# Interim Report-Status of the Study "An Assessment of the Prospects for Inertial Fusion Energy"

ISBN
978-0-309-25457-1

60 pages
8 1/2 x 11
PAPERBACK (2012)

Committee on the Prospects for Inertial Confinement Fusion Energy Systems; National Research Council of the National Academies

# Interim Report—Status of the Study
# "An Assessment of the Prospects for Inertial Fusion Energy"

Committee on the Prospects for Inertial Confinement Fusion Energy Systems
Board on Physics and Astronomy
Board on Energy and Environmental Systems
Division on Engineering and Physical Sciences
NATIONAL RESEARCH COUNCIL
*OF THE NATIONAL ACADEMIES*

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
**www.nap.edu**

**THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001**

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

Support for this project was provided by Contract 10NA001274 between the National Academy of Sciences and the Department of Energy and National Nuclear Security Administration. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the agency that provided support for the project.

International Standard Book Number-13: 978-0-309-24547-1
International Standard Book: 0-309-25547-4

Copies of this report are available free of charge from:

Board on Physics and Astronomy
National Research Council
The Keck Center of the National Academies
500 Fifth Street, N.W.
Washington, DC  20001

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu.

Printed in the United States of America

THE NATIONAL ACADEMIES
*Advisers to the Nation on Science, Engineering, and Medicine*

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

**www.national-academies.org**

# COMMITTEE ON THE PROSPECTS FOR INERTIAL CONFINEMENT FUSION ENERGY SYSTEMS

RONALD C. DAVIDSON, Princeton University, *Co-Chair*
GERALD L. KULCINSKI, University of Wisconsin-Madison, *Co-Chair*
CHARLES BAKER, University of California, San Diego (retired)
ROGER BANGERTER, E. O. Lawrence Berkeley National Laboratory (retired)
RICCARDO BETTI, University of Rochester
JAN BEYEA, Consulting in the Public Interest
ROBERT L. BYER, Stanford University
FRANKLIN CHANG-DIAZ, Ad Astra Rocket Company
STEVEN C. COWLEY, United Kingdom Atomic Energy Authority
RICHARD L. GARWIN, IBM Thomas J. Watson Research Center
DAVID HAMMER, Cornell University
JOSEPH S. HEZIR, EOP Group, Inc.
KATHRYN McCARTHY, Idaho National Laboratory
LAWRENCE T. PAPAY, PQR, LLC
KEN SCHULTZ, General Atomics [Retired]
ANDREW M. SESSLER, E. O. Lawrence Berkeley National Laboratory
JOHN SHEFFIELD, The University of Tennessee, Knoxville
THOMAS A. TOMBRELLO, JR., California Institute of Technology
DENNIS G. WHYTE, Massachusetts Institute of Technology
JONATHAN S. WURTELE, University of California, Berkeley
ROSA YANG, Electric Power Research Institute, Inc.

MALCOLM McGEOCH, Consultant, PLEX, LLC

***Staff***

DAVID LANG, Program Officer, Board on Physics and Astronomy, *Study Director*
GREG EYRING, Program Officer, Division on Engineering and Physical Sciences
TERI THOROWGOOD, Administrative Coordinator, Board on Physics and Astronomy
JONATHAN YANGER, Senior Project Assistant, Board on Energy and Environmental Systems
ERIN BOYD, Christine Mirzayan Science & Technology Policy Graduate Fellow (January-April, 2011)

DONALD C. SHAPERO, Director, Board on Physics and Astronomy
JAMES ZUCCHETTO, Director, Board on Energy and Environmental Systems

## BOARD ON PHYSICS AND ASTRONOMY

## BOARD ON ENERGY AND ENVIRONMENTAL SYSTEMS

## Preface

Recent scientific and technological progress in inertial confinement fusion (ICF), together with the campaign for achieving the important milestone of ignition on the National Ignition Facility (NIF), motivated the Department of Energy's (DOE's) Office of the Under Secretary for Science to request that the National Research Council (NRC) undertake a study to assess the prospects for inertial fusion energy (IFE) and provide advice on the preparation of a research and development (R&D) roadmap leading to an IFE demonstration plant. The statement of task for the full NRC study is given in Appendix B. In response to this request, the National Research Council established the Committee on the Prospects for Inertial Confinement Fusion Energy Systems.

As part of the study, the sponsor also requested that the National Research Council provide an interim report to assist it in formulating its budget request for future budget cycles (see Appendix B). This interim report, which has a limited scope and does not fully address all of the bulleted items in Appendix B, is intended to provide the sponsor with a status report on the committee's progress and a summary of the committee's preliminary conclusions and recommendations based on the information it received during its first four meetings (see Appendix D) and from its review of relevant reports (see Appendix E).

These four meetings were concerned mainly with information gathering through presentations, and the committee is only now carrying out the detailed analysis of the many important topics that will be included in its final report. Important topics that are not addressed in this interim report—but will be addressed to the extent possible in the final report—include an analysis of the cost-effectiveness of inertial fusion energy, a comparison of the various driver options, and an R&D roadmap at the conceptual level for a national program aimed at the design and construction of an inertial fusion energy demonstration plant, including approximate estimates, where possible, of the funding required at each stage. At the outset of the study, the committee decided that the fusion-fission hybrid was outside the scope of the study.

Although the committee is carrying out its work in an unclassified environment, it was recognized that some of the research relevant to the prospects for inertial fusion energy systems has been conducted under the auspices of the nation's nuclear weapons program, and has been classified. Therefore, the NRC established the separate Panel on the Assessment of Inertial Confinement Fusion (ICF) Targets (see Appendix C) to explore the extent to which past and ongoing classified research affects the prospects for practical inertial fusion energy systems. The panel was also tasked with analyzing the nuclear proliferation risks associated with IFE (see Appendix B); although that analysis was not available for inclusion in this interim report, the committee will review and discuss it in its final report.

The Target Physics Panel has exchanged unclassified information informally with the committee in the course of the study process, and the committee is aware of the panel’s evolving conclusions.

The panel plans to produce both a classified and an unclassified report; the timing of the latter is such that it would be available to inform this committee’s final report and would be included as an appendix in that report. The statement of task of the Target Physics Panel is given in Appendix B and the panel’s meeting agendas appear in Appendix F.

## Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the Report Review Committee of the National Research Council (NRC). The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Douglas M. Chapin, MPR Associates
Stirling A. Colgate, Los Alamos National Laboratory
Robert W. Conn, The Kavli Foundation
Michael I. Corradini, University of Wisconsin
James F. Drake, Jr., University of Maryland
R. Paul Drake, University of Michigan
Harold K. Forsen, Bechtel Corporation (retired)
Arjun Makhijani, Institute for Energy and Environmental Research
Robert H. Socolow, Princeton University
Frank N. von Hippel, Princeton University
Stanford E. Woosley, University of California at Santa Cruz

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Louis J. Lanzerotti, New Jersey Institute of Technology. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

# Contents

Appendixes

# 1 Executive Summary

In this interim report, the Committee on the Prospects for Inertial Confinement Fusion Energy Systems reached the following preliminary conclusions and recommendations.

**Conclusion 1: The scientific and technological progress in inertial confinement fusion has been substantial during the past decade, particularly in areas pertaining to the achievement and understanding of high-energy-density conditions in the compressed fuel, in numerical simulations of inertial confinement fusion processes, and in exploring several of the critical technologies required for inertial fusion energy applications (e.g., high-repetition-rate lasers and heavy-ion-beam systems, pulsed-power systems, and cryogenic target fabrication techniques).**

Despite these advances, however, many of the technologies needed for an integrated inertial fusion energy system are still at an early stage of technological maturity. For all approaches to inertial fusion energy examined by the committee (diode-pumped lasers, krypton fluoride lasers, heavy-ion accelerators, pulsed power; indirect drive and direct drive), there remain critical scientific and engineering challenges associated with establishing the technical basis for an inertial fusion energy demonstration plant.

**Conclusion 2: It would be premature at the present time to choose a particular driver approach as the preferred option for an inertial fusion energy demonstration plant.**

The committee recognizes, of course, that such a down-selection among options will eventually have to be made. In its final report, the committee will provide examples of key experimental results that will be needed to inform the decision points regarding which driver-target combinations are most likely to succeed.

The U.S. Department of Energy's (DOE's) National Nuclear Security Administration (NNSA) supports a major national effort in inertial confinement fusion at the National Ignition Facility (NIF) that is focused primarily on addressing technical issues related to stewardship of the nation's nuclear weapons stockpile and national security. An intense national campaign is underway to achieve ignition conditions on the NIF, and there has been considerable initial technical progress toward this major goal, although progress has been slower than originally anticipated.[1]

The current NIF laser, targets, shot repetition rate, production methods, and materials are not specifically designed to be suitable for inertial fusion energy (IFE) applications.

---

[1] Steven Koonin, DOE Under Secretary for Science, "Fourth Review of the National Ignition Campaign," November 8, 2011.

Nevertheless, many experiments that could be done using the NIF would be valuable for IFE even if the achievement of ignition is delayed—particularly those that provide experimental validation of predictive capabilities.

The above discussion led the committee to make the following recommendation.

**Recommendation: Planning should begin for making effective use of the National Ignition Facility as one of the major program elements in an assessment of the feasibility of inertial fusion energy.**

## 2 Background

The National Research Council, National Academy of Sciences, and National Academy of Engineering's America's Energy Future study reviewed current patterns of energy production and consumption in the United States[2] and the growing concerns with energy security and the environmental impacts of current fuels. For example, the study found that the United States depends on fossil fuels (coal, natural gas, and—to a minor extent—oil) for 69 percent of its electricity generation, with nuclear fission accounting for an additional 21 percent. Although the fossil and nuclear fuels used are largely domestic in origin, there are many reasons why using them for electricity generation is less than ideal. Burning fossil fuels releases greenhouse gases such as carbon dioxide that appear to be altering the global climate, while concerns about nuclear fission remain, such as the possibility of accidents, the long-term storage of high-level nuclear waste, and the security and proliferation risks associated with widely distributed and highly radioactive nuclear materials.

Not considered in the America's Energy Future analysis were the prospects for electricity generation from nuclear fusion, which offers the potential for a carbon-free source of energy with an abundant source of fuel and greatly reduced concerns about long-term storage and disposal of radioactive waste compared with existing nuclear fission energy systems.

There are two main approaches to nuclear fusion: inertial confinement fusion (ICF) and magnetic confinement fusion. Historically, the great majority of U.S. Department of Energy (DOE) funding for energy-related fusion research and development (R&D) has supported activities in magnetic confinement fusion, and consequently the technology for magnetic fusion energy is further advanced, with an internationally funded facility now under development to demonstrate several aspects of technical feasibility.[3] However, the DOE's National Nuclear Security Administration (NNSA) supports a major national effort in inertial confinement fusion focused primarily on addressing technical issues related to stewardship of the nation's nuclear weapons stockpile and national security.

The final report of the present study will evaluate the current status and future prospects for one of the two major approaches to nuclear fusion energy—inertial confinement

---

[2] National Academy of Sciences, National Academy of Engineering, and National Research Council, *America's Energy Future: Technology and Transformation*, The National Academies Press, Washington, D.C. (2009).

[3] ITER, formerly known as the International Thermonuclear Experimental Reactor, is a magnetic confinement fusion experiment facility currently under construction in southern France. More information can be found at URL http://www.iter.org/, accessed June 30, 2011.

fusion—to contribute to the U.S. electricity generation mix. This interim report has a much more limited scope and is intended to provide the sponsor with a snapshot of the direction of the committee's thinking after its first four meetings.

The present NRC study focuses on inertial fusion energy (IFE), which is based on the inertial confinement fusion approach. A primer on the principles of inertial fusion energy systems is provided in Appendix A. During the past decade, several prominent studies have reported favorably on the prospects for inertial fusion energy (e.g., see Fusion Energy Sciences Advisory Committee - 2004 panel report on Review of Inertial Fusion Energy Program; Fusion Energy Sciences Advisory Committee - 2003 panel report on Plan for Development of Fusion Energy; 2002 Snowmass meeting on fusion energy; the full bibliographic references for these reports are in Appendix E).

The NNSA's recently commissioned National Ignition Facility (NIF) has the stated goal of achieving ignition[4] with an inertial confinement fusion target by the end of FY2012.[5]

Previous funding sources for inertial fusion energy R&D have been diverse and have included Laboratory Directed Research and Development (LDRD) funds at NNSA laboratories (e.g., Laser Inertial Fusion Energy (LIFE) and pulsed-power approaches), direct funding through the Office of Fusion Energy Sciences (e.g., heavy-ion fusion, fast ignition, magnetized target fusion), and congressionally mandated funding (e.g., the High-Average-Power Laser (HAPL) programs for krypton fluoride (KrF) and diode-pumped lasers).[6]

Thus, while there have been diverse past and ongoing research efforts sponsored by various agencies and funding mechanisms that are relevant to IFE, at the present time there is no nationally coordinated research and development program in the United States aimed at the development of inertial fusion energy that incorporates the spectrum of driver approaches (diode-pumped lasers, heavy ions, krypton fluoride lasers, pulsed power, or other concepts), both indirect-drive and direct-drive target designs (see Appendix G for definitions), or any of the unique technologies needed to extract energy from any of the variety of driver and target options.

---

[4] John D. Lindl, Peter Amendt, Richard L. Berger, S. Gail Glendinning, Siegfried H. Glenzer, Steven W. Haan, Robert L. Kauffman, Otto L. Landen, and Laurence J. Suter, "The Physics Basis for Ignition Using Indirect-Drive Targets on the National Ignition Facility," *Physics of Plasmas*, Vol. 11, Issue 2, 339 (2004); doi:10.1063/1.1578638 (153 pages).

[5] Steven Koonin, DOE Under Secretary for Science, "Fourth Review of the National Ignition Campaign," November 8, 2011.

[6] Research in these various approaches is conducted across multiple labs and universities, although the driver approaches are usually identified with the following institutions: diode-pumped solid-state lasers (Lawrence Livermore National Laboratory and the Laboratory for Laser Energetics at the University of Rochester); pulsed power (Sandia National Laboratories); heavy-ion fusion (Lawrence Berkeley National Laboratory); magnetized target fusion (Los Alamos National Laboratory); and krypton fluoride lasers (Naval Research Laboratory).

## 3 The Committee's Information-Gathering Process

The analysis in this report is based on:

- Review of many past studies on inertial fusion energy systems;[7]
- Briefings received on the ongoing research related to inertial fusion energy systems in the United States and around the world;
- Site visits conducted at major inertial confinement fusion facilities in the United States; and
- Expertise of the committee's membership in key areas relating to inertial confinement fusion.

Meeting agendas and site visits conducted by the committee are provided in Appendix D. A bibliography of past inertial confinement fusion studies consulted by the committee is given in Appendix E.

## 4 Recent Scientific and Technological Advances in Inertial Confinement Fusion

Inertial fusion science and driver/target technologies are in a highly productive period of exploration driven by innovative ideas, precision diagnostics and engineering systems, ever-improving experimental techniques, and advanced numerical simulations. Detailed comparison of experimental results with simulations has proven to be very valuable in improving the understanding of high-energy-density physics, damage to materials under fusion conditions, the relative merits of various drivers, and many other issues relevant to IFE.

In addition, the committee received technical input describing advances on many fronts, including indirect-drive and direct-drive fusion schemes,[8] heavy-ion-beam focusing[9] and pulse compression,[10] and advances in pulsed-power fusion.[11] The committee also

---

[7] See Appendix E.

[8] J.D. Sethian et al., "The Science and Technologies for Fusion Energy with Lasers and Direct-Drive Targets", *IEEE Transactions on Plasma Science,* Vol. 38, 690-703 (2010).

[9] P.K. Roy et al., "Results on Intense Beam Focusing and Neutralization from the Neutralized Beam Experiment," *Physics of Plasmas*, Vol. 11, 2890 (2004).

[10] P.K. Roy et al., "Drift Compression of an Intense Neutralized Ion Beam," *Physics Review Letters*, Vol. 95, 234801 (2005).

[11] S.A. Slutz et al., *Physics of Plasmas*, Vol. 17, 056303 (2010); and Michael E. Cuneo et al., "Pulsed Power IFE: Background, Phased R&D, and Roadmap," presentation to NRC Committee on the Prospects for Inertial Confinement Fusion Energy Systems, April 1, 2011, Albuquerque, New Mexico.

received input concerning exploratory concepts such as shock ignition,[12] fast ignition,[13] and magnetized target fusion,[14,15] which, if their potential is realized, may also have an impact on inertial fusion energy in the longer term.

An intense national campaign is underway to achieve ignition conditions on the NIF, and there has been considerable initial technical progress toward this major goal.[16] While technical progress has been slower than originally anticipated,[17] the eventual achievement of ignition on the NIF, and particularly the achievement of moderate single-shot gain (10–20, say), would provide significant validation of key scientific underpinnings required for developing inertial fusion as a practical energy source.

The committee noted that there is a substantial university community engaged in inertial confinement fusion experiments at the national laboratories[18,19] There is also a strong university community active in high-energy-density science research, both at local facilities and at user facilities, which make important contributions to inertial confinement fusion concepts and techniques. Some of the major contributions that universities make in addition to improved understanding of the physics of extreme states of matter at the fundamental level, are the training of graduate students and postdoctoral associates who provide the source of scientific and engineering manpower, as well as the development and testing of new ideas and long-range technologies that are sometimes difficult to carry out in a mission-focused program.

In parallel with the significant scientific advances, there have been impressive R&D efforts to develop a wide range of driver technologies.[20] However, very little effort has been spent on developing the technology of the reactor chambers or on addressing materials problems peculiar to inertial fusion. Finally, international R&D programs in

---

[12] R. Betti, C.D. Zhou, K.S. Anderson, L.J. Perkins, W. Theobald, and A.A. Solodov, “Shock Ignition of Thermonuclear Fuel with High Areal Density,” *Physics Review Letters*, Vol. 98, 155001 (2007).

[13] M.H. Key, “Status and Prospects for the Fast Inertial Fusion Concept,” *Phys. Plasmas*, Vol. 14, 055502 (2007).

[14] F.J. Marshall et al., *Physical Review Letters*, Vol. 102, 185004 (2009); and T.P. Intrator et al., *Journal of Fusion Energy*, Vol. 28, 165-169 (2009).

[15] P.Y. Chang, G. Fiksel, M. Hohenberger, J.P. Knauer, R. Betti, F.J. Marshall, D.D. Meyerhofer, F.H. Séguin, and R.D. Petrasso, “Fusion Yield Enhancement in Magnetized Laser-Driven Implosions,” *Physics Review Letters*, Vol. 107, 035006 (2011).

[16] E. Moses, “Ignition on the National Ignition Facility: A Path Towards Inertial Fusion Energy,” *Nuclear Fusion*, Vol. 49, 104022 (September 10, 2009).

[17] Steven Koonin, DOE Under Secretary for Science, “Fourth Review of the National Ignition Campaign,” November 8, 2011.

[18] E. Moses and W. Meier, “The National Ignition Facility and the Golden Age of High Energy Density Science,” *IEEE Transactions on Plasma Science*, Vol. 36, 802-808 (2008).

[19] J.D. Sethian et al., “The Science and Technologies for Fusion Energy with Lasers and Direct-Drive Targets,” *IEEE Transactions on Plasma Science,* Vol. 38, 690-703 (2010).

[20] Ibid.

inertial fusion energy are continuing to expand and receive increased emphasis, particularly in Europe,[21] Japan,[22] Russia,[23] and China.[24]

In summary, the committee has consulted with most of the key individuals and laboratories at the forefront of IFE-related research and is impressed with the quality of the science and technology and how much progress has been made in the past decade. It also recognizes how challenging and complex the unresolved issues are and how much remains to be accomplished and understood if IFE is to become a practical energy source. Each potential driver and target combination has advantages and disadvantages, technologies are evolving rapidly, and scientific challenges remain. If the nation intends to establish inertial fusion energy as part of its energy R&D portfolio, it is clear that both science and technology components must be addressed in an integrated and coordinated effort.

## 5 Important Factors from a Power Plant Perspective

For inertial confinement fusion to become a practical energy source, several factors are important from a power plant perspective. These include:

- Cost competitiveness of the capital, fuel, operation, and maintenance costs;
- The ability to operate the plant continuously and with high availability in the extreme radiation environment of 14 MeV neutrons and target debris;
- The difficulty and frequency of the required periodic inspections and maintenance operations;
- The ease of operation; and
- Low environmental, health, and safety consequences (including management of radioactive waste), both in normal operation and under accident conditions.

---

[21] John Collier, “Recent Activities and Plans in the EU and UK on Inertial Fusion Energy,” presented to the National Research Council Committee on Prospects for Inertial Confinement Fusion Energy Systems, June 15, 2011; and Boris Sharkov, “HIF E: Activities in Europe and in Russia” and “Extreme State of Matter Physics at FAIR,” presented to the National Research Council Committee on Prospects for Inertial Confinement Fusion Energy Systems, October 31, 2011.

[22] Hiroshi Azechi, “Inertial Fusion Energy: Activities and Plans in Japan,” presented to the National Research Council Committee on Prospects for Inertial Confinement Fusion Energy Systems, June 15, 2011.

[23] Boris Sharkov, “Heavy Ion Fusion Energy: Activities in Europe and in Russia” and “Extreme State of Matter Physics at FAIR,” presented to the National Research Council Committee on Prospects for Inertial Confinement Fusion Energy Systems, October 31, 2011.

[24] Jie Zhang and Xiantu He, “Inertial Fusion Energy: Activities and Plans in China,” presented to the National Research Council Committee on Prospects for Inertial Confinement Fusion Energy Systems, June 16, 2011.

The committee received presentations and documentation that summarized the reactor design concepts for several driver approaches, including high-average-power diode-pumped lasers and KrF lasers, heavy-ion fusion, and pulsed-power fusion. The current designs of IFE plants have used best-guess cost estimates for components and targets.[25] The most recent detailed study of an IFE system is the Laser Inertial Fusion Energy (LIFE) study, which examined one option (based on indirect-drive targets, a diode-pumped solid-state laser, and a gas-filled, solid first wall).[26] This study, as well as previous power system studies, have provided much useful insight into the issues and challenges facing IFE systems. While considerable progress has been made in the LIFE design and in other approaches, the committee concluded, based on the presentations and materials provided, that it would be premature to down-select among driver options at the present time. The committee further concluded that, to the extent possible, it is critical to continue the development of several promising technologies and driver options to ensure that the most suitable technologies are available for commercial manufacturers to design, license, and build fusion power plants that will operate reliably, safely, and economically. In addition, the committee believes that it would be prudent to direct a portion of the inertial fusion energy R&D portfolio at a time frame longer than 20 or 30 years, in order to examine promising but less explored advanced concepts and technologies.

Finally, it will be important for a number of reasons to achieve a high target gain (~50–200) for a practical inertial fusion power plant. A fraction of the gross power produced by the plant must be used to drive the driver. This fraction is inversely proportional to the product of target gain and driver efficiency. Therefore, higher target gain leads to higher net energy production and lower cost of power. Target types that have higher overall gain can operate at lower driver energy and still produce adequate energy output.[27] This factor is particularly important because a major challenge for achieving competitive fusion power is the capital cost of the facility. Moreover, higher

---

[25] Examples include the following: Thomas M. Anklam, Mike Dunne, Wayne R. Meier, Sarah Powers, and Aaron J. Simon, "LIFE: The Case for Early Commercialization of Fusion Energy," *Fusion Science and Technology*, Vol. 60, 66 (2011); W.R. Meier, "Systems Modeling for a Laser-driven IFE Power Plant Using Direct Conversion," *J. Phys.: Conf. Ser.,* Vol. 112, 032036 (2008); 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 Technology," Vol. 44, 266-273 (September 2003); W.R. Meier, "Systems Modeling for Z-IFE Power Plants," *Fusion Eng. and Design*, Vol. 81, 1661 (2006); W.R. Meier, "Osiris and Sombrero Inertial Fusion Power Plant Designs-Summary, Conclusion, and Recommendations," *Fusion Eng. Des.*, Vol. 25, 145-157 (1994), ; L.M. Waganer, "Innovation Leads the Way to Attractive Inertial Fusion Energy Reactors—Prometheus-L and Prometheus-H," *Fusion Eng. Des.*, Vol. 25, 125-143 (1994).

[26] Hagop Injeyan and Gregory D. Goodno, *High-Power Laser Handbook*, McGraw Hill, 2011.

[27] Experience in preparations for the NIF shows that physical variations among targets and shots are likely to produce significant gain variations. One needs the highest feasible nominal gain and the highest feasible driver energy to minimize the effects of these variations.

gain may lead to reduced target costs because, for fixed driver energy, fewer targets would be required to produce a given quantity of energy. Finally, there are often important limits on chamber repetition rate. Increasing target gain, for a given driver energy and a given plant capacity, leads to lower repetition rates.

## 6 Conclusions and Recommendations

Based on the information gathered by the committee through its first four meetings, its site visits, and on its own analysis, the following is a summary of the committee’s preliminary conclusions and recommendations.

**Conclusion 1: The scientific and technological progress in inertial confinement fusion has been substantial during the past decade, particularly in areas pertaining to the achievement and understanding of high-energy-density conditions in the compressed fuel, in numerical simulations of inertial confinement fusion processes, and in exploring several of the critical technologies required for inertial fusion energy applications (e.g., high-repetition-rate lasers and heavy-ion-beam systems, pulsed-power systems, and cryogenic target fabrication techniques).**

Despite these advances, however, many of the technologies needed for an integrated inertial fusion energy system are still at an early stage of technological maturity. For all approaches to inertial fusion energy examined by the committee (diode-pumped lasers, KrF lasers, heavy-ion accelerators, pulsed power; indirect drive, and direct drive), there remain critical scientific and engineering challenges associated with establishing the technical basis for an inertial fusion energy demonstration plant. In addition, cost estimates for the R&D program leading to an inertial fusion energy demonstration plant are also at an early stage of development. For example, for energy applications, considerable R&D remains to be carried out in the containment of fusion energy releases at high repetition rates, and in improving the performance of the reactor components over long periods of time.

**Conclusion 2: It would be premature at the present time to choose a particular driver approach as the preferred option for an inertial fusion energy demonstration plant.**

The committee recognizes, of course, that such a down-selection among options will eventually have to be made. In its final report, the committee will provide examples of key experimental results that will be needed to inform the decision points regarding which driver-target combinations are most likely to succeed.

The committee notes with favor that the inertial confinement fusion community has begun a process to develop community consensus on critical issues and future inertial fusion energy activities in the United States.[28] This important effort should be encouraged, with the overall goal of developing options for a community-based roadmap for the development of inertial fusion as a practical energy source. Increasing the involvement of the university inertial confinement fusion community, as well as drawing on a broader set of technical expertise in micro-fabrication, materials, laser, accelerator, and pulsed-power disciplines, would greatly strengthen this effort.

The NIF has been focused on demonstrating ignition in order to achieve its stockpile stewardship mission, and, as such, no shots have been devoted primarily to inertial fusion energy research. Furthermore, the NIF laser, targets, shot repetition rate, production methods, and materials are not specifically designed to be suitable for inertial fusion energy applications. Nevertheless, many experiments that could be done using the NIF would be valuable for inertial fusion energy even if the achievement of ignition is delayed—particularly those that provide experimental validation of predictive capabilities.

The above discussion led the committee to make the following recommendation.

**Recommendation: Planning should begin for making effective use of the National Ignition Facility as one of the major program elements in an assessment of the feasibility of inertial fusion energy.[29]**

## 7 Path Forward to Complete the Final Report

This interim report provides an overview of the committee's preliminary conclusions and recommendations based on information gathered through its first four meetings. The committee is mindful that inertial fusion science and technology are evolving rapidly, and an effort has thus been made not to draw technical conclusions in the interim report that may change by the time the final report is issued in the summer of 2012. Thus, the interim report is intended to provide the sponsor with a relatively robust sense of the direction of the committee's assessment and to assist the Department of Energy in planning future-year budget requests for inertial fusion energy, while maintaining the discussion at a moderately high level. After completing its data gathering and analysis process in future meetings, the committee will provide a more detailed description of its

---

[28] "In January of 2010 representatives from the major National Nuclear Security Administration (NNSA) Inertial Confinement Fusion (ICF) institutions were challenged by Christopher Deeney, Director of the Office of Inertial Confinement Fusion ICF and Kim Budil, Senior Advisor to the DOE Under Secretary for Science, to develop a consensus position on inertial fusion energy in preparation for the upcoming National Academy of Sciences (NAS) review." The result was reported by M. Hockaday et al., "White Paper Compilation on Inertial Fusion Energy (IFE) Development (U)," LA-UR 11-01934, 2011.

[29] A similar recommendation was made in FESAC: A Plan for the Development of Fusion Energy, March 2003.

final findings and recommendations alongside its full assessment of the prospects for inertial fusion energy with regard to each of the bulleted tasks in Appendix B. The committee's final report is planned to include as an appendix an unclassified version of the Target Physics Panel Report.[30]

---

[30] The role of the Target Physics Panel is explained in the Preface. Meeting agendas from the Target Physics Panel's first four meetings are attached to this interim report as Appendix F.

# Appendixes

## Appendix A: The Basic Science of Inertial Fusion Energy

The aim of inertial confinement fusion is to ignite a target containing compressed fusion fuel—deuterium (heavy hydrogen) and tritium (super-heavy hydrogen)—so that it will burn (react) significantly before the target blows itself apart. Clearly, if this is to be of use for energy production, the energy required to initiate the burn must be significantly less than the energy released by the fusion reactions. Furthermore the energy release of the target must also be sufficiently small that it can be contained and converted into useful power. This appendix outlines the basic physics of the process as it is currently envisaged.

The thermonuclear reaction between deuterium and tritium (DT) yields helium (an alpha particle) and a neutron. The neutron is used to "breed" tritium from lithium in a secondary reaction (see Figure A.1). The energy released is huge: burning only 12mg of a 50-50 DT mixture yields 4.2GJ of energy—equivalent to one ton of TNT.

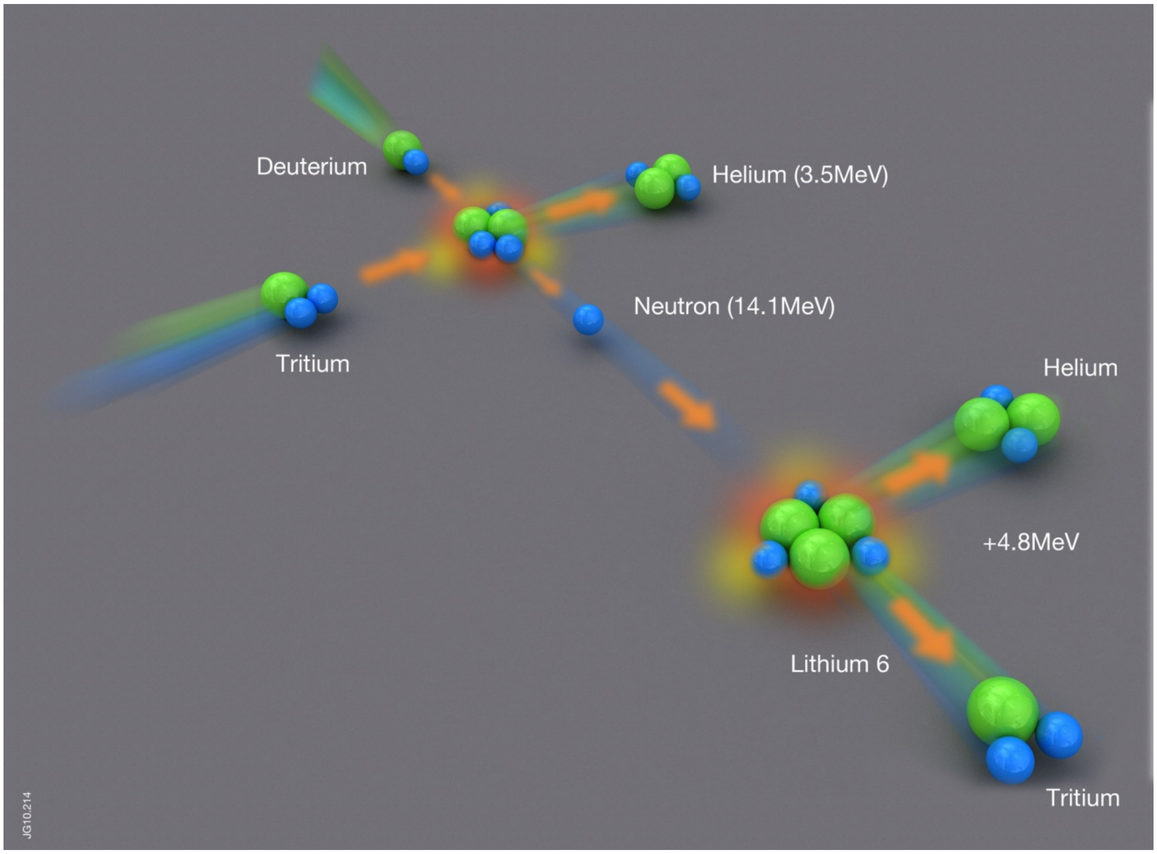

Figure A.1. The deuterium-tritium fusion reaction and the tritium breeding reaction from lithium 6. SOURCE: Steve Cowley, United Kingdom Atomic Energy Authority and Imperial College London.

In a DT plasma at temperatures over about 50 million degrees, random collisions of D and T produce more energy via the fusion reaction than is radiated away by photons. This is the expected initiation temperature for fusion burn—typically the plasma would then heat itself to above 200 million degrees while burning. The reaction rate per particle depends on temperature and density. At 200 million degrees the reaction rate per particle is $5.2 \times 10^7 \rho \ s^{-1}$ where $\rho$ is the DT mixture's mass density in grams per cubic centimeter. The disassembly time of an isothermal sphere is roughly $R/(3C_s)$ where R is the radius and $C_s$ the sound speed—at 200 million degrees $C_s$ is roughly $10^8$ cm/s. Thus (very approximately) we must have the *areal density,* $\rho R$, >3-7g/cm$^2$ in order to get a significant proportion of the nuclei to react in the disassembly time. At DT liquid density this would require a sphere of 10-30 centimeters radius and a huge release of energy. To keep the energy to initiate fusion small and the energy released manageable a small sphere (weighing a few milligrams) must be used. This requires compression. The areal density rises during compression (at fixed mass $\rho R \propto R^{-2}$) until it reaches a substantial fraction of fusion-relevant levels (of order 3-7g/cm$^2$). For 3mg of solid/liquid DT an increase of the density of order a thousand is needed.

In most inertial confinement fusion (ICF) schemes, a shell of cryogenic deuterium and tritium fuel is accelerated inward and compressed by the reaction force from an ablating outer shell. The ablating outer shell is heated either by direct laser irradiation (called *direct drive*) or by the x-rays produced by heating a high Z enclosure (hohlraum) that surrounds the fuel target (called *indirect drive*). The hohlraum in indirect drive schemes may be driven (heated) by lasers, particle beams, or pulsed power systems. During compression the fuel is kept as cold as possible to minimize the work needed for compression. At stagnation, a central hot spot enclosing a few percent of the total mass is heated and ignited. Ignition occurs when the alpha-particle heating of the hot spot exceeds all the energy losses. Ignition triggers a runaway process (the thermonuclear instability) resulting in a large amplification of the hot spot energy. If the inertia of the surrounding dense DT shell confines the ignited hot spot pressure long enough, the thermonuclear burn will propagate from the central hot spot to the dense shell and the entire fuel mass will burn. The burn is driven by the fusion alpha particles depositing their energy in the cold dense fuel. The burn lasts until the target disassembles, and the fuel burn-up fraction increases with the shell areal density.

Compressing a target to ignition conditions is very challenging and is yet to be fully realized in experiments, although major advances have been made. Drivers must deliver very uniform ablation; otherwise the target is compressed asymmetrically. Asymmetric compression excites strong Rayleigh-Taylor instabilities that spoil compression and mix dense cold plasma with the less dense hot spot. Preheating of the target can also spoil compression. For example, mistimed driver pulses can shock heat the target before compression. Also interaction of the driver with the surrounding plasma can create fast electrons that penetrate and preheat the target.

A widely used parameter to assess the performance of an ICF target is the target gain, G, representing the ratio of the fusion energy output to the driver energy entering the target chamber. Clearly a high gain is desirable for fusion energy and must remain a central focus of any inertial fusion energy program.

The fraction of driver energy that couples to the fusion fuel contained in the target is typically small—a few percent—but the fusion gain can still be substantial. In a National Ignition Facility indirect-drive ignition target driven by ~1MJ of UV laser light into the hohlraum, the shell of fuel implodes with an expected kinetic energy of about 15−20kJ. Roughly half of that energy (7−10kJ) is used to heat up the hot spot and the other half to compress the surrounding shell. If the fusion yield (alpha and neutron energy) is 1MJ (i.e., $G = 1$), the hot spot energy is amplified 100x by the thermonuclear instability. At 1MJ fusion yield, the alpha particles have deposited 200kJ of energy into the hot spot and surrounding fuel, about 20 times the energy provided by the compression of the hot spot. The thermonuclear burn stays localized near the hot spot and propagates within about 5 times the initial hot spot mass (partial burn). If the burn propagates through the entire DT mass, the gain of a NIF target will exceed ~10 (full burn and 10MJ yield). While a NIF implosion yielding G»1 would elucidate many aspects of the ignition and basic burn physics, a gain of $G \geq 10$ is required for demonstrating full burn propagation over the inertial confinement time of the compressed shell (i.e., fuel burn-up fraction compatible with the fuel inertia).

While the target gain can be used to validate the target physics, a new parameter is required for assessing the viability of a fusion energy system. The so-called "Engineering Q" or "$Q_E$" is often used as a figure of merit for a power plant. It represents the ratio of the total electrical power produced to the (recirculating) power required to run the plant—i.e., the input to the driver and other auxiliary systems. Clearly $Q_E = 1/f$, where f is the recycling power fraction—see Figure A.2. Typically $Q_E \geq 10$ is required for a viable electrical power plant. For a power plant with a driver wall-plug efficiency $h_D$, target gain G, thermal-to-electrical conversion efficiency $h_{th}$ and blanket amplification $A_B$ (the total energy released per 14.1 MeV neutron entering the blanket via nuclear reactions with the structural, coolant, and breeding material), the engineering Q is $Q_E = h_{th}h_DA_BG$ (see Figure A.2). An achievable value of the blanket amplifications and thermal efficiency might be $A_B \sim 1.1$ and $h_{th} \sim 0.4$ and should be largely independent of the driver. Therefore, the minimum required target gain is inversely proportional to the driver efficiency. For a power plant with a large recirculating power f = 20% ($Q_E = 5$), the required target gain is G = 75 for a 15% efficient driver, and G = 160 for a 7% efficient driver.

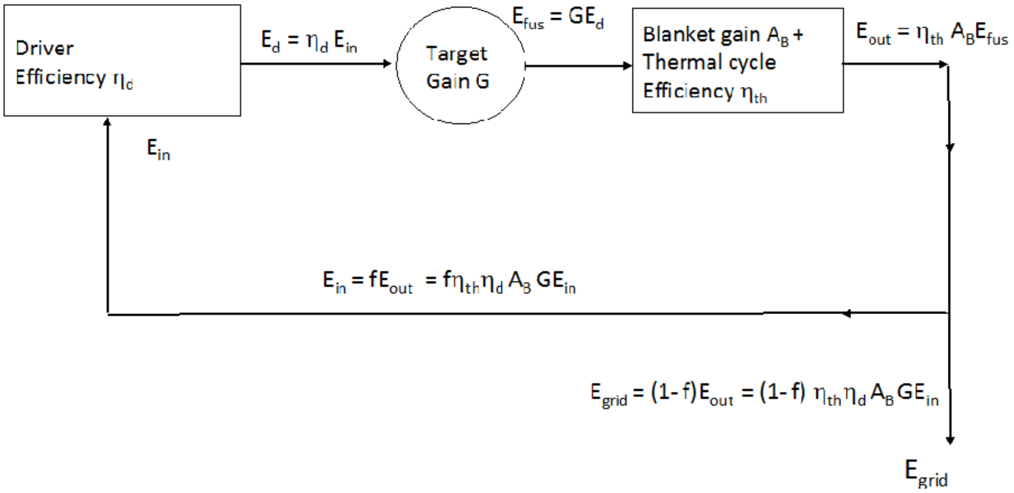

Figure A.2. Energy flow in a conceptual inertial fusion energy plant. Note $Q_E = 1/f$.

Energy gain does not, of course, guarantee commercial viability. Key challenges remain even after high gain is achieved. These will be discussed in detail in the final report, but they include:

- *Low-cost targets*. For example, a target producing a fusion energy, $E_D$, of 200MJ could make net electricity, $E_{grid}$ ~ 80MJ ~ 22kWh, or about \$1 worth of electricity at current prices. The target cost should be some small fraction of this.
- *Repetitive ignition of targets*. To produce a gigawatt of electrical power, targets with $E_D$ = 200MJ must be ignited roughly 12 times a second.
- *Reliable target chamber and blanket to extract power and breed tritium*, a challenge shared with magnetic fusion.

## Appendix B: Statements of Task

### For the Committee on the Prospects for Inertial Confinement Fusion Energy Systems

The statements of task for both the committee's final report and interim report (underlined) are shown below. The scope of the final report will be much broader than that of this interim report. The statement of task for the separate and supporting study by the Panel on the Assessment of Inertial Confinement Fusion (ICF) Targets is also shown. The statement of task for the committee is as follows:

> The Committee will prepare a report that will:
>
> - Assess the prospects for generating power using inertial confinement fusion;
> - Identify scientific and engineering challenges, cost targets, and R&D objectives associated with developing an IFE demonstration plant; and
> - Advise the U.S. Department of Energy on its development of an R&D roadmap aimed at creating a conceptual design for an inertial fusion energy demonstration plant.
>
> The Committee will also prepare an interim report to inform future year planning by the federal government.
>
> A Panel on Fusion Target Physics with access to classified information as well as controlled-restricted unclassified information will serve as a technical resource to the committee and will describe, in a report containing only publicly accessible information, the R&D challenges to providing suitable targets on the basis of parameters established and provided by the Committee. The Panel will also assess the current performance of various fusion target technologies.

### For the Panel on the Assessment of Inertial Confinement Fusion (ICF) Targets

The statement of task for the supporting panel is as follows:

> A Panel on Fusion Target Physics ("the Panel") will serve as a technical resource to the Committee on Inertial Confinement Energy Systems ("the Committee") and will prepare a report that describes the R&D challenges to providing suitable targets, on the basis of parameters established and provided to the Panel by the Committee.
>
> The Panel on Fusion Target Physics will prepare a report that will assess the current performance of fusion targets associated with various ICF concepts in order to understand:
>
> 1. The spectrum output;

2. The illumination geometry;
3. The high-gain geometry; and
4. The robustness of the target design.

The Panel will also address the potential impacts of the use and development of current concepts for Inertial Fusion Energy on the proliferation of nuclear weapons information and technology, as appropriate. The Panel will examine technology options, but will not provide recommendations specific to any currently operating or proposed ICF facility.

## Appendix C: Panel Membership and Staff for the Panel on the Assessment of Inertial Confinement Fusion (ICF) Targets

### *Panel Members*

John Ahearne, Sigma Xi, *Chair*
Robert Dynes, University of California at San Diego
Douglas Eardley, Kavli Institute for Theoretical Physics
David Harding, University of Rochester
Thomas Mehlhorn, Naval Research Laboratory
Merri Wood-Schultz, Consultant
George Zimmerman, Consultant

### *Staff*

Sarah Case, Study Director and Program Officer, Nuclear Radiation Studies Board
Greg Eyring, Program Officer, Division on Engineering and Physical Sciences
LaNita Jones, Administrative Coordinator, Board on Energy and Environmental Systems

# Appendix D: Agendas from Committee Meetings and Site Visits

## First Meeting
## National Academies – Keck Center – Washington, D.C.

### Thursday, December 16, 2010

| | | | |
|---|---|---|---|
| Closed Session | | | |
| 7:30 am | | *Breakfast available* | |
| 8:30 | | **Committee discussion** | *Ron Davidson &<br>Jerry Kulcinski, Co-Chairs* |
| 12:00 pm | | *Working Lunch (continued discussion)* | *Committee* |
| Open Session | | | |
| 1:00 | | **Welcome** | *Ron Davidson &<br>Jerry Kulcinski, Co-Chairs* |
| 1:15 | | **Perspectives from the DOE Office of Science** | *Steve Koonin* |
| 1:45 | | *Discussion* | |
| 2:00 | | **Perspectives from NNSA Stockpile Stewardship** | *Chris Deeney* |
| 2:20 | | *Discussion* | |
| 2:30 | | **Perspectives from the DOE Office of Fusion Energy Science** | *Ed Synakowski &<br>Mark Koepke* |
| 3:00 | | *Discussion* | |
| 3:15 | | *Break* | |
| 3:30 | | **Findings from the 2003 FESAC report: "A Plan for the Development of Fusion Energy"** | *Robert Goldston,<br>Michael Campbell* |
| 4:00 | | *Discussion* | |
| 4:15 | | **Findings from the 2004 FESAC report: "Review of the Inertial Fusion Energy Program"** | *Rulon Linford* |
| 4:45 | | *Discussion* | |
| 5:00 | | **Public Comment Session** | *Audience* |
| 6:00 | | *Meeting adjourns for day* | |

| CLOSED SESSION | | | |
|---|---|---|---|
| 6:30 | | *Working Dinner* | |

**Friday, December 17, 2010**

| CLOSED SESSION | | | |
|---|---|---|---|
| 7:30 am | | *Breakfast* | |
| 8:30 | | **Committee discussion** | *Co-Chairs* |
| OPEN SESSION | | | |
| 9:00 | | **Perspectives from the DOE Office of Science** | *Bill Brinkman* |
| 9:30 | | *Discussion* | |
| 9:45 | | **Perspectives from NNSA Defense Programs** | *Donald Cook* |
| 10:15 | | *Discussion* | |
| 10:30 | | *Break* | |
| 10:45 | | **Challenges to Developing an ICF-based Energy Source** | *Harold Forsen* |
| 11:15 | | *Discussion* | |
| 11:30 | | **Perspectives from OSTP** | *Steve Fetter* |
| 11:45 | | *General Discussion* | |
| CLOSED SESSION | | | |
| 12:15 pm | | *Working Lunch (including discussion of the below topics)* | |
| 1:00 | | **Committee discussion** | *Committee* |
| 3:00 | | *Adjourn* | |

## Second Meeting

## San Ramon, California

**Saturday, January 29, 2011**

| | | | |
|---|---|---|---|
| 7:30 am | | *Breakfast available* | |
| OPEN SESSION | | | |
| 8:00 am | | **Welcome and Opening Remarks** | *Ron Davidson &<br>Jerry Kulcinski, Co-Chairs* |
| 8:15 am | | **Laser-Driven Inertial Fusion Energy; Indirect-Drive Targets**<br>(including Q&A)<br>**Lawrence Livermore National Laboratory** | *Michael Dunne, Edward Moses, Jeff Latkowski, Tom Anklam, LLNL* |
| 10:15 am | | *Break* | |
| 10:30 am | | **Laser-Driven Inertial Fusion Energy; Direct-Drive Targets**<br>(including Q&A)<br>**University of Rochester** | *Robert McCrory, Stanley Skupsky, Jonathan Zuegel, LLE* |
| CLOSED SESSION | | | |
| 12:30 pm | | **Working Lunch: preparation of questions for Speakers from morning sessions** | |
| OPEN SESSION | | | |
| 1:00 pm | | **Krypton-Fluoride-Driven Inertial Fusion Energy**<br>(including Q&A)<br>**Naval Research Laboratory** | *John Sethian, Stephen Obenschain, NRL* |
| 3:00 pm | | *Break* | |
| 3:15 pm | | **Ion-Beam-Driven Inertial fusion Energy**<br>(including Q&A)<br>**Lawrence Berkeley National Laboratory** | *Grant Logan, LBNL* |
| CLOSED SESSION | | | |
| 4:45 pm | | **Discussion and Preparation of Questions for Speakers from Afternoon Sessions** | |
| OPEN SESSION | | | |
| 5:00 pm | | **Question and Answer Session with Speakers on All Driver Concepts** | |
| 6:00 pm | | *Adjourn open session* | |

| | | | |
|---|---|---|---|
| CLOSED SESSION | | | |
| 6:00 pm | | **Committee discussion** | |
| 9:00 pm | | *Adjourn for day* | |

**Sunday, January 30, 2011**

| | | | |
|---|---|---|---|
| CLOSED SESSION | | | |
| 7:30 am | | *Breakfast* | |
| OPEN SESSION | | | |
| 8:00 am | | **Pulsed-Power Inertial Fusion Energy & Targets**<br>(including Q&A)<br>**Sandia National Laboratories** | *Michael Cuneo,*<br>*Mark Herrmann,*<br>*SNL* |
| CLOSED SESSION | | | |
| 9:30 am | | **Discussion and Preparation of Questions for Morning Speaker** | |
| OPEN SESSION | | | |
| 9:45 am | | **Questions and Answer Session with Morning Speaker** | |
| 10:00 am | | **Perspectives from Los Alamos National Laboratory**<br>(including Q&A) | *Juan Fernández, LANL* |
| 10:45 am | | **Overview of IFE Target Designs**<br>(including Q&A)<br>*(During lunch)* | *John Perkins, LLNL* |
| 11:45 am | | *Break for lunch* | |
| 12:00 pm | | **Overview of Chamber and Power Plant Designs for IFE**<br>(including Q&A) | *Wayne Meier, LLNL* |
| 1:00 pm | | **Target Fabrication and Injection**<br>(including Q&A) | *Dan Goodin,*<br>*General Atomics* |
| 2:00 pm | | **Perspective of Stephen Bodner**<br>(including Q&A) | *Stephen Bodner* |
| 2:45 pm | | **General Question & Answer Period** | |
| 3:15 pm | | **Public Comment Session** | *All* |
| 4:15 pm | | *Adjourn open session* | |
| CLOSED SESSION | | | |
| 4:15 pm | | **Committee discussion** | |
| 8:30 pm | | *Adjourn for day* | |

**Monday, January 31, 2011**

| OPEN SESSION | | | |
|---|---|---|---|
| 7:15 am | | *Gather in hotel lobby* | |
| 7:30 am | | *Leave for LLNL via rental cars* | |
| 8:00 am | | **Site Visit: Lawrence Livermore National Laboratory** | |
| 11:15 am | | *Gather at rental cars* | |
| 11:30 am | | *Leave for LBNL via rental cars* | |
| 12:15 pm | | *Arrive at LBNL* | |
| 12:30 pm | | *Lunch at LBNL* | |
| 1:30 pm | | **Site Visit: Lawrence Berkeley National Laboratory** | |
| 4:00 pm | | *Return to hotel via rental cars / Depart for airports* | |
| 4:00 pm | | *Meeting adjourns* | |

## Third Meeting

## Albuquerque, New Mexico

**Tuesday, March 29, 2011**

| CLOSED SESSION | | | |
|---|---|---|---|
| 7:00 pm | | **Inertial Confinement Fusion and Inertial Fusion Energy Tutorial** *(committee only)* | *Steve Cowley &<br>Riccardo Betti* |
| 9:00 pm | | *Adjourn for day* | |

**Wednesday, March 30, 2011**

| CLOSED SESSION | | | |
|---|---|---|---|
| 7:30 am | | *Breakfast available* | |
| 8:00 am | | **Welcome and opening remarks**<br>• Plans and goals for the meeting | *Ron Davidson &<br>Jerry Kulcinski, Co-Chairs* |
| 8:30 am | | **Balance and composition discussion for new members** | *David Lang* |
| 8:45 am | | *Break* | |
| OPEN SESSION | | | |
| 9:00 am | | **Welcome and opening remarks** | *Ron Davidson &<br>Jerry Kulcinski, Co-Chairs* |
| 9:05 am | | **The National Ignition Campaign** | *John Lindl, LLNL* |
| 10:00 am | | *Discussion* | |
| 10:15 am | | **Role of the National Ignition Facility Beyond the National Ignition Campaign: NNSA Perspective** | *Chris Deeney, NNSA* |
| 10:45 am | | *Discussion* | |
| 11:00 am | | **LIFE Delivery Plan** | *Mike Dunne et al, LLNL* |
| 12:00 pm | | *Discussion* | |
| CLOSED SESSION | | | |
| 12:15 pm | | *Lunch* | *Committee only* |
| OPEN SESSION | | | |
| 1:00 pm | | **Fast Ignition for Inertial Fusion Energy** | *Richard Freeman,<br>Ohio State University* |

| | | | |
|---|---|---|---|
| 1:45 pm | | *Discussion* | |
| 2:00 pm | | *Adjourn open session for the day* | |
| CLOSED SESSION | | | |
| 2:15 pm | | **Discussion with ICF Target Physics Panel Chair** | *John Ahearne, Chair, Target Physics Panel (by telecon)* |
| 3:15 pm | | **Committee discussion** | |
| 8:30 pm | | *Adjourn for day* | |

## Thursday, March 31, 2011

| | | | |
|---|---|---|---|
| CLOSED SESSION | | | |
| 7:30 am | | *Breakfast* | |
| OPEN SESSION | | | |
| 8:00 am | | **Magnetized Target Fusion** | *Glen Wurden, LANL, &<br>Irv Lindemuth, Univ. of Nevada at Reno* |
| 8:45 am | | *Discussion* | |
| 9:00 am | | **Chamber Materials Challenges for Inertial Fusion Energy** | *Steve Zinkle, ORNL* |
| 10:00 am | | *Discussion* | |
| 10:15 am | | *Break* | |
| 10:30 am | | **Lessons in Engineering Innovation** | *Elon Musk, SpaceX, Tesla Motors, Solar City (by videoconference)* |
| 11:00 am | | **Public Comment Session** | |
| 12:00 pm | | *Adjourn open session and break for lunch* | |
| CLOSED SESSION | | | |
| 12:00 pm | | *Lunch* | *Committee only* |
| 1:00 pm | | **Committee discussion** | |
| 8:30 pm | | *Adjourn for the day* | |

## Site Visit to Sandia National Laboratories

**Friday, April 1, 2011**

| | |
|---|---|
| 7:20 – 8:00 am | Committee travel and badging |
| 8:00 – 8:30 am | Remarks on Sandia and IFE<br>Steve Rottler,<br>Vice President Science and Technology and Research Foundations, and Chief Technology Officer |
| 8:30 – 10:00 am | Various presentations |
| 10:00 – 10:15 am | Break |
| 10:15 – 10:25 am | Walk to the Z facility |
| 10:25 – 10:55 am | Tour of the Z facility |
| 11:00 – 11:45 am | Mykonos facility |
| 12:00 pm | Depart for hotel and meeting adjourns |

## Fourth Meeting

## Rochester, New York

**Wednesday, June 15, 2011**

| CLOSED SESSION | | | |
|---|---|---|---|
| 8:00 am | | *Breakfast available* | *Seminar Room* |
| 8:30 am | | **Welcome and opening remarks** | *Ron Davidson &<br>Jerry Kulcinski, Co-Chairs* |
| 8:45 am | | *Break* | |
| OPEN SESSION | | | |
| 9:00 am | | **Welcome and opening remarks** | *Ron Davidson &<br>Jerry Kulcinski, Co-Chairs* |
| 9:05 am | | **Inertial Fusion Energy: Activities and Plans in the UK and EU** | *John Collier, UK Science and Technology Facilities Council* |
| 10:15 am | | *Discussion* | |
| 10:35 am | | *Break* | |
| 10:50 am | | **Inertial Fusion Energy: Activities and Plans in Japan** | *Hiroshi Azechi, Institute of Laser Engineering,<br>Osaka University* |
| 12:00 pm | | *Discussion* | |
| 12:20 pm | | *Lunch* | *Seminar Room* |
| 1:00 pm | | **Integrated design of a laser fusion target chamber system** | *John Sethian,<br>Naval Research Laboratory* |
| 2:00 pm | | *Discussion* | |
| 2:20 pm | | *Adjourn open session for the day* | |
| CLOSED SESSION | | | |
| 2:30 pm | | **Discussion** | |
| 8:30 pm | | *Adjourn for day* | |

## Thursday, June 16, 2011

| | | | |
|---|---|---|---|
| CLOSED SESSION | | | |
| 8:00 am | | *Breakfast* | *Seminar Room* |
| OPEN SESSION | | | |
| 8:30 am | | **Nuclear Power Plant Financing** | *Philip M. Huyck, Encite, LLC (formerly of Credit Suisse First Boston & Trust Company of the West)* |
| 9:30 am | | *Discussion* | |
| 9:45 am | | **Inertial Fusion Energy: Activities and Plans in China** | *Zhang Jie<br>President,<br>Shanghai Jiao Tong University* |
| 11:00 am | | *Discussion* | |
| 11:20 am | | **Public Comment Session** | |
| 11:30 am | | **General Discussion with All Speakers** | *Committee & Speakers* |
| 12:00 pm | | *Adjourn open session and break for lunch* | |
| CLOSED SESSION | | | |
| 12:00 pm | | *Lunch* | *Seminar Room<br>Committee only* |
| 1:00 pm | | **Discussion with ICF Target Physics Panel Chair** | *John Ahearne, Chair, Target Physics Panel* |
| 2:00 pm | | **Continued discussion** | |
| 8:30 pm | | *Adjourn for the day* | |

## Site Visit to the Laboratory for Laser Energetics

### Friday, June 17, 2011

| | | | |
|---|---|---|---|
| CLOSED SESSION | | | |
| 7:30 am | | *Breakfast available* | *Seminar Room* |
| 8:00 am | | **Discussion** | *All* |
| 9:30 am | | *Break & Gather at Seminar Room for site visit* | |
| OPEN SESSION | | | |
| 9:45 am | | **LLE overview** *(in Seminar Room)* | *R.L. McCrory* |
| 10:15 am - 12:00 pm | | **Site tours and posters**<br>• Break Panel into three groups each with a primary tour guide. Tour guides:<br>○ R.L. McCrory<br>○ D.D. Meyerhofer<br>○ P. McKenty<br>• Three Stations, each with two posters and facility presenter (~1/2 hour at each station)<br>○ OMEGA<br>▪ S. Morse<br>▪ Poster on Cryogenic target performance and Polar Drive– V Goncharov<br>▪ Poster on Omega as a User Facility – J. Soures<br>○ OMEGA EP<br>▪ D. Canning<br>▪ Poster on Fast/Shock Ignition – W. Theobald<br>▪ Poster on new technologies for EP – J. Zuegel<br>○ OMAN<br>▪ A. Rigatti<br>▪ Poster on high damage threshold coatings – J. Oliver<br>▪ Poster on diffractive optics – T. Kessler | |

| | | | |
|---|---|---|---|
| | | | |
| 12:00 pm | | ***Tour ends at Seminar Room.***<br>***Adjourn site visit, adjourn meeting, and depart.*** | |

## Appendix E: Bibliography of Previous Inertial Confinement Fusion Studies Consulted by the Committee[31]

National Research Council, *Review of the Department of Energy's Inertial Confinement Fusion Program*, National Academy Press, 1986.

National Research Council, *Review of the Department of Energy's Inertial Confinement Fusion Program*, National Academy Press, 1990.

Fusion Energy Advisory Committee, "Panel 7 Report on Inertial Fusion Energy," *Journal of Fusion Energy*, Vol. 13, Nos. 2/3, 1994.

National Research Council, *Review of the Department of Energy's Inertial Confinement Fusion Program: The National Ignition Facility*, National Academy Press, 1997.

Fusion Energy Advisory Committee, "Report of the FEAC Inertial Fusion Energy Review Panel: July 1996," *Journal of Fusion Energy*, Vol. 18, No. 4, 1999.

Fusion Energy Sciences Advisory Committee, "Opportunities in the Fusion Energy Sciences Program," June 1999.

Fusion Energy Sciences Advisory Committee, "Report of the FESAC Panel on Priorities and Balance," September 13, 1999.

Fusion Energy Sciences Advisory Committee, "Review of the Fusion Theory and Computing Program," August 2001.

Report from the 2002 Fusion Summer Study, "2002 Fusion Summer Study Report," Snowmass, Colorado, July 8-19, 2002.

Fusion Energy Sciences Advisory Committee, "Report of the Fusion Energy Sciences Advisory Committee Burning Plasma Strategy Panel: A Burning Plasma Program Stratregy to Advance Fusion Energy," September 2002.

Fusion Energy Sciences Advisory Committee, "Report of the Fusion Energy Sciences Advisory Committee Fusion Development Path Panel: A Plan for the Development of Fusion Energy," March 2003.

National Research Council, *Frontiers in High Energy Density Physics: The X-Games of Contemporary Science*, The National Academies Press, 2003.

---

[31] NOTE: For brevity, the committee presents here only studies it consulted that were produced by the National Research Council and federal advisory committees. A full list of materials consulted by the committee is available through the National Academies' Public Access Records Office.

Fusion Energy Sciences Advisory Committee, “Review of the Inertial Fusion Energy Program,” March 2004.

National Research Council, *Burning Plasma: Bringing a Star to Earth*, The National Academies Press, 2004.

Fusion Energy Sciences Advisory Committee, “Scientific Challenges, Opportunities and Priorities for the U.S. Fusion Energy Sciences Program,” April 2005.

National Research Council, *Plasma Science: Advancing Knowledge in the National Interest*, The National Academies Press, 2007.

Fusion Energy Sciences Advisory Committee, “Panel on High Energy Density Laboratory Plasmas: Advancing the Science of High Energy Density Laboratory Plasmas,” January 2009.

Executive Office of the President, President’s Council of Advisors on Science and Technology, “Report to the President on Accelerating the Pace of Change in Energy Technologies Through an Integrated Federal Energy Policy,” November 2010.

## Appendix F: Agendas from Meetings of the Panel on the Assessment of Inertial Confinement Fusion (ICF) Targets

### First Meeting: February 16-17, 2011
### Keck Center of the National Academies, Washington, D.C.

### Wednesday, February 16, 2011

### DATA-GATHERING SESSION: OPEN TO THE PUBLIC

10:15 am **Welcome and Call to order**
*John Ahearne, panel chair*

10:20 am **Review of charge to the panel, the U.S. Department of Energy's interests in the committee and panel reports, and nuclear weapons proliferation risks for an inertial fusion energy program**
*David Crandall, Office of the Under Secretary for Science, U.S. Department of Energy*

10:50 am Questions and discussion

11:05 am **Indirect drive target physics at the National Ignition Facility (NIF)**
*John Lindl, Lawrence Livermore National Laboratory*

11:25 am Questions and discussion

11:50 am **Direct drive target physics at the Naval Research Laboratory (NRL)**
*Andrew Schmitt, Naval Research Laboratory*

12:10 am Questions and Discussion

**WORKING LUNCH (12:35 pm – 1:15 pm)**

1:15 pm **Direct drive target physics at NIF**
*David Meyerhofer, Laboratory for Laser Energetics*

1:35 pm Questions and Discussion

2:00 pm **Heavy ion target physics**
*John Perkins, Lawrence Livermore National Laboratory*

2:20 pm Questions and Discussion

| | |
|---|---|
| 2:45 pm | **Z pinch target physics**<br>*Mark Herrmann, Sandia National Laboratories* |
| 3:00 pm | Questions and Discussion |
| 3:15 pm | **Opportunity for Public Comment** |
| 3:30 pm | **Adjourn Data-Gathering Session Open to the Public** |

**Thursday, February 17, 2011**

## DATA-GATHERING SESSION: OPEN TO THE PUBLIC

| | |
|---|---|
| 8:15 am | **Non-proliferation considerations associated with inertial fusion energy**<br>*Raymond Jeanloz, University of California, Berkeley* |
| 8:35 am | Questions and Discussion |
| 8:55 am | Opportunity for public comment |
| 9:00 am | **Adjourn Data-Gathering Session Open to the Public** |

## DATA-GATHERING SESSION: NOT OPEN TO THE PUBLIC

**This session from 9:15 a.m. to 1:00 p.m. will involve information restricted from public release.**

| | |
|---|---|
| 9:15 am | **Call to order**<br>*John Ahearne, panel chair* |
| 9:20 am | **Additional comments from sponsors**<br>*David Crandall, Office of the Under Secretary for Science* |
| 9:35 am | Questions and Discussion |
| 9:50 am | **Test data relevant to inertial confinement fusion (ICF) and further Q&A on indirect drive target physics at NIF**<br>*Douglas Wilson, Los Alamos National Laboratory*<br>*Steven Haan, Lawrence Livermore National Laboratory* |
| 10:20 am | Questions and Discussion |

**BREAK (10:50 a.m. - 11:00 a.m.)**

11:00 am **Z-pinch target physics, continued**
*Mark Herrmann, Sandia National Laboratories*

11:20 am Questions and Discussion

11:45 am **Non-proliferation considerations associated with inertial fusion energy, continued**
*Raymond Jeanloz, University of California, Berkeley*

12:15 pm **Non-cryogenic ignition targets**
*John Perkins, Lawrence Livermore National Laboratory*

12:35 pm Questions and Discussion

1:00 pm **Adjourn Data-Gathering Session Not Open to the Public**

## Second Meeting: April 6-7, 2011
## Pleasanton and Livermore, California

## AGENDA

### Wednesday, April 6, 2011

### DATA-GATHERING SESSION: OPEN TO THE PUBLIC

**Location: Pleasanton Marriott, Danville Room**
**11950 Dublin Canyon Road, Pleasanton, California 94588**

9:00 am **Welcome and Call to order**
*John Ahearne, panel chair*

### DISCUSSION 1: THE CONTRIBUTION OF THE NATIONAL IGNITION FACILITY (NIF) PROGRAM TO INERTIAL FUSION ENERGY (IFE)

9:05 am **System Considerations for IFE**
*T. Anklam, Lawrence Livermore National Laboratory (LLNL)*

9:50 am **Overview of Laser Inertial Fusion Energy (LIFE) System and Key Considerations for IFE Targets**
*M. Dunne, LLNL*

**BREAK (10:50 – 11:00)**

11:00 am **Open Question and Discussion Session**

11:45 am **Opportunity for Public Comment**

12:00 pm **Adjourn Data-Gathering Session Open to the Public**

*12:00 pm -12:45 pm: Travel to Livermore*

## DATA-GATHERING SESSION: NOT OPEN TO THE PUBLIC

**This session from 12:45 p.m. to 5:00 p.m. will involve information restricted from public release.**

**Location: Lawrence Livermore National Laboratory**
**7000 East Avenue, Livermore, CA 94550**

**WORKING LUNCH (12:45 pm – 1:30 pm) – Continued Q&A from morning briefings**

1:30 pm **Options:**

- **Tour of NIF and Q&A;**
  *Ed Moses, LLNL*
- **Briefing on NIF in conference room and Q&A.**

## DISCUSSION 2: CALIBRATION AND VALIDATION OF PLANS FOR ACHIEVING IGNITION AND HIGH GAIN

2:00 pm **NIC Overview and Challenges that must be addressed to validate ICF ignition physics**
*J. Lindl, LLNL*

**BREAK (3:00 – 3:10)**

3:10 pm **Code Modeling and Benchmarking**
*J. Lindl and M. Marinak*

4:10 pm **Open Question and Discussion Session**

5:00 pm **Adjourn Data-Gathering Session Closed to the Public**

## THURSDAY, APRIL 7, 2011

*7:00 am* *Meet in Lobby of Pleasanton Marriott for transport to Livermore*

7:30 am **Breakfast available at Livermore**

### DATA-GATHERING SESSION: NOT OPEN TO THE PUBLIC

**This session from 8:15 a.m. to 12:30 p.m. will involve information restricted from public release.**

### DISCUSSION 3: LIFE TARGET SYSTEM DESIGN AND DEVELOPMENT

8:15 am **LIFE Target system design**
*P. Amendt, LLNL*

9:00 am **LIFE Development Plans**
*TBA, LLNL*

10:00 am **Open Question and Discussion Session**

**BREAK (10:45 a.m. - 11:00 a.m.)**

### DISCUSSION 4: PROLIFERATION

11:00 am **Nonproliferation and IFE**
*R. Lehman, LLNL*

12:00 pm **Open Question and Discussion Session**

12:30 pm **Adjourn Data-Gathering Session Not Open to the Public**

## Third Meeting: May 10-11, 2011
## Albuquerque, New Mexico

### Tuesday, May 10, 2011

### DATA-GATHERING SESSION: OPEN TO THE PUBLIC

8:30 am **Welcome and Call to order**
*John Ahearne, panel chair*

8:35 am **Inertial Confinement Fusion (ICF) Targets at Los Alamos National Laboratory**
*Juan Fernandez, Los Alamos National Laboratory*

9:05 am Questions and Discussion

9:35 am **Design and simulation of Magnetized Liner Inertial Fusion targets**
*Steve Slutz, Sandia National Laboratories (SNL)*

10:05 am Questions and Discussion

10:35 am **Opportunity for Public Comment**

10:45 am **Adjourn Data-Gathering Session Open to the Public**

*10:45 am -11:45 am: Travel to Sandia*

### DATA-GATHERING SESSION: NOT OPEN TO THE PUBLIC

**This session from 11:45 p.m. to 4:30 p.m. will involve information restricted from public release.**

**Location: Sandia National Laboratories**

**WORKING LUNCH (11:45 am – 12:30 pm) – Q&A with Juan Fernandez, LANL**

12:30 pm **Welcome to Pulsed Power Sciences Center**
*Keith Matzen, SNL*

12:45 pm **Options:**
- **Tour of Z facility and Q&A;**
  *TBA*
- **Briefing on Z facility in conference room and Q&A.**
  *TBA*

1:45 pm **The potential for a Z-pinch fusion system for IFE and target design**
*Mark Herrman, SNL*

2:30 pm Questions and Discussion

**BREAK (3:00 – 3:15)**

3:15 pm **Fusion target experiments and technical contract**
*Dan Sinars, SNL*

4:00 pm Questions and Discussion

4:30 pm **Adjourn Data-Gathering Session Closed to the Public**

## WEDNESDAY, MAY 11, 2011

## DATA-GATHERING SESSION: NOT OPEN TO THE PUBLIC

**This session from 8:00 a.m. to 10:30 p.m. will involve information restricted from public release.**

8:00 am **Z-pinch target design and development**
*Stephanie Hansen, SNL*

8:45 am Questions and Discussion

9:15 am **Fusion target simulations and validation**
*Charlie Nakhleh, SNL*
10:00 am Questions and Discussion

10:30 am **Adjourn Data-Gathering Session Not Open to the Public**

**Fourth Meeting: July 6-8, 2011**
**Rochester, New York**

**Wednesday, July 6, 2011**

## DATA-GATHERING SESSION: OPEN TO THE PUBLIC

8:25 am **Welcome and Call to order**
*John Ahearne, panel chair*

8:30 am **Welcome and Overview of LLE's ICF program**
*Robert McCrory, LLE*

9:15 am Questions and Discussion

10:00 am **Direct-Drive Progress on OMEGA**
*Craig Sangster, LLE*

10:30 am Questions and Discussion

**BREAK (11:00 – 11:15 am)**

11:15 am **Polar Drive Target Design**
*Radha Bahukutumbi, LLE*

11:45 am Questions and Discussion

**WORKING LUNCH (12:15 – 1:15 pm) – Free Q&A with Speakers**

1:15 pm **Facilitating NIF for Polar Drive**
*David Meyerhofer, LLE*

1:35 pm Questions and Discussion

2:00 pm **Fast and Shock Ignition Research**
*David Meyerhofer, LLE*

2:30 pm Questions and Discussion

**BREAK (3:00 – 3:15)**

3:15 pm **LPI Issues for Direct Drive**
*Dustin Froula and Jason Myatt, LLE*

3:45 pm Questions and Discussion

4:15 pm **Opportunity for Public Comment**

4:30 pm **Adjourn Open Session**

## THURSDAY, JULY 7, 2011

## DATA-GATHERING SESSION: OPEN TO THE PUBLIC

8:00 am **OPTIONAL: Tour of OMEGA**

9:00 am **Heavy Ion Target Design**
*B. Grant Logan, Lawrence Berkeley National Laboratory*

9:45 am Questions and Discussion

**BREAK (10:30 – 10:45 am)**

10:45 am **Discussion of LIFE Targets and Program**
*Mike Dunne, Lawrence Livermore National Laboratories*

11:15 am Questions and Discussion

**WORKING LUNCH (11:45 am – 12:45 pm) – Free Q&A with Speakers**

12:45 pm **Technical Feasibility of Target Manufacturing**
*Abbas Nikroo, General Atomics*

1:15 pm Questions and Discussion

1:45 pm **Opportunity for Public Comment**

2:00 pm **Adjourn Open Session**

## Appendix G: Glossary of Terms and Acronyms Used in This Report

### Terms

Cryogenic: involving very low temperatures

Diode-pumped lasers: lasers wherein laser diodes illuminate a solid gain medium (such as a crystal or glass).

Direct drive: inertial confinement fusion (ICF) technique whereby the driver energy strikes the fuel capsule directly.

Driver: The mechanism by which energy is delivered to the fuel capsule. Typical techniques use lasers, heavy-ion beams, and Z-pinches.

Fast ignition: ICF technique whereby the driver gradually compresses the fuel capsule, at which point a high-intensity, ultrashort-pulse laser strikes the fuel to trigger ignition.

Gain: ratio of the fusion energy released by the target to the driver energy applied to the target in a single explosion.

Heavy-ion fusion: ICF technique whereby ions of heavy elements are accelerated and directed onto a target.

High average power: maintaining a high, repeatable driver power that is suitable for an inertial confinement fusion-based power plant.

High-energy-density science: the study of the creation, behavior, and interaction of matter with extremely high energy densities.

High repetition rate: maintaining a high rate for engaging the driver or igniting the target, suitable for an inertial confinement fusion-based power plant (e.g., 10 Hz).

Ignition (broad definition): the condition in a plasma when self-heating from nuclear fusion reactions is at a sufficient rate to maintain the plasma, its temperature and fusion reactions, without the need to apply any external energy to the plasma.

Ignition (IFE): a state when fusion gain exceeds unity, i.e., when the fusion energy released in a single explosion exceeds the energy applied to the target.

Indirect drive: inertial confinement fusion technique whereby the driver energy strikes the fuel capsule indirectly, i.e., by the x-rays produced by heating a high-Z enclosure (hohlraum) that surrounds the fuel capsule.

Inertial confinement fusion (ICF): concept in which a driver delivers energy to the outer surface of a pellet of fuel (typically containing a mixture of deuterium and tritium), heating and compressing it. The heating and compression then initiate a fusion chain reaction.

Inertial fusion energy: concept whereby ICF is used to predictably and continuously initiate fusion chain reactions that yield more energy than that incident on the fuel from the driver for the ultimate purpose of producing electrical power.

Krypton fluoride (KrF) laser: a gas laser that operates in the ultraviolet at 248nm.

Magnetic target fusion: ICF technique whereby a magnetic field is created surrounding the target, and the magnetic field is then imploded around the target, initiating fusion reactions.

Pulse compression: a technique whereby the incident pulse is compressed to deliver the energy in a shorter time.

Pulsed-power fusion: ICF technique whereby a large electrical current is used to magnetically implode a target.

Reactor chamber: The apparatus in which the fusion reactions would take place in an inertial fusion energy power plant, and which would contain and capture the resulting energy released from repeated ignition.

Shock ignition: ICF technique that uses hydrodynamic shocks to ignite the compressed hot spot.

Target: the fuel capsule, together with a holhraum or other energy-focusing device (if one is used), that is struck by the driver’s incident energy in order to initiate fusion reactions.

**Acronyms**

| | |
|---|---|
| DOE | U.S. Department of Energy |
| $GW_e$ | Gigawatts of electrical power |
| ICF | Inertial confinement fusion |

| | |
|---|---|
| IFE | Inertial fusion energy |
| LIFE | Laser Inertial Fusion Energy |
| MeV | Million electron volts |
| MFE | Magnetic fusion energy |
| NIF | National Ignition Facility |
| NNSA | National Nuclear Security Administration |
| NRC | National Research Council |
| OFES | Office of Fusion Energy Sciences (DOE) |
| R&D | Research and development |