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STATUS OF TARGET PHYSICS FOR INERTIAL CONFINEMENT FUSION

Report on the Review Held on November 14-17, 1988

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**United States Department of Energy
Assistant Secretary for Defense Programs
Deputy Assistant Secretary for Military Application
Office of Weapons Research, Development and Testing
Inertial Fusion Division**

March 1990

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Report on the Review
at
DOE Headquarters
Germantown, MD
on
Nov. 14-17, 1988

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MASTER

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FOREWORD

This document is an unclassified report on a classified meeting covering a classified subject. By necessity, all classified information has been deleted at the expense of completeness and continuity.

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FOREWORD

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EXECUTIVE SUMMARY

A four day review to assess the status of target physics of inertial confinement fusion was held at U.S. Department of Energy (DOE) Headquarters on November 14-17, 1988. This review completes the current series of reviews of the inertial fusion program elements to assess the status of the data base for a decision to proceed with the proposed Laboratory Microfusion Facility (LMF) that is being planned. In addition to target physics, the program elements that have been reviewed previously include the driver technology development for KrF and solid-state lasers, and the light-ion beam pulsed power system. To provide DOE with unencumbered views, independent reviewers who are recognized experts in relevant fields but not currently associated with the ICF program were utilized.

This series of reviews was undertaken for internal DOE assessment in anticipation of the ICF program review mandated by the Congress in 1988 to be completed in 1990 to assess the significance and implications of the progress that has been realized in the laboratory and the underground Halite/Centurion experiments. For this target physics review, both the direct and the indirect drive approaches were considered. The principal issues addressed in this review were: (1) Is the present target physics data base adequate for a decision to proceed with design and construction of LMF now as opposed to continue planning activities at this time? (2) What specific additional target physics data are desirable to reduce the risk for a DOE decision to construct an LMF? (3) What is the role for continuation of Halite/Centurion experiments? (4) What priority should be given to the direct drive approach? (5) Are the program elements optimally structured to resolve the critical issues for an LMF decision? Specific findings relating to these five issues are summarized in the following.

1. Is the present target physics data base adequate for a decision to proceed with design and construction of LMF now as opposed to continued planning activities at this time?

The aim of the ICF program is to implode a capsule containing deuterium and tritium (D/T) with directed energy from a driver to achieve core ignition and propagation of the D/T burn to achieve high fusion yield. The original concept for ICF is by direct drive. There was concern, however, that the coupled

requirements for driver illumination symmetry, suppression of plasma instabilities in the corona, and maintenance of the stability of the implosion required by the direct drive approach may be difficult to meet simultaneously. The indirect drive approach differs from the direct drive approach in the use of a hohlraum to convert the directed beam energy to X-rays that then drive the capsule that is suspended inside the hohlraum. This approach was expected to relax and uncouple some of the critical requirements. A recognized disadvantage, however, is the somewhat higher energy requirements associated with indirect drive. For these reasons, on balance, indirect drive has been pursued in the last few years as the mainline approach with direct drive considered as a backup option.

A principal finding of the review is that recent experiments have demonstrated the physics to validate the basic concept of ICF. Even with these and NOVA experimental results, there is a unanimous consensus among the independent reviewers that the present target physics data base is not adequate for a decision to proceed with the design and construction of LMF at this time. However, in light of the promising results that have been achieved, continued planning for the LMF is highly appropriate.

2. What specific additional target physics data are desirable to reduce the risk for a DOE decision to construct an LMF?

For indirect drive, driver beam quality and beam-plasma interaction are expected to be issues of concern in the efficient conversion of driver beam energy to X-rays for symmetric illumination of the capsule. These basic physics issues have not been addressed adequately and still need to be resolved.

For the direct drive approach, significant advances have been realized in improving beam uniformity and understanding the suppression of beam-plasma instabilities. Furthermore, promising techniques have been developed for beam profile smoothing and pulse shaping to achieve required target illumination symmetry. However, there is still the need to demonstrate scaling of these techniques to power levels required for LMF sized targets.

3. What is the role for continuation of Halite/Centurion experiments?

As noted, the Halite/Centurion experiments have allowed demonstration of excellent performance, putting to rest fundamental questions about basic feasibility to achieve high gain. Beyond present planning, the utility of this type of experiment should be reassessed.

4. What priority should be given to the direct drive approach?

The direct drive approach has been considered as a backup option because of concerns for meeting multiple plasma physics and driver technology requirements that are strongly coupled. In the last few years, the direct drive community has made significant progress in developing techniques and physics understanding to alleviate some of these concerns which are now shared by the indirect drive approach. At the same time, the driver energy required to achieve stable implosion by direct drive is edging toward levels comparable with the lower range of indirect drive approach. For these reasons, efforts to develop the direct and indirect drive approaches are now more complementary than competitive. Therefore, the direct drive program should be continued, not only as a backup and potential alternative option, but also to complement the indirect drive program in addressing some of the common critical issues.

5. Are the program elements optimally structured to resolve the critical issues for an LMF decision?

At present, the progress that can be expected in resolving the remaining target physics issues are largely resource and facility limited but the pace and plans are on track to provide the necessary target physics data base for a decision on the LMF in a 3 to 5 year time frame. Additional resources would increase the probability of resolving key physics issues associated with the LMF decision in a timely way. Both the direct and indirect drive programs should address the physics issues that could reduce the minimum size of the LMF without additional technical risk. Priorities should continue to buttress and not compromise the physics research. Continued planning for the LMF at this time is well justified and the ICF community should develop a strategy of cooperation to resolve the remaining critical issues. In particular, significant additional resources are

required to develop the data base on driver technology to determine energy, power and cost scaling that will also be needed for the LMF decision. However, the additional resources for driver development cannot be generated at the expense of the target physics program without severely damaging the possibility of an LMF decision in the time frame desired.

I. INTRODUCTION

A four day review to assess the status of target physics for proceeding with the planning of the Laboratory Microfusion Facility (LMF) was held at DOE headquarters from November 14 through 17, 1988. The review was divided into two parts. The first three days were devoted to the indirect drive program with presentations by Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL) and Sandia National Laboratory, Albuquerque (SNL) and to opportunities for structured comments by all laboratories participating in the U. S. Department of Energy's Inertial Confinement Fusion (ICF) Program. The fourth day was devoted to the direct drive approach with presentations by Naval Research Laboratory (NRL), the Laboratory of Laser Energetics at the University of Rochester (UR/LLE) and information relevant to the direct drive approach by LLNL. The presentations were followed by additional structured comments by other laboratories. This review was held at the direction of Dr. Sheldon Kahalas, Director of the Inertial Fusion Division (IFD), Office of Weapons Research, Development and Testing (WRDT), of Defense Programs (DP), U. S. Department of Energy. An agenda of the review is attached as Appendix A.

The present review completes the current CY 1988 series to assess the program elements of ICF to determine the appropriateness for a decision in the 1991-1992 time frame to proceed with the design and construction of the LMF. The previous reviews were directed to address specific driver technologies. The KrF laser was reviewed on January 27, 1988; solid state laser on June 14-15, 1988; and light ions on October 27, 1988. This review was directed to address target physics issues only, uncoupled from critical issues relating to drivers.

Attendance to this classified meeting was controlled. Laboratories represented included LLNL, LANL, SNL, NRL, UR/LLE and KMS Fusion. The reviewers were Timothy Coffey of NRL, Alexander Glass representing himself as a private consultant, William Lokke of LLNL, Gene McCall of LANL, Robert Sproull of the University of Rochester, Thomas Stratton of LANL and Roy Woodruff of LLNL. The reviewers were chosen for their knowledge of the field, but none of the reviewers were associated with the ICF programs at their respective

laboratories*. They were asked to participate as individual consultants knowledgeable in the subject to provide independent expert opinions. The review was organized by Gregory D'Alessio of DOE/IFD. Preparation of this report was coordinated by James T. Woo of InterScience, Inc. under contract from DOE/IFD. A list of the participants is included in Appendix B. The professional histories of the reviewers are included in Appendix C.

During the review, the status and plans for addressing the indirect and direct drive target physics issues were presented by each of the laboratories. Each of the reviewers, as independent consultants, was asked to provide his individual assessment on the status of the program and critical issues that need to be resolved for a decision to proceed with an LMF. Specific findings and recommendations shared or expressed individually by the independent consultants for resolving the target physics issues for both the indirect and direct drive approaches are summarized in IV. These views were expressed by the consultants individually as expert opinions for consideration by DOE and are not to be construed as views having been accepted by DOE.

*It is to be noted that Dr. Glass was an independent consultant at the time of the review, but has since assumed a position at LLNL.

II. ASSESSMENT ON INDIRECT DRIVE

The independent consultants were asked to address two questions relating to the status of target physics in the context of planning for the inertial confinement fusion program. The questions are: (1) Is the present target physics data base adequate for an LMF decision? and (2) What specific additional target physics data are required to provide a firm basis for a DOE decision to construct an LMF? If the first question is interpreted to mean does a sufficient data base exist at this time for a decision to proceed immediately to the construction of LMF as opposed to the continued planning for such a facility, then there is a unanimous consensus that the answer is "no", while continued planning for the facility is strongly endorsed. Recent program results give confidence that ICF in the laboratory is attainable and there is every reason to continue vigorously with the ICF program at this time. On the other hand, the feasibility and desirability of proceeding with the LMF hinges on the ability to realize high-gain conditions with an affordable amount of driver energy [in the range of 10 Megajoules (MJ)] if the driver cost can be reduced to the hundred dollars per joule range. However, driver issues were not the concern for this review. In the target physics area, several critical issues were identified that need to be resolved before the feasibility of the LMF can be fully established. Therefore, the focus of this assessment is directed largely toward responding to the second question and how these issues can be resolved for a decision to proceed with the LMF in the 1991-1992 time frame.

The relevant issues relating to the status of target physics by the indirect drive approach are: (A) hohlraum physics, (B) implosion physics, (C) (Text Deleted) (D) target design and fabrication, and (E) driver beam quality related issues. This assessment is organized to discuss these issues in that order. Although this review was intended to address only the target physics issues, some coupling to specific drivers is unavoidable. In particular, the critical issues relating to hohlraum physics was discussed only for laser drivers. Therefore, the assessment is also concerned with laser plasma interactions in the hohlraum. Most of the work on implosion physics and target design have been done by LLNL and LANL. As a result, most of the comments in those sections are also directed mainly toward the LLNL and LANL efforts. To the extent possible, discussions on

driver (or laboratory) specific target physics issues have been isolated into a separate sub-section (E).

A. Hohlraum Physics

The role of the hohlraum is to convert driver energy to X-rays characterized by a desired radiation temperature inside the hohlraum. When the driver energy interacts with the material of the hohlraum wall, it generates X-rays to drive the capsule. Hohlraum design then becomes an important issue for indirect drive capsules. The critical issue is the effect of the interaction of the driver beam energy in the hohlraum.

There was a consensus among all the independent consultants that while problems associated with hohlraum design are generally well recognized by both laboratories, their potential seriousness has not been adequately addressed nor are the proposed solutions convincingly demonstrated at this time. The problem is not intractable but will be a challenging problem.

All of the independent consultants concurred that relevant experiments to address hohlraum physics should be carried out, as LLNL plans to do, with high priority. Mr. Stratton pointed out that implosion symmetry is to be established by the design of the hohlraum and can be affected by plasma effects. Mr. McCall noted that hohlraum symmetry question is being addressed with appropriate emphasis. He also suggested that the question of X-ray conversion and transport efficiency should be addressed in basic experiments to significantly reduce the present uncertainty even if true LMF conditions cannot be achieved. These and other discrepancies need to be resolved.

B. Implosion Physics

A key to realizing high gain is to achieve good symmetry in the implosion of a capsule designed to achieve high convergence. Assuming that the driver energy is uniformly absorbed on the surface of the capsule, the critical issues are: being able to predict the shape of the gain versus driver energy curve, requirements for maintaining the stability of the implosion, ability to model the mix and burn physics, and validation of the computer codes to predict performance. The

principal physics design tool is the LASNEX code, validated by target physics data.

The main target uncertainties are the drive energy required for high gain, the sensitivity of the gain to drive energy and the scaling of gain to lower absorbed energy. These and other uncertainties must be resolved before the LMF is designed.

With regard to degradation of normalized yield at lower absorbed energy, there is a sharp difference between LLNL and LANL in the interpretation. Several explanations were offered for the degradation. The two laboratories disagree on whether these effects are sufficiently understood at this time such that they can be properly controlled. LLNL presented NOVA data on high-convergence targets which fell within the predicted range. However, the range of uncertainty on the experimental data was large and LANL maintains that when measured parameters are used, there is no agreement.

Both laboratories agree that target performance is very sensitive to mix and asymmetry. Both Mr. Lokke and Mr. Coffey expressed confidence that, in their opinions, the important effects are being properly modeled and good agreement with experimental data should be forthcoming in the next few years. Mr. McCall also suggested that this is a subject very appropriate for collaboration with universities. The mix model developed by LLNL was greeted by Mr. Lokke as a major advance. He suggested that this should be further refined along with improvements to the 2-dimensional implosion model, possibly by using the Eulerian approach or allowing for slip. Mr. McCall also would like to see more options for transport calculation. To resolve the controversy between LLNL and LANL regarding whether the mix model is adequate for explaining the observed normalized yield degradation, both Mr. Coffey and Mr. McCall suggested that some experiment should be defined and carried out in the laboratory. Mr. McCall concurs with LANL that determining the sensitivity of the model to initial conditions is important and should be verified experimentally.

Mr. Coffey noted that it was pointed out during the review that radiation transport calculations do not adequately treat diffraction, the effect of non-LTE, etc. Mr. Lokke expressed the opinion that the target radiation flow and capsule

performance information form a consistent set of data which gives him confidence that while important details still need to be refined, description of the basic processes are well in hand. Mr. McCall suggested that view factors should be integrated into LASNEX to take hydrodynamic motion into account. He would also like to see additional post-processing codes while Mr. Lokke would like to see more plasma physics incorporated into LASNEX.

C. Target Design and Fabrication

To achieve high gain with < 10 MJ of driver energy, the present capsule designs are based on specific configurations. The design looks attractive but it must also be made practical. An approach for the fabrication of such configuration is being developed at KMS, LANL and LLNL.

There is very little effort and no data on target designs for light ions at this time. Mr. McCall suggested that SNLA needs help from the weapons laboratories in this area if light-ion driver is to be a contender for LMF. Furthermore, in developing their design, they should quote beam energy, intensity, and uniformity, etc., for pulse shapes believed to be possible for pulsed-power technology. Symmetry considerations and mix models should also be included.

D. (Title Deleted)

(Text Deleted)

E. Driver Beam Quality Related Issues

The principal driver candidates are solid state lasers with frequency tripling or quadrupling, KrF lasers, and light ions. Although a heavy ion driver is also a potential candidate, there is only a low level program to develop it at the present time. Issues relating to target physics that are driver or facility specific are considered in this subsection.

1. Solid State Lasers and NOVA

At the present time, NOVA is the only driver capable of doing indirect drive implosion experiments. Therefore, if LMF target physics issues are to be resolved in the next few years for an LMF decision, they must come (Text Deleted). LLNL plans to improve the energy and power balance and alignment of NOVA in what is called "precision NOVA". Mr. Glass emphasized that this improvement of NOVA is very important. He also recommended improvement of beam uniformity on at least one beam of NOVA for plasma physics experiments. It is difficult to characterize nonlinear effects with a beam subject to 4 to 1 intensity variations as is the case with NOVA at the present time. Mr. Lokke observed that the NOVA plan for pulse shaping experiments also seems very appropriate, given that precision pulse shaping is crucial for LMF capsules. They both agree that with these improvements, NOVA can then be used for further implosion and hohlraum physics studies to give greater confidence in target designs. Mr. Stratton suggested that these experiments should be carried out at LMF relevant parameters to validate compression at high convergence ratio and the new mix model.

Mr. McCall noted that the results of target experiments on NOVA are impressive and he has high hopes for definitive answers to the physics questions. He noted a discrepancy in the experimental bang-time with calculations and suggested that it deserves attention. He further suggested that hohlraum physics at 0.25 micron wavelength can be addressed by using one beam-line of NOVA into the 2-beam target area without disturbing the 10-beam experiments. If laser-plasma interaction at 0.35 micron should be found to be a problem, the availability of this data will be extremely important if the program is to be kept on a reasonable schedule.

2. KrF Lasers and AURORA

LANL has advanced the position that because of present uncertainties in target physics for scaling to LMF size, there should be an intermediate driver at the 1 MJ level as the next step. There was general consensus among all the independent consultants that the case made by LANL to postpone the decision for the LMF in favor of an intermediate drive as the next step is not very compelling.

Mr. Sproull pointed out that while such a step would be less risky, the slow down to the program would be quite intolerable. Mr. Lokke stated that there are no substitutes for studying unscalable problems in full scale. Mr. Woodruff pointed out that the cost for such an intermediate driver using existing technology would not be significantly less than the anticipated cost for the LMF driver. Furthermore, the NOVA facility is available to reduce the uncertainties associated with scaling to the LMF (to the same extent as an intermediate driver). Mr. Coffey urged that the community should try hard to obtain all the necessary data with existing facilities.

With regard to the application of KrF laser to target physics, Mr. Stratton suggested that experiments on AURORA should be directed to investigate pre-pulse and other target interaction issues with a target in the beam. However, a major target physics interaction program is not necessary since all the relevant issues can be addressed on NOVA. As pointed out by Mr. McCall, data on 0.25 micron wavelength can probably be obtained on NOVA more quickly at low additional cost, especially if crystals from NOVETTE still exist.

3. Light Ions and PBFA-II/HERMES-III

Although light-ion technology is being actively developed as a driver candidate at this time, its role in the LMF decision is very unclear at this time because there are no target physics data. In addition to developing the driver technology, as is the principal thrust at both LLNL and LANL, SNL must also develop a target data base at the same time in order to be in contention. The weapons laboratories have offered that as soon as light ions can show sufficient intensity for target experiments, they will be willing to provide the necessary help in developing the target designs. Therefore, the proper focus of the light-ion beam program should be for achieving beam intensities in the 100 TW/sq. cm. range as soon as possible.

III. ASSESSMENT ON DIRECT DRIVE

The direct drive approach is presently being pursued in the ICF program as a backup for indirect drive. It has been funded at a lower level than indirect drive and, therefore, is at an earlier stage of development. It is presently being supported as a more open ended basic research program. Fundamental research is still needed, as it was in the indirect approach several years ago. To assess the direct drive approach, the independent consultants were asked to respond to three questions: (1) Should direct drive target approach be pursued in the program with enough resources so it can be a competitor for the LMF? (2) What priority should be given to direct drive augmentation, (Text Deleted) and (3) What would be the minimum achievement for direct drive target physics to be considered a serious competitor to indirect drive for the LMF? In response to these questions, the comments by the independent consultants can be grouped into three topical areas and summarized accordingly in the following subsections: (1) status of the direct drive approach, (2) relative priority, and (3) critical issues.

A. Status of Direct Drive

Direct drive has been considered as a backup option to the indirect drive approach because of doubts about the feasibility of meeting the strongly coupled design requirements for driver illumination symmetry, plasma physics in the corona and stability of the implosion. A major finding shared by all the independent consultants, if not explicitly stated by each, is the opinion that the direct drive approach is not only very competitive with the indirect approach, but the efforts in advancing the two approaches are also highly complementary. This was found to be the case in all three critical areas: driver development, laser-plasma interaction, and implosion dynamics.

In the driver development area, illumination symmetry requirements are being met by beam smoothing techniques such as induced spatial incoherence (ISI) being developed at NRL and by spectral dispersion through the use of random phase plates at UR/LLE. These developments not only advance the feasibility of the direct drive approach, it now appears that they may also be

needed for the indirect drive approach. At the same time, the previously anticipated higher overall energy efficiency for direct drive has largely disappeared. More realistic estimates of driver energy required to achieve high gain from credible direct drive target designs is in the few MJ range and may approach 10 MJ, similar to the requirement for indirect drive. Mr. Lokke suggested that this may be viewed as an advantage for the program in the sense of more options for the same driver development goals.

A similar situation exist in the area of laser-plasma interaction. Laser-plasma interaction is a concern to direct drive because the laser beam must penetrate the corona around the capsule generated in the ablation process. The concerns are for prevention or minimization of hot-electron production, beam filamentation, and excitation of plasma instabilities. (Text Deleted). It was recognized by all the independent consultants that the physics in the two cases are essentially the same. These issues remain to be addressed by both the direct and the indirect drive approaches.

Hydrodynamic stability of the implosion is an issue that is also common to both the direct and the indirect approaches. However, because of the use of high aspect ratio targets for direct drive, the requirement for maintaining stability is also severe. On the other hand, if stability can be maintained for higher aspect ratio targets, then the driver energy requirement can be reduced. NRL presented designs with in-flight aspect ratio of 150 that can yield high gain with < 1 MJ of driver energy. Both Mr. Coffey and Mr. McCall expressed skepticism about the credibility of such designs in terms of maintaining stability. In view of the potential impact, all of the independent consultants urged that more experiments and calculations should be carried out to determine if such designs can be credible. While the data showing compression to 100 times liquid density by the University of Rochester is impressive, the large discrepancy between measured and calculated neutron yields raises serious questions about the symmetry and stability of the implosion as well as capability of codes to predict the yield. The discrepancies between the NRL and UR/LLE codes with LASNEX need to be quickly resolved and the credibility of the codes improved by comparison with experiments.

B. Relative Priority

It is clear that more is known about the indirect drive approach than the direct drive approach. Mr. Woodruff noted that the requirements for beam smoothing, beam symmetry, low preheat absorption in the corona, and implosion stability are design specific issues that still need to be favorably resolved to establish the feasibility of direct drive. Mr. Stratton also observed that it is too late to pursue direct drive with resources comparable to that for the indirect drive at this time. On the other hand, the recent results have advanced the direct drive approach to be not only competitive with indirect drive, but complementary in addressing the critical issues. For this reason, there is unanimous consensus among the independent consultants that both programs should be pursued and commonalties exploited. It should be recognized, however, as pointed out by Mr. Glass, direct drive may not provide as much information relevant to military applications, but at present, that appears to be a secondary consideration.

In terms of relative priority with the indirect drive approach (Text Deleted). Mr. Glass also noted that with the present program structure, the direct drive approaches compete with (Text Deleted) primarily only for money and much less so for facilities or people. Because of the commonalties of the critical issues that have been identified in this review, the resources can largely be distributed on the basis of cooperation instead of competition. As pointed out by Mr. Stratton, the direct and indirect drives are working on different aspects of a common problem. (Text Deleted).

In terms of experimental facilities, Mr. Glass suggested that NOVA is the only laser capable of addressing the laser-plasma interaction and implosion dynamics issues in the relevant parameter regime for both approaches. However, Mr. Sproull observed that there is some question as to whether NOVA can be adapted for direct drive experiments and, if so, if it would be available and be cost effective for direct drive experiments. Mr. Glass noted that each of the ICF laboratories has proposed upgrades or expanded facilities and has presented valid arguments to support their proposals. However, in the current funding situation, in Mr. Glass' opinion, the program cannot even afford to add "free" facilities and he believes that operation of expanded experimental facilities will add an

insupportable burden to the already overtaxed operating budget of the ICF program. Therefore, a higher degree of cooperation between the laboratories to address the common problems is absolutely essential.

C. Critical Issues

The critical issues for direct drive are parallel to the indirect drive approach. These are: driver development, laser-plasma interaction, target design and fabrication, and implosion hydrodynamics.

In the area of driver development, in view of the commonality of driver requirements, the critical issues are essentially the same. Continued emphasis by the direct drive community on beam conditioning will benefit both approaches.

In the area of laser-plasma interactions, the physics of the critical issues for both approaches are also essentially the same. In the direct drive approach, the relevant intensity is 10^{13} to 10^{14} W/cm² per beam with overall irradiance in the 10^{14} to 10^{15} W/cm² regime. The concern is for filamentation and excitation of plasma instabilities which produce hot electrons. Mr. McCall is of the opinion that problems with laser-plasma interaction are potential show-stoppers and suggested that experiments at LLNL on NOVA should include participation by NRL and UR/LLE. Mr. Coffey urged that experiments in appropriate parameter regimes should be carried out in a cooperative fashion and such experiments can clearly benefit both approaches. Specifically, Mr. Stratton suggested that experiments with overlapping beams at intensity regimes of interest to both approaches are needed. Mr. Glass emphasized that experiments to study the physics of intense laser beam propagation in long scale-length plasmas should be devised.

A critical issue for direct drive is the stability of high convergence ratio pellets. Although this is also an issue for indirect drive, the requirements are being identified whereas for the direct drive, much less is known at this time. For the direct drive approach, OMEGA is the primary facility for exploring implosion dynamics in spherical geometry. Many of the key hydrodynamic issues can be addressed in planar geometry and this is being carried out at NRL. The very low

neutron yield from the experiment that achieved compression to one hundred times liquid density is puzzling in terms of understanding the hydrodynamics. All of the independent consultants expressed the opinion that this discrepancy must be properly explained for direct drive to be credible. Mr. McCall suggested, that the very least, this experiment should be repeated with higher accuracy to account for the discrepancy from calculations. He is of the opinion that even when the large distortion claimed by UR/LLE is included, it is not sufficient to explain the observed discrepancy. Mr. Lokke emphasized that it is important to demonstrate an understanding of the implosion dynamics before any upgrade is taken. Mr. Glass pointed out that a kilojoule (kJ) of energy deposited in the ablator in this experiment is very marginal for extrapolation to the LMF scale and Mr. Stratton suggested that experiments at higher energy (presumably with NOVA beams with appropriate modifications) to study implosion stability should be encouraged. The observed discrepancy in expected neutron yield is a serious concern. Mr. Woodruff noted that relevant implosion experiments can also be carried out on NOVA. Mr. Stratton also suggested that to develop the direct drive with the limited resources, there is the need to bootstrap on the indirect drive results and facilities. In particular, experiments at higher energy to study implosion stability should be encouraged.

Calibration of independently developed hydro codes at NRL and UR/LLE is clearly a critical issue that can significantly impact the credibility of the direct drive target designs. Mr. Coffey noted that both NRL and LLNL computationally arrived at the same expression for the growth rate of the Rayleigh-Taylor (RT) instability and any disagreements are probably overstated at the present time. Both Mr. Coffey and Mr. McCall urged that a code comparison program should be established to evaluate well defined test problems. They believe that such comparisons could lower the contention level in the program greatly and the technical importance of such comparisons cannot be overemphasized. Mr. Lokke expressed the opinion that DOE is not getting its money's worth if code comparison is being resisted due to either bureaucratic problems or personal reluctance.

To respond to the question, "What would be the minimum achievement for direct drive target physics to be considered a serious contender for the LMF?", a number of items were identified. The first is to demonstrate the propagation of

laser light at intensities of 10^{13} to 10^{14} W/cm² range through a plasma of relevant parameters to achieve superposed irradiance intensities of 10^{14} - 10^{15} W/cm² without the occurrence of Stimulated Raman Scattering (SRS) or filamentation. A second one is demonstration of implosion burn yield consistent with theoretical predictions. A third is demonstration of implosion stability at sufficiently high convergence ratio required for direct drive with yields approaching clean one-dimensional predictions. The fourth is calibration of hydro codes with inclusion of mix. Mr. Woodruff also suggested that a self-consistent design which meets the stability and plasma constraints for a 10 MJ class driver must be completed. As a direct comparison with indirect drive, Mr. Glass suggested comparing experimental results obtained on Omega and Nova with comparable energies deposited in the ablator by direct and indirect drive. In this case, target performance can be measured in a variety of ways, including "rho-R", temperature, convergence, neutron yield, and the ratio of yield to the clean, one-dimensional calculations. A direct comparison of this sort would have to be interpreted in light of computational projections of LMF-scale target performance.

IV. FINDINGS AND RECOMMENDATIONS

A. FINDINGS

- o The Halite/Centurion experiments have allowed demonstration of excellent performance, putting to rest fundamental questions about basic feasibility to achieve high gain.
- o In order to proceed to the Laboratory Microfusion Facility, there are a number of critical issues relating to target physics for both the direct and the indirect drive approaches that still need to be resolved.
- o Progress is largely resource and facility limited at the present time but the pace and plans for resolving the critical issues relating to target physics are reasonably on track to provide an adequate data base for a decision on LMF in a 3 to 5 year time frame.
- o Advances in improving the laser beam quality made by the direct drive community has significantly improved the prospect for this approach to be competitive with indirect drive.
- o The requirements and critical issues for both the direct and indirect drive approaches now appear to be very similar.
 - a. For 100 fold energy gain, the driver energy requirement is currently projected to be in the 5-10 MJ range. The expectation that high gain is attainable with lower energy requirement by direct drive needs to be further developed with additional research.
 - b. Precision pulse shaping and beam smoothing are required for direct drive
 - c. Problems associated with laser-plasma interaction may occur in both approaches and the physics issues are also closely related.

- d. Stability of high convergence ratio capsule design is critical to both approaches; the conditions may be slightly more severe for the direct drive targets.
- e. (Text Deleted)
- o The present program for the direct and indirect drive approaches are working on different aspects of a common problem and have complemented each other in addressing some of the common critical issues while providing options for ICF.
- o (Text Deleted)
- o (Text Deleted)
- o The NOVA facility has the potential capability for addressing many of the critical target physics issues within the present time scale for the LMF decision if it is appropriately upgraded.
- o The physics of 0.25 micron radiation interaction with plasma can also be studied on NOVA.
- o The data base on the adequacy of target design for light ions is largely lacking at this time.
- o There is no significant risk minimization advantage to consider an intermediate driver step at this time instead of developing the driver technology and physics data base for proceeding directly to the LMF.
- o The status of target physics is sufficiently promising to justify additional driver development effort at this time providing that these efforts do not detract from addressing ongoing target physics issues.
- o Significant additional resources are required for the ICF program to develop the data base on driver technology to determine energy, power and cost scaling that will also be needed for the LMF decision.

B. GENERAL RECOMMENDATIONS

- o (Text Deleted) LLNL and LANL should form a working group to identify issues that can be addressed in the Centurion/Halite (H/C) experiments and make maximum use of these experiments. The continued utility and cost effectiveness of the H/C program should be assessed.
- o The ICF community needs to develop a strategy of cooperation among all the laboratories to resolve the remaining critical issues within realistic resource expectations available to the ICF program.
- o The direct drive program should be continued, not only as a backup and potential alternative option, but also to complement the indirect drive program in addressing some of the common critical issues.
- o Development of cryogenic cooled targets are on the critical path to the LMF.
- o Suitable techniques for the fabrication and characterization of these targets must be given adequate attention.
- o Improving the beam quality on NOVA to establish it as an experimental facility that can be used to address both direct and indirect drive target physics issues should be considered by LLNL.
- o The practicality of making NOVA available with adequate diagnostics for addressing LMF relevant target physics issues with participation by the other laboratories should be considered. Experiments could include:
 - a. Laser-plasma interaction studies at LMF relevant parameters.
 - b. High convergence ratio target implosion
 - c. Test mix models

- o Light-ion beams must demonstrate adequate power density on target soon in order to remain in contention as a driver candidate for the LMF.
- o A sustained effort to benchmark and integrate useful codes should be carried out.
- o UR/LLE needs to resolve the large discrepancy in yield in the OMEGA experiment from clean one-dimensional calculations to lend confidence to the physics understanding of the direct drive approach.
- o The direct drive community should emphasize work on improving the beam quality and target uniformity to achieve the required specifications.

C. INDIVIDUAL RECOMMENDATIONS (*)

- o The use of multiple frequencies to suppress plasma instabilities should be examined for non-overlapping beams, such as will occur in an LMF configuration. (AG)
- o Many of the issues relating to beam transport and hohlraum physics can be addressed on NOVA as presently planned. They should be carried out to establish confidence in the target design. (AG)
- o LLNL should consider upgrading NOVA to 100 kJ energy as an LMF plasma physics simulator to carry out well diagnosed plasma physics studies. (WL)
- o The program for studying hohlraum physics should be greatly expanded (GM).

* Letters in parenthesis designate the specific individual making the comments: TC for Tim Coffey, AG for Alex Glass, WL for Bill Lokke, GM for Gene McCall, RS for Robert Sproull, TS for Tom Stratton, and RW for Roy Woodruff.

- o The possibility of using NOVA with frequency quadrupling to develop 0.25 micrometer data earlier and cheaper as an alternative to using AURORA should be investigated. (GM)
- o The ability to calculate focal-spot motion should be demonstrated (GM).
- o A series of hohlraum experiments with small changes in conditions should be performed to see if calculations can track the sensitivity to initial conditions at the level believed to be important in implosion. (GM)
- o A survey of useful codes for addressing symmetry problem should be carried out. (GM)
- o The recommendation by the 1986 Happer Committee report: "We strongly recommend that the DOE establish an Inertial Fusion Advisory Committee (IFAC) to provide technical advice and guidance on a continuing basis to the Assistant Secretary for Military Application." would benefit the program. (RS)
- o A joint design team should be formed within the ICF community to develop conceptual designs for the LMF that can provide common recommendations for the LMF by the design laboratories and other program participants. (RS, TS)

APPENDIX A
REVIEW AGENDA

AGENDA

TARGET PHYSICS REVIEW

Day One - November 14, 1988
Indirect Drive Target Physics Data Base Presentations

07:30 Check In

IFD Introduction

07:45 - 08:10 Kahalas/Woo - Introduction/Logistics
08:10 - 08:30 Bixler - LMF Requirements

LLNL Presentation

08:30 - 09:00 Storm - Overview
09:00 - 09:30 Lindl - Hohlraum Physics
09:30 - 10:15 Campbell - Nova Hohlraum Experiments
10:15 - 10:45 Suter - Nova Hohlraum Analysis
10:45 - 11:00 Break
11:00 - 12:00 Lindl/Kruer - High Gain Hohlraums
12:00 - 12:45 Lindl - Implosion Physics, Instability and Mix
12:45 - 13:15 Break for working lunch setup
13:15 - 14:15 Haan - Mix Models
14:15 - 15:00 Kilkenny - NOVA Capsule Experiments
15:00 - 15:30 Hatchett - NOVA Capsule Analysis
15:30 - 15:45 Break
15:45 - 16:30 Lindl - High Gain Capsules
16:30 - 16:45 Storm - Summary and Conclusions

TARGET PHYSICS REVIEW

Day Two - November 15, 1988

Indirect Drive Target Physics Data Base Presentations - Continued

LANL Presentation

08:00 - 08:45	Cartwright - LANL Views and Issues
	Henderson - ICF and Weapons-Related Physics
08:45 - 10:00	Mead - Characteristics of LMF Targets
	o Capsule Performance
	o Hohlraum Performance
	o LMF Target Issues
	- Indirect Drive
	- Direct Drive
10:00 - 10:15	Break
10:15 - 11:45	Driver-Target Coupling
	Jones - Laser-Plasma Coupling
	Magelssen - Drive Conditions
11:45 - 12:15	Break for working lunch setup
12:15 - 14:45	Capsule Performance and Design
	Hoffman - Progress and Status of (Deleted)
	Hoffman - Mix and Instability
	Varnum - Symmetry
	Fisher - Burn Physics
	Coggeshall - LMF Capsule Designs
14:45 - 15:45	Mead - Recommendations
15:45 - 16:00	Cartwright - Summary

SNLA Presentation

16:00 - 16:30	Allshouse - Baseline LMF Target Design
16:30 - 17:00	Olsen - New Target Concepts
17:00 - 17:20	Cook - Near-Term PBFA Target Experiments
17:20 - 17:40	VanDevender - Implications on LMF Design

TARGET PHYSICS REVIEW

Day Three - November 16, 1988

Indirect Drive Target Physics Data Base - Structured Discussions

Rebuttals

08:00 - 08:20	Bodner - NRL
08:20 - 08:40	McCrary/Soures - UR/LLE
08:40 - 09:00	Berger - KMSF
09:00 - 09:20	Allshouse - SNLA
09:20 - 09:40	Mead - LANL
09:40 - 10:00	Storm - LLNL
10:00 - 12:00	Open Discussions
12:00 - 13:00	Lunch Break
13:00 - 17:30	Executive Session

TARGET PHYSICS REVIEW

Day Four - November 17, 1988
Direct Drive Target Physics Data Base

NRL Presentation

08:00 - 08:15	Bodner - Introduction
08:15 - 08:40	Gardner - Hydrodynamic Theory
08:40 - 09:20	Obenschein - Coupling and Implosion Experiments
09:20 - 09:30	Bodner - Future Program Goals
09:30 - 09:45	Break

UR/LLE Presentation

09:45 - 10:30	McCrory - Direct Drive Target Design
10:30 - 11:15	Verdon - Omega Results/High Gain Data Base
11:15 - 11:45	Break for working lunch setup

LLNL Presentation

11:45 - 13:15	Lindl/Drake - Direct Drive Data and Analysis
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End of Direct Drive Presentations

13:15 - 14:15	Rebuttals
14:15 - 14:45	Open Discussions
14:45 - 18:00	Executive Session

APPENDIX B
LIST OF ATTENDEES

TARGET PHYSICS REVIEW

November 14 - 17, 1988
Room A-410, DOE Headquarters

REVIEWERS (7)

Timothy Coffey
Alexander Glass
William Lokke
Gene McCall
Robert Sproull
Thomas Stratton
Roy Woodruff

PRESENTERS (OBSERVERS)

LANL (18)

David Cartwright
Michael Henderson
William Mead
Roger Jones
Steven Coggeshall
Nelson Hoffman
(Ruth Holt)
(Thomas McDonald)
(Philip Goldstone)
(Douglas Wilson)
(Henry Fisher)
(William Varnum)
(Charles Fenstermacher)
(Joseph Figueira)
(Gerald Stephenson)
(Glen Magelsson)
(Jeffrey Colvin)
(Don Sandoval)

LLNL (17)

Erik Storm
John Lindl
E. Michael Campbell
Lawrence Suter
William Kruer
Steven Haan
Joseph Kilkenny
Stephen Hatchett
Paul Drake
(William Hogan)
(Thomas Bernat)
(Lamar Coleman)
(Howard Lowdermilk)
(James Davis)
(Charles McDonald)
(Donald Correll)
(Robert Kauffman)

SNLA (5)

George Allshouse
Richard Olson
Donald Cook
J. Pace VanDevender
Milton Clauser

KMSF (4)

Richard Berger
(Timothy Henderson)
(C. Armentrout)
(Roy Johnson)

NRL (3)

Stephen Bodner
John Gardner
Stephen Obenschian

UR/LLE (3)

Robert McCrory

Charles Verdon

John Soures

DOE STAFF and CONTRACTOR (13)

Richard Hahn
David Bixler
Steven Goldstein
Dennis Neely

Richard Schriever
Gary Chenevert
Robert Jones
Orville Barr

Sheldon Kahalas
Gregory D'Alessio
Thomas Owen
James Woo

APPENDIX C
PROFESSIONAL HISTORIES OF THE SEVEN INDEPENDENT REVIEWERS

**Timothy Coffey
Professional History**

1982 - Present Director of Research, Naval Research Laboratory

Career Assignments:

1963 - 1964	Research Assistant, University of California
1964 - 1965	Research Physicist, Air Force Cambridge Research Laboratories
1965 - 1966	Teaching Fellow and Research Assistant in Physics Department, University of Michigan
1966 - 1971	Scientific Consultant, EG&G, Inc.
1971 - 1975	Head, Plasma Dynamics Branch, Plasma Physics Division, Naval Research Laboratory
1975 - 1980	Superintendent, Plasma Physics Division, Naval Research Laboratory
1980 - 1982	Associate Director of Research for General Science and Technology, Naval Research Laboratory

Scientific Specialties:

Dr. Coffey is recognized as an authority on the theory of nonlinear oscillations. He has played a major role in the national program on high altitude nuclear effects. He has made several fundamental contributions to the theory of electron beam-plasma interaction and to the understanding of plasma processes in the earth's ionosphere.

Education: Ph.D. Physics, University of Michigan, 1967

Alexander J. Glass
Professional History

Private Consultant (at the time of ICF Target Physics Review)

Career Assignments:

1968 - 1970	Branch Chief for Laser Physics at the Naval Research Laboratory
1973 - 1977	Head of Laser Theory and Design Analysis Group, LLNL
1978 - 1981	Assistant Associate Director for Lasers, LLNL
1968 - 1981	Academic Affiliations: <ul style="list-style-type: none">o Catholic University of America, Lecturero University of California, Lecturer, Department of Applied Scienceo Wayne State University, Professor of Electrical Engineeringo Wayne State University, Department of Electrical Engineering, Chairman (1973 - 1981)
1981 - 1987	President and Chief Operating Officer, KMS Fusion, Inc.
1983 - 1987	Chairman and Chief Executive Officer, Covalent Technology Corp.
Education:	Ph.D. in Physics, Yale University, 1963

**William Anton Lokke
Professional History**

1957 - Present Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94550

Specific Assignments:

1957 - 1966	Staff member of T-Division; code development, atomic physics, thermonuclear weapon design
1966 - 1969	Spartan ABM Warhead Project Leader
1969 - 1973	Associate Division Leader for A-Division for physics code development
1973 - 1978	Head, A-Division (lead physics division for research and design of thermonuclear devices)
1978 - 1984	Deputy Associate Director for Physics
1984 - Present	Department Head for Magnetic Fusion Energy Program
1988 - Present	Department Head for Beam Research Program
Education:	University of Minnesota, B.S., Physics 1957

**Gene H. McCall
Professional History**

1982 - Present Laboratory Fellow, Los Alamos National Laboratory

Career Assignments:

1960 - 1963 Bell Telephone Laboratories, Member of Technial Staff

1967 - 1969 University of Washington, Post-doctoral Research Associate

**1969 - 1981 Los Alamos National Laboratory:
Division Leader, Laser Research and Technology Division
Alternate Division Leader, Laser Research and
Technology Division
Group Leader, Laser Target Experiments and Diagnostics
Staff Member**

**1986 - 1987 Professor, Physics Department, Atomic
Weapon Research Establishment, U.K., Visiting
Staff Member**

1986 - Present Chief Scientist, Hypervelocity Particle Project

**AWARDS: E.O. Lawrence Award; Award of Excellence of Department of Energy;
Distinguished Performance Award and Selection as Laboratory Fellow of Los
Alamos National Laboratory.**

**PROFESSIONAL/SCIENTIFIC/HONORARY SOCIETIES and BOARDS: United
States Air Force Scientific Advisory Board; American Physical Society; Sigma Xi;
NASA Predoctoral Fellowship at Princeton University; Phi Kappa Phi
Engineering Honor Society, Tau Beta Pi Engineering Honor Society; Eta Kappa
Nu Engineering Honor Society of Georgia Tech.**

**FIELD OF SPECIALITY: Plasma Physics, Hydrodynamics, Radiation transport,
Explosive system design, shock wave diagnostics, Laser-matter interactions,
Hypervelocity particle acceleration.**

Education: Ph.D., Physics, Princeton University 1967

Robert L. Sproull
Professional History

President Emeritus of University of Rochester

Career Assignments:

1943 - 1948	Physicist, RCA Laboratories Lecturer in Physics, Princeton University and University of Pennsylvania
1948 - 1956	Faculty Member, Cornell University
1956 - 1968	Full Professor, Cornell University
1959 - 1960	Director, Laboratory of Atomic and Solid State Physics, Cornell University
1960 - 1963	Director, Materials Science Center, Cornell University
1963 - 1965	Director, Advanced Research Project Agency, Department of Defense (on leave from Cornell University)
1968 - 1970	University of Rochester, Provost and University Vice President as well as Professor of Physics
1970 - 1984	President of University of Rochester; 1983 served as the Chairman on Council of Presidents of University Research Associates; Retirement in 1984

Post-Retirement Activities:

Since retirement as President of the University of Rochester, he has served in a voluntary role as member of Roundtable Council of the National Academy of Sciences and Chairman of the Study of the Institute of Medicine Committee. Since 1986, he has been the Chairman for the Basic Energy Sciences Advisory Committee of the U.S. Department of Energy.

Affiliations:

Dr. Sproull is a member of Sigma Xi, Phi Beta Kappa, and Phi Kappa Phi honorary societies. Among the professional societies, he is a Fellow of the American Physical Society, American Academy of Arts and Sciences, and the American Association for the Advancement of Science. He has also served on various government boards and committees that include the Materials Advisory Board of the National Academy of Sciences, the Statutory Visiting Committee of the National Bureau of Standards, Defense Science Board, Advisory Committee for Planning and Institutional Relations of the National Science Foundation, and the Naval Research Advisory Committee. He is a member of the Board of Directors of United Technologies Corporation, Sybron Corporation, Xerox Corporation, and Bausch & Lomb.

Education: B.A. (1940) and Ph.D. (1943), Cornell University

Thomas F. Stratton
Professional History

1954 - Present Los Alamos National Laboratory
Los Alamos, New Mexico

General Assignments:

Plasma and nuclear physics applied to problems in accelerators, lasers, and nuclear weapons.

1958 Leave assignment to Harwell, U.K.

1967 Leave assignment to Battelle

1985 Leave assignment to Department of Defense

Present Fellow in the Physics Division at LANL

Education: Ph.D. in nuclear physics, University of Minnesota, 1954

**Roy D. Woodruff
Professional History**

1968 - Present Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94550

Specific Assignments:

1968-1974 Physicist/Senior Scientist:
Responsible for the design of numerous complex nuclear explosives including the device used in Project Rio Blanco, a key test in the Plowshare program.

1974 - 1980 Division Management:
After initial managerial assignments, assumed leadership of the experimental weapons physics division in 1976 and the theoretical weapons physics division responsible for thermonuclear design in 1978.

1980 - 1985 Weapons Program Management:
Served as the Associate Director for Nuclear Design until 1984, when given responsibility for the entire \$300 million LLNL Defense Systems program. This assignment integrated the weapons research, development and testing activities under common management.

1985 - Present Treaty Verification/Intelligence Analysis:
After completing key intelligence assessments of the status of Soviet weapons research, assumed leadership of the LLNL Treaty Verification program in 1987. This program is playing a major role in ongoing US-USSR treaty negotiations.

Education: B.S. Physics, San Jose State University, 1968
Military: U.S. Air Force, 1960-1964