Answers to NAS questions for LBNL March 21, 2011

(F1) Key scientific issues important to national security versus commercial energy

General: Given political turmoil in the Middle East, and the US dependence on imported oil, it is clear that energy security will remain a key aspect of US national security for decades. NIF DT capsule implosions for stockpile stewardship applications, as well as target physics for commercial energy applications require high peak beam power, precision symmetry, and control of hydrodynamic instabilities. Thus the scientific basis for ignition and energy gain in the NIF laboratory using lasers underpins both energy security and stockpile stewardship objectives, and both should be viewed as important to national security. Specific: A variety of implosion experiments producing fusion yield can be tested on NIF, including indirect drive, room-temperature metal shells with DT gas, both single shells and double shells, and polar drive with shock ignition. Those target experiments can be tailored in a variety of ways to apply to both stockpile stewardship and energy applications. Heavy ion beams could potentially be used to drive many of the same target types for energy applications (e.g. indirect drive, polar-drive with shock ignition) as NIF laser driven targets, with greater driver efficiency and greater target coupling efficiency (good for energy). However, near term heavy ion beam focal spot sizes will not be as small as those for laser beams, so maximum target compressions and pressures that could be accessed for stockpile stewardship experiments near term will be less using heavy ion beams than those accessible with lasers on NIF. An example is the X-target [Henestroza, B. G. Logan, and L. J. Perkins, "Quasi-spherical fuel compression and fast ignition in a heavy-ion-driven X-target with one-sided illumination," *Phys. Plasmas*, **18**, 032702 (2011) http://link.aip.org/link/?PHP/18/3/htmltoc], which offers a robustly stable target for energy applications with moderate densities of 30g/cm^3 and low implosion convergence ratios of 5-7, but as such may be less useful for stockpile stewardship near term as NIF lasers. There are also scientific issues related to the feasibility of precision and high gain of targets emplaced and fired at high pulse rates, to gas-dynamic turbulence issues related to clearing chambers at pulse rates needed for power production, to compatibility of driver-chamber interfaces in a high-average fusion power environment, and to fusion nuclear science issues related to damage-resistant materials, heat transfer, tritium breeding and high temperature energy conversion, all of which are not needed for the stockpile stewardship mission, but are critical to commercial energy needed for national energy security. For example, hydrodynamics of chambers protected with high velocity thick liquid jets of lithium-bearing molten salt is not needed for stockpile stewardship, but needed for a faster and cheaper development path for addressing fusion nuclear issues for compatible driver/target combinations such as heavy ion accelerators driven targets.

(O2)(O3)(A1) Development Path for Heavy Ion Fusion

The cost, schedule and risk of the heavy ion fusion energy development path are described in three steps (R&D phases) with key technical performance criteria preceding each step to manage successively higher cost and risk steps. Phase I (First five years @~ 40 $M/yr) includes integrated single beam experiments (e.g., NDCX-II and HCX-II) for accelerator beam brightness, efficiency, and pulse rate with enabling accelerator, target, and chamber technology development. The deliverables at the end of the first five year Phase I are those required to select an optimal heavy ion accelerator and target approach for Phases II and III: Completed 2-D HIF target designs with drive efficiency x gain products > 10, and with relevant NIF + Omega hydrodynamic stability data sufficient to select an HIF target; measurements to validate models of beam brightness @ 5 Hz sufficient to drive the selected target; and sufficient supporting target and chamber technology R&D to enable Phase II and III. Phase II (Next 10 years @ ~100 $M/yr) would construct and operate a 10 to 100 kJ scale, multiple-beam Heavy Ion Driven Implosion eXperiment (HIDIX) to test the selected target pulse shaping, coupling efficiency and hydrodynamic stability in sub-ignition single shots, plus targets injected into a liquid test chamber in 5 Hz bursts. The HIDIX accelerator might be built in two phases, starting with a 10 kJ, 100 MeV front end, and then extended to ~100 kJ, 1 GeV. Since induction linacs increase in efficiency and decrease in cost per joule with energy, the HIDIX would need to demonstrate a minimum efficiency of 10% at costs less than ~ 10^4 $/J to validate scaling to a power plant. The deliverables at the end of Phase II are HIDIX data, plus supporting accelerator technology development, sufficient to validate a completed design of accelerator, chamber and target fabrication/injection needed for an ignition and DEMO design for Phase III. Phase III (Next 20 years @ ~$300M/yr) would construct a 2-3MJ HIF ignition test facility for single shot ignition tests but using an accelerator designed for 5 Hz (at very small incremental cost). Following successful ignition tests that optimize the pulse shape and target design details for best gain and robust stability, the chamber and fusion power systems would then be added to support steady operation (weeks) as a DEMO with ~ 150 MW thermal power, with the goal of sustained driver efficiency x gain products >10, and with self-sufficient tritium breeding and extraction from Flibe molten salt circulated through the chamber. The DEMO operation would include safety tests by shutting off Flibe pumps for LOCA and LOFA tests to demonstrate small afterheat temperature excursions (inherent safety), to aid licensing of commercial power plants. **(J1) Cost and schedule to DEMO.** The above described three phases total an estimated 7.2 B$ total over 35 years to go from existing single-beam accelerators [NDCX-II (0.25J, 100 MW), GSI-SIS18 (45J, 350 MW) and LHC (100MJ, 1 TW)] to required fusion scale, multiple-beam accelerators (30kJ, 4 TW) per beam X 100 beams @ ion ranges 0.03 to 0.5 g/cm^2 needed for DEMO. **(P1) Development cost & schedule compared to other IFE approaches.** This above integrated overall cost through HIF DEMO is probably similar as for other IFE approaches, if one includes the cost of the last three decades of NNSA/ICF development in laser and pulsed power technology. The schedule may be longer from the start of phase I for HIF to DEMO because the HIF program never received the funding levels NNSA has put into lasers and pulsed power in past decades.

(G1) How the axes of the X-target and the beams are to be kept in alignment.

The X-target [Henestroza, B. G. Logan, and L. J. Perkins, "Quasi-spherical fuel compression and fast ignition in a heavy-ion-driven X-target with one-sided illumination," *Phys. Plasmas*, **18**, 032702 (2011)], has a preferred axis with an axi-symmetric metal case in the shape of a hemi-spherical cone of revolution, filled with hard-frozen DT (no-beta layering needed). The symmetry of its fuel compression could still be affected by large offset and tilt errors of its axis with respect to the axis of annular drive beams due to injection errors into the target chamber, as in other target types such as hohlraums. As in other targets previously studied such as hohlraums, the X-target position and tilt during injection may need to be tracked for real-time steering of the driver beams with fast dipole correction magnets, but such fast corrections might be avoided if the misalignments are small enough and the tolerances of the X-target to misalignments are large enough. 3-D implosion studies to determine the tolerance of the X-target to misalignment errors have not yet been done, but the low implosion fuel convergence ratios < 5-7 required for the x-target should allow relatively larger errors. Also, the relatively high strength and rigidity of a solidly-filled, thick-metal-case cryo-X-target compared to high aspect ratio DT fuel capsules should allow X-targets to be injected with 1000 times higher spin frequencies compared to conventional targets (e.g., $g_\phi \sim 10^7$ centrifugal acceleration in g units vs. $g_z \sim 10^4 m/s^2$ axial gravity g units), keeping the X-target axis well aligned during injection like a gyroscope with very high angular momentum.

(I3) Projected efficiency of HIB drivers.

The induction acceleration modules are the most important factor in overall accelerator efficiency. Based on core and pulser losses, driver systems studies show an accelerator efficiency of ≈40% (excluding the constant power load for cryo-cooling of superconducting focusing magnet coils and pulser switch heating). A high efficiency, high repetition-rate test for 1 us pulse duration, showed that an induction core efficiency, η>50%, including core loss, switch loss, and pulse forming loss (Faltens 1983). This representative system would be attractive from long pulses down to somewhat below 1 us, but would be too slow for, say, a ≈0.2 μs pulse duration of most of the driver, because rise and fall time were each > 0.1 μs, and this would lower efficiency and require additional induction core material. For shorter pulses, and accounting for only core losses, we have measurements suggest that acceleration efficiency might be 50% (Faltens 2002) The core loss is only one of the loss mechanisms. The additional losses are the reset circuit, the capacitive energy in the module gap at the time the last particle passes and which is lost, and the various charging losses and refrigeration losses. Research opportunities include, for example, solid state switches enabling faster rise and fall times for beam pulse durations of 50 to 200 ns. This would make the acceleration more efficient for most of the accelerator.

A. Faltens et al., IEEE Trans. Nucl. Sci., NS-30, 4 (1983) 3669.
A.W. Molvik and A. Faltens, “Induction core alloys for heavy-ion inertial fusion-energy accelerators,” Phys. Rev. ST Accel. and Beams 5, 080401 (2002).

(Q3) Pros/cons and costs of induction versus RF accelerators, and which is recommended.

The three main types of heavy ion drivers are synchrotrons, RF linacs (with storage rings) and induction linacs. RF accelerators are appealing because of the extensive experience in high energy and nuclear physics; and induction accelerators, because of their much higher efficiency and higher particle beam current (10 kA in some applications). The US effort has focused on induction accelerators because of significantly higher efficiency (20-50%) and because there is no need to accumulate charge in multiple storage rings. Fewer parallel beams would be needed to drive HIF targets of given driver energy with induction linacs because of higher beam currents relative to RF, simplifying the interface between driver, final focus, and chamber. For RF linacs, average acceleration gradient limits are related to breakdown across metal-to-metal gaps in vacuum and multipactoring, and these depend on frequency, geometry, and surface conditions. With years of development, a cavity gradient of >80 MV/meter has been attained (Ruth, 1996). The 493-meter Spallation Neutron Source linac at ORNL accelerates intense proton bunches to 1 GeV with an *average* accelerating gradient of ≈ 2 MV/m using mostly superconducting RF cavities. Within the cavities, the *local* acceleration gradient is ≈18 MV/m. At low energies with microsecond-long pulses such as DARHT-II, induction cores tend to be big, with a large radial build. At high energies with submicrosecond pulses, core radial builds can be less than the core inner radius, and the acceleration rate can increase. Due to magnetic core losses and switching power tending to increase with shorter pulses, heavy-ion induction linacs may not be able to achieve as high a gradient, and as short a length, as RF linacs, just by using shorter pulses. However, relatively less R&D has been devoted to increasing induction linac gradients, and so a significant R&D opportunity exists for improving the accelerating gradients of induction linacs up to perhaps ~ 3MV/m, especially at higher ion kinetic energies needed for HIF, by e.g., exploring the use of shorter beam pulses ~ 50 ns, higher-gradient, multi-layer insulators, and all solid state switching (Birx, 2005). Insulating columns and switches can be expensive, thus, research on switches, new insulating materials, grading, and acceleration module design will be essential together with systems analysis of cost-performance tradeoffs using updated component costs. The pros and cons of induction versus RF drivers for heavy ion fusion will be revisited in an upcoming national workshop "Accelerators for Heavy Ion Fusion" (May 23-26,2011)-see website http://www.regonline.com/HIF11

R. Ruth et al., LINAC'96 http://accelconf.web.cern.ch/AccelConf/l96/PAPERS/THP01.PDF
D.L.Birx, et.al., "Technology of Magnetically Switched Accelerators", IEEE Transactions on Nuclear Science, Vol. NS-32, No. 5, October 2005.

(F4) Relative potential advantages and disadvantages of direct drive and indirect drive

The relative potential advantages and disadvantages of direct drive (DD) and indirect drive (ID) depend on the type of driver, on the type of ignition heating [central hydrodynamic (diesel-like) ignition, or spark ignition (shock ignition or fast ignition)], and on NIF results (TBD) on symmetry and hydrodynamic instabilities at high capsule implosion velocities and convergence ratios. For both laser and accelerator drivers, direct drive is generally expected to give potentially higher gain, especially with shock ignition, (better coupling efficiency and lower implosion velocity with shock ignition). Moreover, the potential advantages of shock ignition are not realizable in ID because the hohlraum radiation temperature can't be raised sufficiently rapidly. But 4π direct drive illumination could complicate chamber/blanket design (may worsen power plant maintenance, availability), unless polar drive with <<4π illumination can be used (2-D designs TBD). The desire for liquid chambers, and minimum bending of heavy ion beams between driver and chamber makes polar direct drive the most practical DD option for accelerator drivers. While LPI makes the relative advantages of DD vs. ID uncertain for lasers, the shorter pulse, higher peak powers required for shock or fast ignition makes relative advantages of those approaches to polar-DD vs. ID uncertain for accelerator drivers. If NIF ID ignition is achieved quickly at gains that scale favorably for power, indirect drive approaches will receive an early validation advantage before direct drive. Preliminary planning is underway to test polar direct drive with shock ignition on NIF in the intermediate term and might lead to higher gain prospects for both laser and heavy ion drivers. Besides NIF ignition, quantitative NIF target data leading to better predictive scaling on Rayleigh-Taylor instability mix vs. convergence ratios and implosion velocities could prove invaluable to allow many types of IFE target designs to better optimize Cost of Electricity in the tradeoff between highest **energy gain** (lowest recirculating power) **and robustness** (predictability, reliability, and repeatability of high yields).

(G30) Possibilities for heavy ion accelerator drivers for D-He3 or P-boron fusion.
Studies of advanced fuel ICF using isobaric (central hot-spot) ignition (M. Tabak, Nuclear Fusion 36, No 2 (1996)) and using isochoric (fast) ignition, S. Atzeni and C. Ciampi, Nuclear

Fusion 37, 1665 (1997) both showed large fuel ρr ~ 10 g/cm^2 and higher burn temperatures ~100 keV required for DD-catalyzed or D-He3 fusion because of lower reaction rates. The high burn temperatures were generated from a burn wave starting from relatively small ignition zones enriched with T bred from DD side reactions recovered from unburned target products. Both studies found compressed ignition fuel assemblies of order 0.5-1 MJ required in order for self-bred T sustainability. Given NIF compressed fuel assembly energy of 30 kJ requiring ~ 1.3 MJ of laser energy input, it's no surprise those studies concluded that > 20 MJ laser drivers might be required, and further work was thus discouraged. (P-boron would have even lower fusion reactivity, and require even larger compressed fuel masses and driver energies). However, since tamped, hydro-coupled direct drive targets can in principle achieve >25 % overall drive efficiency for fuel compression, heavy ion beam drivers that can penetrate thick metal cases (tampers) such as direct drive cannonballs or X-targets might be candidates for cat-DD or DHe3 fusion ultimately with ~ 5 MJ driver energies. More design work is needed to explore these possibilities. A key motivation: both of the above studies found that besides the higher charged particle fractions from cat-DD or DHe3 fusion, DD and DT neutrons from side reactions are also down-scattered within the burning fuel ρr ~ 2 x neutron range; thus, nearly all the energy output would be available for direct conversion.

(I1) Significance of driver efficiency for power plant credibility.
A key parameter for inertial fusion energy applications is the product of the target gain G and the efficiency of the driver η (electrical to beam on target) and expresses the degree of internal recirculating power required to drive the plant. Typically, we require the product to be η•G ≳ 10 because, around this threshold, the power that can be sent out and thus sold is only about 75% of that produced, while the rest goes into powering the driver and the rest of the plant. Such recirculating power fractions of ~25% are around the maximum that a utility would consider for an economically attractive plant. In the case of heavy ion fusion, this η•G product ≳ 10 allows for G ≳ 50 targets to be used economically with η = 20% accelerator drivers, thus implying an acceptably low recirculating power fraction. Based on existing induction linac technology, and their fundamentally high efficiency, η > 20% is relatively low risk aspect , and a high-value feature, of the drivers.
(see J. Perkins, http://fire.pppl.gov/IFE_NAS2_LLNL_perkins_Hi_Gain_target.pdf). The response to question I3 gives the basis for the efficiency estimates.

(J3) a. Major technology needs for HIF
Multi-beam ion sources and injectors: The challenge here is to develop ion sources that can provide ions with low ion temperature yet high emission current density, and high total beam current. Furthermore, the injector must be capable of transporting high current beams at low energy as limited by the beam potential due to the space charge force.
Insulators for accelerator modules: One factor limiting the acceleration gradient is the breakdown limit which is due to flashover across insulators. The insulating columns tend to be expensive and influence the driver design. Relatively low rate limits in the MV/m range have been imposed because there is little experience in several MV/m imposed across meter length gaps which are separated from the neighboring gaps with arrays of superconducting quadrupoles. It is such a type of column to which we would try applying higher voltages as part of an R&D program.

Pulsed power: much lower cost FET arrays or similar linear amplifiers would enable faster rise times and reduced stored energy before and after the passage of the bunch.
Superconducting quadrupole design: compact arrays of quadrupoles are needed to minimize the inner diameter of the induction cores. At the edge of the array the fields must be terminated such that the field quality in the outer beam apertures remains high, and the return flux of the quadrupoles do not saturate nearby induction core materials. Good progress was made for HIF driver style single magnets. The R&D is poised to develop and test prototype multiple beam quadrupole arrays.
Liquid wall protection must be immune to jet disruption from the fusion yield. The materials science overlaps with fission reactor research using liquid salt coolants.

b. Areas of HIF research common to other IFE systems.

Target fabrication and injection common with other IFE approaches.
Reactor materials and components must be robust against radiation and mechanical shock.
High power switches and capacitors.

(G31) Spin off possibilities of HIF R&D.

High current and brightness ion sources: Advances in ion source and injector development will benefit not only HIF but also many areas of accelerator applications that require high flux rate, e.g., ion implantors, neutral beam injectors (for tokamaks), medical accelerators, and induction linacs.
Accelerator waste transmutation: See "High current induction linacs," W. Barletta, A. Faltens, E. Henestroza, and E.P. Lee, AIP 346, pp. 219-228 The International Conference on Accelerator-Driven Transmutation Technologies And Applications; doi:10.1063/1.49154 http://link.aip.org/link/?APCPCS/346/219/1
Induction synchrotrons: See "Principles of Induction Accelerators" K. Takayama, R.J. Briggs (editors), DOI: 10.1007/978-3-642-13917-8_3

(G27) What computer codes for economic analysis are available for access by the Committee that your group may have written?

We currently have operational only one such code for economic analysis (most recent unit costs as of 2000): IBEAM (Ion Beams for Energy Applications Modeling). brief descriptions of this code are given in the following references.

W. R. Meier, R. O. Bangerter, and A. Faltens, "An integrated systems model for heavy ion drivers," *Nucl. Inst. and Meth. in Phys. Res. A*, **415**, 249 (1998).

J. J. Barnard, R. O. Bangerter, E. Henestroza, I. D. Kaganovich, B. G. Logan, W. R. Meier, D. V. Rose, P. Santhanam, W. M. Sharp, D. R. Welch, and S. S. Yu, "A final focus model for heavy-ion fusion driver system codes," *Nucl. Inst. and Meth. in Phys. Res. A* **544**, 243 (2005)

S.S. Yu, W.R. Meier, R.P. Abbott, J.J. Barnard, T. Brown, D.A. Callahan, C. Debonnel, P. Heitzenroeder, J.F. Latkowski, B.G. Logan, S.J. Pemberton, P.F. Peterson, D.V. Rose, G.-L. Sabbi, W.M. Sharp, and D.R. Welch, "An Updated Point Design for Heavy Ion Fusion," *Fusion Science and Tech.* **44 (2)**, 266-273 (2003).

(G28) The authors listed above in (G27) are the contact people on economics for HIF.