgroup of the IFE Concepts sessions.

The current leading direct-drive target design promises high gain (~130) and consists of a CH capsule with low density CH foam inside and a thin high-Z coating outside. The foam is ~100-250 µm thick, is filled with solid DT and surrounds an additional ~100-200 µm of pure DT. This design appears simple and should be fabricable by techniques already explored in the ICF target fabrication program. However, there is still some physics uncertainty associated with the design and the fabrication tolerances (foam cell size and allowed material, density and dimensional variations) have not been explored. The thermal protection of this target may be favorable in that it has a thin outer layer of high-Z material that could potentially be highly reflective to thermal radiation. However, the fabrication technique for, and properties of this layer, have not been determined.

The current leading candidate design for indirect-drive HIF targets utilizes a low density distributed radiator in the hohlraum walls to convert heavy ion beam energy to the x-rays that compress the capsule. It promises high gain (~50-130) by use of a "close-coupled" design with the hohlraum fitting closely around the capsule, and a beryllium capsule. Concern was expressed over how to fabricate the low density, high-Z radiator materials, which do not have an ICF target analog. Callahan-Miller pointed out that a number of alternate material choices are possible and suggested that a number of techniques might work to achieve the low density, including foams, fibers and foil layers. Dimensional tolerances need to be defined, but are almost certainly less stringent than those of capsules, and no more strict than what must be achieved for the NIF. The beryllium capsule is similar to capsules being developed for the NIF, but low cost fabrication techniques and low tritium inventory fill techniques for mass production have not been identified. A high density plastic, such as polyimide, could be substituted for the beryllium ablator for a modest increase in driver energy.

Target Fabrication

Ken Schultz pointed out that targets currently fabricated for ICF experiments have many of the characteristics that will be needed for IFE, although the size is smaller (capsule diameter ~ 0.5 mm for Nova, ~ 1 mm for Omega and ~ 2-3 mm for the NIF vs. ~4-5 mm for IFE). The current ICF target fabrication techniques were not intended to be particularly well-suited to economical mass production of IFE targets. For a power plant to be economically competitive, the target cost for a ~500 MJ yield target must be ≤$0.30. However, some of the current ICF fabrication processes do extrapolate well to economical IFE and design studies suggest alternatives for those that do not. Specific target fabrication techniques were discussed further during the afternoon IFE Target Technologies sessions.

All current IFE target designs require low density components of various kinds for the converters, hohlraums or capsules. A potentially attractive way to achieve these low densities is to use foam materials for these components. Warren Steckle reviewed the many possibilities for materials composition, morphology and configuration that are available with foam materials. The next logical steps in fabrication of IFE targets is to understand the physics design requirements, select the materials and develop the fabrication processes.

Target fill and layering are important steps in the target fabrication process that will have a large impact on the overall attractiveness of IFE power plants. Gottfried Besenbruch discussed these issues as part of the afternoon IFE Target Technologies sessions. Targets for ICF experiments are filled by permeation and a uniform DT ice layer is formed by a process known as "beta layering". By use of very precise temperature control, excellent layer thickness uniformity and surface smoothness of about 1 μm RMS can be achieved. These processes are suited to IFE, although the long fill and layering times needed may result in large (up to ~10 kg) tritium inventories. Permeation filling of beryllium capsules may be particularly challenging.

DT layer smoothness is a potential performance limitation for IFE. The smoothness needed for NIF indirect drive plastic ignition targets appears to be very close to the limits of smoothness that can be achieved by beta layering. If IFE targets need DT ice smoothness better than ~1μm to achieve high gain, new layering techniques will be needed, such as the infra-red and microwave heating techniques that have so far shown about a factor of 2 improvement in DT ice surface smoothness. Since IFE targets have thicker DT ice layers than NIF ignition targets, they may be more tolerant of ice roughness. Use of polyimide or beryllium capsules may relax the surface smoothness required by factors of several. Since the ignition curve is very sensitive to smoothness, a small variation in surface roughness might make a large difference in target gain. If the target gain is significantly reduced or if it is highly variable from shot to shot, this would be a performance limitation for IFE.

Target Injection and Tracking

Preliminary design studies of target injection for both direct-drive and indirect-drive IFE power plants were done as part of the SOMBRERO and OSIRIS studies completed in early 1992. The direct-drive SOMBRERO design proposed a light gas gun to accelerate the cryogenic target capsules enclosed in a protective sabot. After separation of the sabot by centrifugal force, the capsule would be tracked using cross-axis light sources and detectors, and the laser beams were steered by movable mirrors to hit the target when it reached chamber center. Target steering after injection was not proposed. The indirect-drive OSIRIS design proposed a similar gas gun system for injection and crossed dipole steering magnets to direct the beams.

Ron Petzoldt summarized the work done to develop injection and tracking systems. A gas gun indirect drive target injection experiment was done at LBNL. The results showed that relatively simple gas gun technology could repeatable inject a non-cryogenic simulated indirect drive target to within about 5 mm of the driver focus point, within the range of laser or beam steering mechanisms to hit, but not sufficient to avoid the need for beam steering to achieve the ±200 μm accuracy needed. The LBNL experiment also demonstrated target tracking and real time target position prediction which approximately meets the ±200μm accuracy needed. Experiments with the same gas gun using a simple magnetically separated sabot showed simulated room temperature direct drive targets could achieve the same placement accuracy. Direct drive will require ±20 μm target tracking and beam steering accuracy. The choice between beam steering and target steering should be studied.

Thermal protection of the cryogenic targets as they are injected into the high temperature target chamber is a serious concern for IFE power plants. For indirect drive, the hohlraum will provide adequate thermal insulation for the capsule. For direct drive, reflective coatings will reduce the radiation heating of a target and are actually part of the current leading direct drive target design. The SOMBRERO dry-wall chamber used 0.5 Torr of Xenon gas to reduce the rate at which x-ray and plasma energy would be deposited on the chamber wall surface. This kept the chamber surface temperature excursion below the value for which significant ablation would occur. However, chamber gas at this pressure is sufficient to change the position of a direct drive target by order of 20 cm and require in-chamber target tracking. With high reflectivity targets and gas filled chambers, the majority of the target heating will be from the gas rather than from radiation. We do not have a reliable model for the gas heating of a target in the pressure, temperature, and target speed regimes we expect to operate in. The reduced x-ray emissions from current low-z target designs may reduce the requirement for a protective gas in the chamber and should be evaluated. We also do not know with certainty what temperature profile will be required to avoid changes in the target that would reduce target gain. These are two important areas for near term study. A wetted chamber wall design such as was used in OSIRIS, Prometheus and Koyo could eliminate the need for a chamber gas. The use of magnetic fields to divert the charged particle debris from the wall should also be investigated.

<u>Development pathway</u>

IFE Target Fabrication and Injection are part of the IFE Roadmap. Ken Schultz summarized the current plans. Activities are divided into Phase I, planned over the next 4 years (FY00-03), and Phase II, planned for the following 9 years (FY04-12) when the IFE Integrated Research Experiment(s) (IRE) will be built and operated.

During Phase I, we will carry out the following tasks to support the decision as to whether to proceed with the IFE IRE, and if so, what target technologies to use:

Target Fabrication

- Work with target designers and chamber developers to select promising target designs that optimize target gain, robustness and cost.
- Develop materials for IFE target requirements, such as robust foams, doped ablators and distributed converter hohlraums for HIF.
- Develop mass production techniques by reviewing and identifying suitable industrial technologies (such as microencapsulation, fluidized bed coaters, injection molding of hohlraum parts, etc.), demonstrating on the lab bench that they can achieve the accuracy needed, and projecting that they can meet IFE coat goals.
- Develop statistical quality control characterization concepts.

Target Injection

- Work with target designers and chamber developers to select promising target and chamber designs and to define their injection requirements.
- Select, design and develop the target injection systems best suited for direct drive and indirect drive targets.
- Demonstrate injection and tracking of simulated targets at room temperature.
- Measure the thermal response of cryogenic targets and demonstrate methods for thermal protection in the laboratory.

During Phase II of the IFE Roadmap, we will carry out the following tasks:

Target Fabrication

- Carry out bench scale tests of IFE target production processes.
- Evaluate proposed and alternative processes for accuracy, reliability/repeatability and cost.
- Provide prototype targets for experiments on the IRE.

Target Injection

- Add cryogenic target capability and a high temperature surrogate target chamber to the Phase I injector-tracking system for injection experiments.

- Provide a target injection-tracking system to the IRE for integrated system experiments.

The cost of this IFE Target Fabrication and Injection development activity, which is part of the IFE Chamber and Target Element of the OFES Virtual Laboratory for Technology, is estimated to be approximately $3M/yr for 4 years (FY 2000 - FY 2003) to complete Phase I. The costs for Phase II can be estimated when the driver choice(s) for the IRE have been made.

Conclusions

IFE target fabrication, fill, layering, injection and tracking are key features of an IFE power plant. Numerous issues exist that must be resolved for IFE to be a practical energy alternative. However, numerous possible solutions also exist that, at least on paper and in design studies, appear attractive. For indirect-drive HIF IFE, target fabrication is the main issue. Significant design and development work is needed on fabrication of the distributed radiator hohlraum/beryllium capsule target. For laser direct-drive IFE, target survival during injection is the main issue. Thermal protection of the capsule is essential and will require serious re-evaluation of the dry-wall target chamber concept. It is essential that close coordination be established between the target designers, the chamber developers, the target fabricators and the target injection system designers. The basic approach that is recommended is to take maximum advantage of the target fabrication, fill and layering work that is being done by the ICF Program for the NIF. In parallel, we must carry out IFE design studies on specific components and issues, and modest scale laboratory development activities to demonstrate and select the appropriate options. This effort is expected to result in the demonstration that a credible pathway exists to practical IFE target fabrication and injection with a high probability of success. This information will contribute to the decision in about 2003 of whether or not to proceed with an IFE IRE and if so, what technologies to use. These will then be applied to the IRE, demonstrating many of the target fabrication and injection technologies needed for IFE.

Subgroup 4: IFE Metrics and Development Paths

(Wayne Meier, John Perkins)

IFE Metrics and Development Paths Summary (Wayne Meier)

This session of the IFE working group covered two related topics: the IFE development path for various driver options and the metrics by which options are judged to be ready to advance to the next stage of development.

Following are summaries of the two sessions on Metrics and Pathways.

Question 4A: What are the metrics for an entire IFE system for each step of development (e.g., concept exploration, proof of principle, performance extension, fusion energy development, DEMO, attractive commercial fusion power plant)? How are these incorporated into the IFE Road Map? How do we insure that there is a mechanism in place for new concepts to initiate a development path?

Session Leader: **John Perkins**
Speakers to initiate discussions:

FESAC Metrics	Charles Baker
Deliverable metrics, IFE Road Map and mechanisms for new concepts	John Perkins

Session Summary (John Perkins)

The IFE "roll-back" road map and metrics were discussed in an IFE plenary session. Critical issues were posed as four questions: What is the proposed development path that rolls back from the attractive power plant? What are the objectives at each stage of the road map? (attractive reactor, DEMO, ETF, IRE, PoP, CE). What are the decision/performance metrics that permit concepts to be promoted from stage to stage? How do we formally accommodate new initiatives/innovations into the development path at the exploratory concept level for both advanced physics and technology? To resolve critical issues, it was proposed to direct an IFE "tiger team" to condense present goals into a unified, concise "bible" containing objectives and decision metrics for each stage of the development path for all concepts.

Regarding new concepts, a possible formalism for accommodating new ideas at the Concept Exploration level was suggested. A possible plan might have:

(1) New funding starts every year with a recognized date for calls and submissions; reviewed every year.
(2) Competition for seed money in one of two tiers, say, $50k - $300k, and $300k - $3M .
(3) Strict peer review (including an additive "power plant implications" metric).
(4) A 3 or 4 year lifetime with a rolling horizon. After this time, project competes for programmatic funding.
(5) Program solicits innovative proposals on advanced physics <u>and</u> advanced technology <u>and</u> reactor paradigms.
(6) Consider the DOE Laboratories' LDRD IR&D program as a possible model.

Question 4B: What is the status and development path of each present IFE scenario?

Session Leader: **Wayne Meier**

Suppliers of discussion material on:

Target design	Max Tabak, Debra Callahan-Miller, Jill Dahlburg, Rick Olson
HIF development	Roger Bangerter
DPSSL development	Howard Powell
KrF development	John Sethian
LIF development	Mike Cuneo
Z-pinch development	Rick Spielman
Target fab/injection	Ken Schultz
Chamber technology	Wayne Meier

Session Summary (Wayne Meier)

<u>Development Paths</u>

Information was presented on the status of various development plans for target design, different driver candidates, chamber technology, and target fabrication and injection. Key issues and near term plans were discussed for each of these areas. We also identified opportunities for cost-effective development which was one of the objectives of the Snowmass Summer Study.

<u>Status of Plans</u>

Over the past year significant effort has gone into developing a integrated R&D plans for heavy ion and laser (both DSSL and KrF) driven IFE. These include definition of near term (3-4 years) tasks for the drivers, chambers, target fabrication and injection systems, and target design work for both indirect-drive and direct-drive targets needed by these approaches. The estimated cost of this work is $50M per year.

At the concept exploration level, for z-pinch, LIF, and other concepts, little detailed planning has been done since these programs are not currently funded. Preliminary plans for the most important near term tasks were presented at this meeting.

Issues

Top level issues are summarized in Table 11. More extensive discussions of issues occurred in the subtopic groups on targets, drivers, and power plants, but it was generally agreed that this list was a reasonable summary of the key issues in each area.

Opportunities for Cost-Effective Development

For each element of the IFE program, an effort was made to identify characteristics or procedures that could contribute to cost effective development of IFE. These are summarized in Table 12. Perhaps one of the most important features is that the driver technologies can be developed in a modular way, by demonstrating a single beamline (for lasers or light ions) or single key components of the heavy ion driver. Another important opportunity longer term, is the ability to operate an engineering test facility (ETF) at modest scales. Chambers can be tested at about 1/10 full yield, and it was also argued that the heat transfer systems could be developed at about 1/10 or 300 MWt.

Table 11. Top Level Issues for IFE

Area	**Issues**
Target Design	High gain – experiments and calculations to validate Interface issues (materials, spot size, illumination geometry)
Drivers	
Heavy ions	Cost / beam quality (focusability)
DPSSL	Cost / beam smoothing
KrF	Efficiency / durability
Light ions	Source / emittance growth / durability / focusability
Z-pinch	High rep-rate, recyclable MITL / integrated power plant concept
Chambers / Final Optics	HIF final transport Clearing for liquid wall chambers Lifetime for dry-wall chambers Laser optics design / survivability (x-rays, debris, neutrons) HI final magnet/chamber interface (configuration/heating/activation)
Target	Low cost fabrication process / tritium inventory

Fabrication & Injection	Accurate, reliable injection Target survival (mechanical and thermal loads)
Safety & Environmental	Designs to meet no evacuation criteria / T inventory / wastes Recycling of target material

Table 12. Opportunities for Cost-Effective Development

Area	**Opportunities**
Target Design	Leverage off ICF work High gain at low driver energy for low energy ETF Fast ignitor
Drivers	Demonstrate end-to-end technology at single beamline scale for lasers Test single, full-scale components (e.g., cores) of ion drivers Utilize / upgrade existing facilities (e.g., pulsed power machines)
Chambers	HI final transport experiments and simulations Scaled hydraulic tests with water Sub-scale tests at ETF level Reduce neutron source requirements (fluid walls) Synergy with MFE on materials development and qualification
Target Fabrication & Injection	Leverage off of ICF fab work Develop / test injector with non-cryo systems to begin
Integrated Systems (e.g., IRE, ETF)	Do integrated target injection and chamber tests with IRE prior to ETF Beam switching to test multiple chambers Vary rep-rate and yield to test at low power Develop breeding blankets, heat recovery at modest scale (~300 MWt)
Safety & Environmental	Synergy with MFE on analytical tools, data, etc.