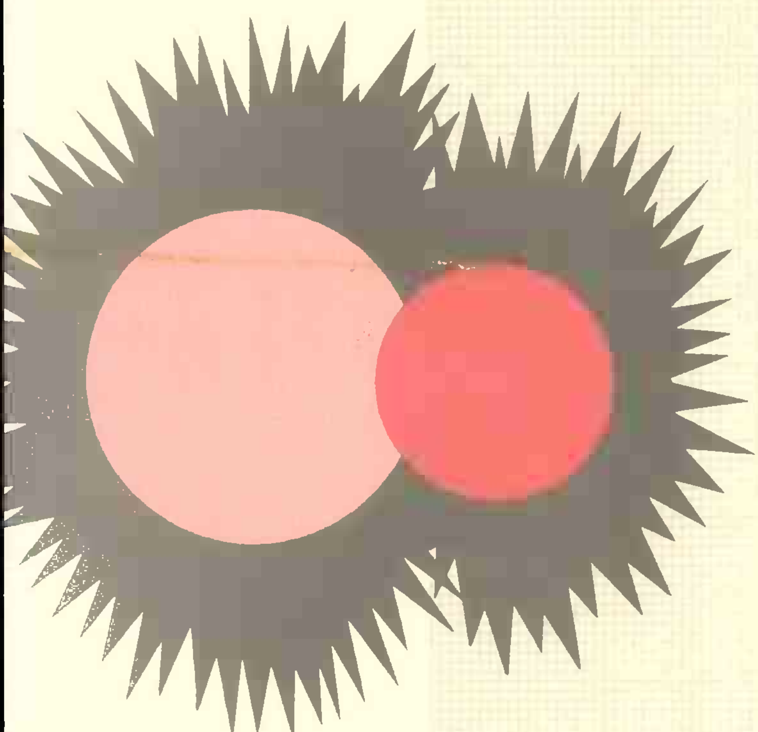
DOE/DP-0069

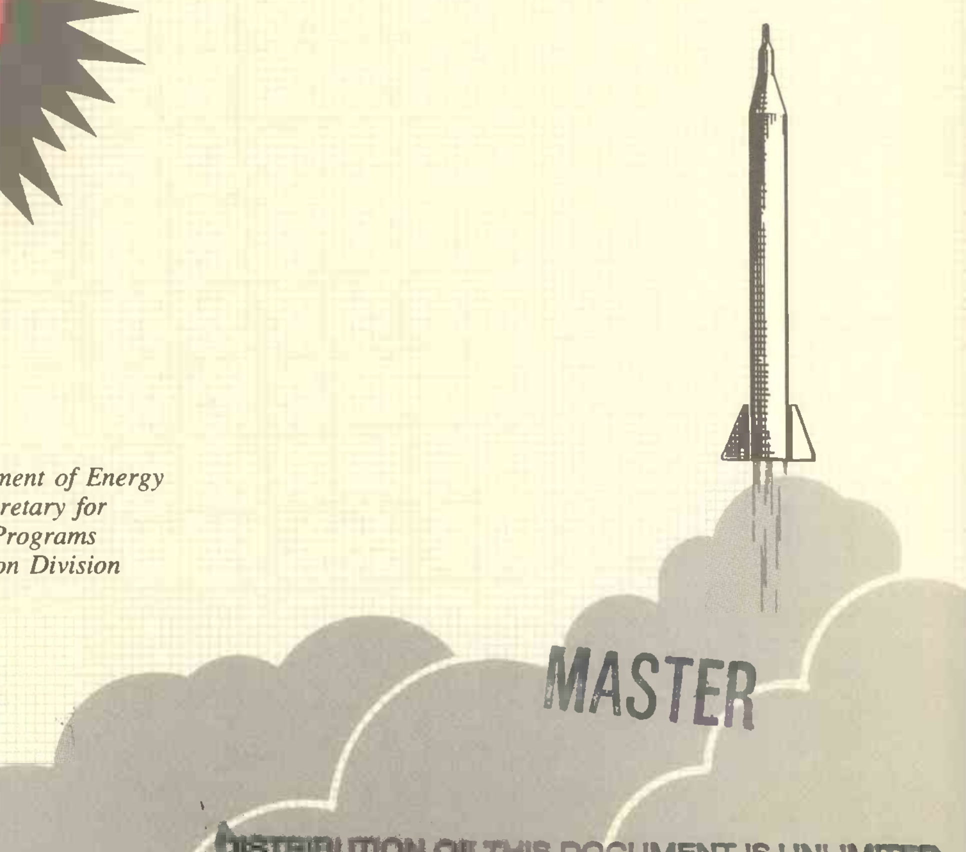
LMF

Laboratory Microfusion Capability Study

Phase I Summary



U.S. Department of Energy
Assistant Secretary for
Defense Programs
Inertial Fusion Division



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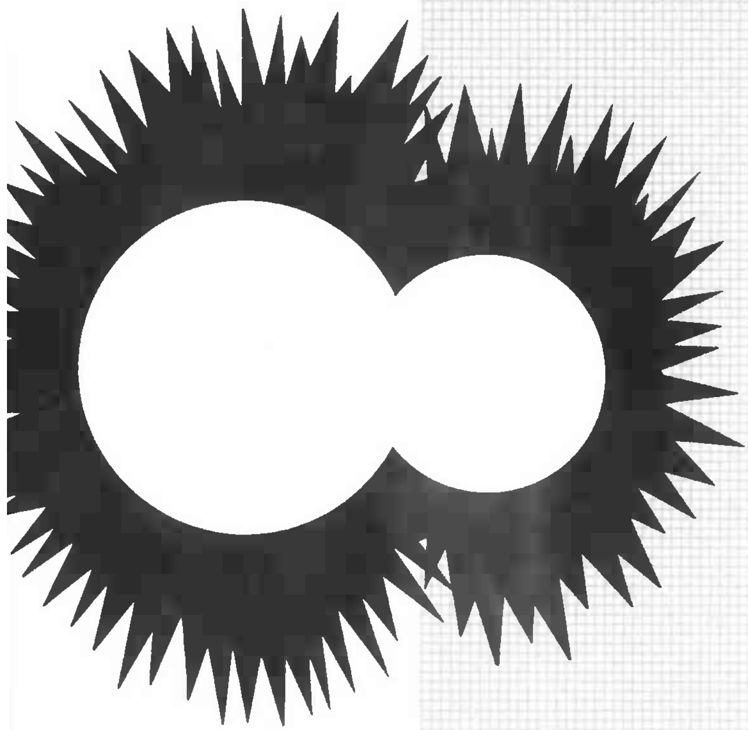

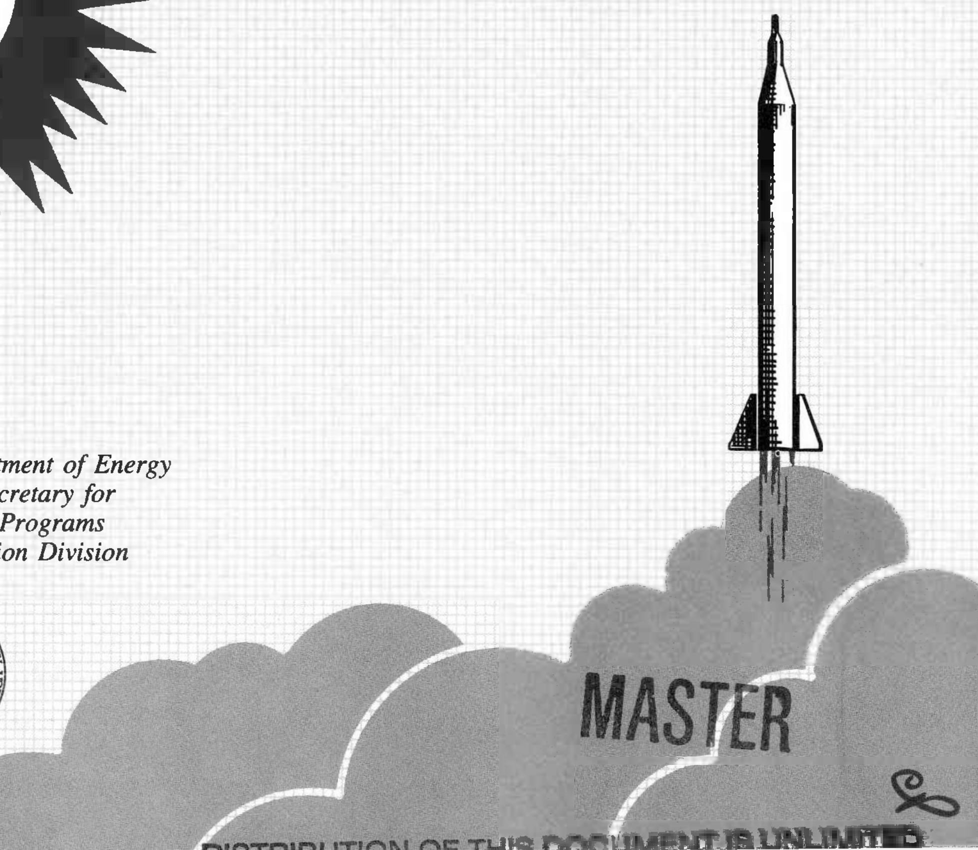

U.S. Department of Energy
Assistant Secretary for Defense Programs
Inertial Fusion Division

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I FOREWORD SECTIONS

I.A PREFACE

The purpose of this study is to elucidate the issues involved in developing a Laboratory Microfusion Capability (LMC). This supports a number of Department of Energy (DOE) management needs: (1) provides DOE with insight into a project that supports the near-term goal of the inertial confinement fusion (ICF) program; (2) affords guidance to the ICF laboratories in planning their research and development programs; (3) informs Congress and others of the details and implications of the LMC; (4) identifies criteria for selection of a concept for the Laboratory Microfusion Facility (LMF); and (5) develops a coordinated plan for LMF development.

A review of the technical progress and overall status of the ICF program was conducted in 1985 by the National Academy of Sciences (NAS). In a favorable report, the NAS review panel reported that at the current level of effort, the ICF program would need about five years to "resolve critical technical issues of ICF feasibility." The ICF program has recently achieved remarkable progress in understanding the complexities of the inertial fusion process. By mid-1986, radiation-driven targets were being imploded in the Nova facility at the Lawrence Livermore National Laboratory (LLNL), and significant strides had been made in the experimental programs at the University of Rochester's Laboratory for Laser Energetics (LLE) and the Naval Research Laboratory (NRL). Target performance never before seen has been demonstrated in the Halite/Centurion program. Progress continues on developing the light-ion driver at Sandia National Laboratories, Albuquerque (SNLA), advanced solid-state laser drivers at LLNL, and the krypton-fluoride excimer laser driver at Los Alamos National Laboratory (LANL). A heavy-ion driver concept is under development at the Lawrence Berkeley Laboratory (LBL).[1] In response to more stringent requirements of ICF, increasingly sophisticated techniques of fuel capsule fabrication and characterization are under development at KMS Fusion, Inc., as well as LLNL and LANL. Experimental results of significant note have continued to come forth, as the ICF program shows encouraging progress toward satisfactorily addressing the issues of feasibility identified by the National Academy of Sciences review panel. Indeed, once the laboratory feasibility of ICF is established, many questions and uncertainties will remain to be addressed; but it is the purpose of the LMC itself to address these.

Recognizing the very fruitful progress of the ICF program, DOE initiated the LMC study in late 1986. The DOE plan for the study was introduced and adopted at the ICF Program Managers Meeting of October 17, 1986. A steering committee was formed to provide guidance for the study. The committee was chaired by DOE, with representatives from the six ICF laboratories and LBL. Initially, the study centered on defining a generic capability, hence the LMC. Later, as it became more clearly defined and directed, the study focused on specifying a facility, hence the LMF. In this document, the term LMC is used unless reference is being made to the specific facility, when the term LMF is used. At the early steering committee meetings, the study tasks were defined, and task teams made up of personnel from the ICF laboratories were established. InterScience, Inc., was retained under contract to contribute to specific parts of the study, as well as to integrate the contributions of the ICF laboratories, LBL, and DOE into a cohesive report.

The LMC study is divided into two phases. The first phase identifies the LMC purpose and potential utility, the regime of its performance parameters, its development goals and requirements, and associated technical, management, staffing, environmental, and other developmental and operational issues. The second phase identifies the driver-dependent LMC issues, such as cost and performance. The study considers four options as the driver for an LMF: the

1. This effort is under the aegis of Energy Research at DOE, since this concept's characteristics of high repetition rate and efficiency lend it well to satisfying the civilian power production mission.

neodymium-glass laser, the krypton fluoride excimer laser, the light-ion accelerator, and the heavy-ion induction linac. The neodymium-glass laser, the first to be adapted as an ICF driver, has received the most development support and thus is the most mature of all driver technologies. Heavy-ion accelerator technology is being developed at a lower level of effort than the other three options, which are under the aegis of Defense Programs. Because of this, the heavy-ion accelerator is considered an option for the LMF only in the long term.

Phase I, described in the present report, focuses on driver-independent issues. The general definition and requirements of an LMC are discussed here. Phase II will deal with driver-dependent issues. The essence of that part will be derived from point designs for the first three options. The information on the heavy-ion accelerator option will be taken from a less rigorous, top-down design. Were this option to be considered a serious near-term contender for the LMF, a more detailed design would be required. Phase II will treat the cost and development issues of an LMC in more detail than in Phase I.

For the content of this report, DOE depended heavily on the ICF laboratories, whose contributions are extensive. This does not mean that all participants in the ICF program are in agreement on all the issues of an LMC and its proper development path. All agree on the importance and utility that an LMC would hold. All agree on the definition of an LMC in terms of the general physical and operational characteristics given in this document. But each ICF laboratory has a unique program, most evident in the particular driver and target drive concept that it supports. Differing policies, philosophies, and stages of development bring about diverse opinions on some of the topics discussed here. But the study is not intended as a survey of opinions among the ICF laboratories (except for a portion of Section V.B); rather, it is a DOE initiative to present the issues of LMC development with the potential customer in mind.

For the reader to whom ICF physics and terminology may be somewhat new, a brief tutorial and glossary are included in the appendices of this report.

The cost of an LMF will probably be greater than $500 million and less than $2 billion.[2] The final figure will depend on a large number of variables. While this study addresses the key issues, its scope does not include the decisions or the actual selection process. Phase II will point out the features, including the advantages and disadvantages, of each driver option, and will provide sufficient data to independent reviewers so that they can establish the overall merit of one option over another. Phase II, however, does not include the technology decision for the LMF driver.

This study bounds the problem of LMC development. Yet, in addressing a specific set of issues, the effort has also raised a number of questions. How important is it to maintain the flexibility in the LMF to address both target drive approaches (direct drive and indirect drive)? How will a decision be obtained on the LMF driver selection? How best will all of the ICF laboratories' accomplishments and capabilities be integrated into the LMF development program? What are the implications of a heavy-ion accelerator as an ICF driver, since this concept is being developed primarily as an option for energy production? Although weapon designers were consulted in determining the utility of an LMC in this study, a more active presence of the weapons community in the Phase II effort would be valuable. Also, DOD participation in terms of weapon effects applications would be desirable. All of these issues should be addressed in future ICF program planning, but prior to a selection of a driver concept for the LMF.

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2. The lower extreme is inferred from the estimated cost of driver-independent portions of the LMF (see Section VIII.C, "Cost Estimate"). The upper extreme is drawn from conservative interpretation of laboratory projections of near-term advances in driver capabilities.

I.B EXECUTIVE SUMMARY

1. Introduction

Over the past several years the DOE Inertial Confinement Fusion (ICF) program has made significant progress in all major aspects. These advances now make it feasible to define the requirements needed to support the program's major objectives: achievement of high gain in ICF targets, development of laboratory nuclear weapon physics experiments, enhancement of laboratory experimental capabilities for weapon effects studies, and eventual production of commercial power. Significant experimental achievements have been realized at the ICF facilities at LLNL, NRL, KMS Fusion, and the University of Rochester, and on the tests of the Halite/Centurion program. Combined with the progress on light-ion drivers, krypton-fluoride and solid-state lasers, with advances in direct-drive target and system designs, with major steps in design and fabrication of cryogenic targets, and with the improvement in predictive computer models, these achievements stimulate interest in and enhance the credibility of achieving a laboratory microfusion capability (LMC) of 200 to 1000 megajoules (MJ) of thermonuclear yield.

2. LMC Objectives

The LMC is intended to:

- develop and demonstrate in ICF targets the high gain required by potential applications;
- utilize the unique laboratory environment (high temperatures, high pressures, and x-ray, gamma-ray, and neutron fluxes) created by those targets for advanced weapon physics experiments;
- utilize the output of those targets to complement laboratory experimental and underground test capabilities for DOE and DOD nuclear weapon effects simulation and vulnerability studies;
- advance the understanding of the technological requirements for eventual commercial power applications; and
- support other applications ranging from nuclear materials production (defense and other) to space propulsion concepts.

These objectives, along with environmental and safety requirements, form the basis for the requirements of the LMC defined in this study. The envelope of requirements define a region of performance wherein the greatest utility could be realized for the anticipated cost. The significant feature of the LMC is that it is not only an essential step on the way to achieving far-term applications of ICF, but it is a valuable capability for many near-term applications. And, a high-yield LMF has more near-term applications than does one of moderate yield. The utility of an LMC increases sharply as a yield of about 200 MJ is reached and continues to increase substantially until about 1000 MJ. Thus, this LMC study establishes that a fundamental requirement is a projected 200-MJ yield, and a significant measure for comparison of candidate drivers is how well they approach the goal of 1000-MJ yield. This, of course, is but one of a number of requirements and figures of merit which are established in the present study. A facility of 2000-MJ yield would have more utility than one of 1000 MJ, but the additional difficulty and cost of achieving and containing the higher yield outweigh the resulting benefits. Conversely, an ICF facility which achieves target ignition, but not LMC yields, would have considerable experimental value, but the benefit-to-cost ratio of such a facility is much less favorable than for an LMC scale facility.

3. LMC Phases

The study is divided into two phases. The subject of this report, Phase I, considers issues and requirements that are independent of driver technology. Phase II of the LMC study will address issues and requirements which depend on the selected driver technology. Accordingly, Phase II will include early conceptual design studies addressing each driver technology alternative. The driver invariant requirements addressed in the present report are expected to be common to all alternatives examined in Phase II. These include the fundamentals of target yield, experimental capability, experimental rate, and target fabrication technology.

This phase I study reached several important results. First, the study team considered the various driver-independent elements in an LMC and successfully performed the requirements-scoping study in an applications-driven manner. Agreement was reached on the minimum fuel-capsule absorbed energy required for a performance design point. The study also provided a first estimate that the cost of the non-driver-specific portions of the required facility will be about 300 million dollars.

4. LMF Experiments

From the identified needs of the potential users, the facility output was chosen to be between 200 and 1000 MJ. Most weapon effects and civilian power application requirements identified can be met with about 200 MJ of ICF target yield, while the weapon physics experiments identified productively span the range of yields from 100 to 1000 MJ. High-gain target development is a necessary precursor to these applications. Early LMF target performance will be at low yields, perhaps much less than the driver energy, and progressively approach the 1000 MJ level. Once high-gain, high-yield targets are developed for applications experiments, target development will continue in order to achieve high gain at lower driver energies and to explore commercial power and other applications. Specific application experiments are envisioned for the LMC, including:

- ICF high-gain target development

  - hohlraum physics experiments
  - implosion and symmetry studies
  - ignition experiments
  - propagating burn experiments
  - high target gain
  - high target yield
  - mix and shell break-up experiments
  - reduced drive studies

- Weapon physics experiments

  - equation of state
  - opacity measurements
  - thermonuclear burn physics
  - mixing studies
  - non-LTE physics
  - radiochemical tracer modeling
  - effects of shock waves on burn
  - radiation flow modeling
  - x-ray laser physics
  - hypervelocity fragment development
  - other classified experiments

- Weapon effects, vulnerability, and survivability

  - special source development
  - electronic component testing
  - weapon system testing
  - reentry body testing
  - satellite systems testing
  - small satellite testing
  - utilization of total x-ray spectral fidelity
  - concurrent x-ray and neutron effects
  - EMP testing

- Commercial power application

  - high-gain target development
  - materials development
  - data for design of test reactor

- Other application experiments

  - strategic nuclear material production
  - fissile fuel breeding
  - space propulsion
  - basic research

This work forms the basis for future detailed studies of yield-versus-utility. These in turn will provide a quantitative basis for critical program decisions.

5. LMF Minimum Energy

A consensus was reached among target-design representatives in this study regarding the amount of energy required to be absorbed in radiatively driven (indirectly driven) ICF fuel capsules for a reasonable confidence of producing high gain with yields of up to 1000 MJ.

Indirectly driven targets require driver energies of several times the energy absorbed in the capsule because of several inefficiencies in the target system. These inefficiencies--the driver energy conversion, the hohlraum-to-capsule coupling, and the capsule absorption--are driver dependent. The best current estimate is that indirectly driven LMC targets will require 10 to 20 MJ of laser or ion beam energy.

For directly driven targets the energy absorbed in the capsule is equal to the product of the driver energy times the ablator absorption efficiency. There is reasonable confidence of producing high gain in directly driven targets with 6 to 12 MJ of incident laser energy, if the energy is delivered with acceptable pulse shape, spectral characteristics, and symmetry. While direct drive may require less driver energy, it probably places more stringent requirements on the driver in terms of symmetry and spectral characteristics.

Greater effort has been devoted to understanding indirectly driven than directly driven targets in the national ICF program. Accordingly, despite the driver energy advantage enjoyed by direct drive, indirect drive is the current principal approach for the LMF. Additionally, LMC high-gain target requirements are predicated on the use of indirectly driven target designs.

The experimental requirements arise from the potential users' needs. Fundamental to all applications are the abilities to do the following:

- handle cryogenic indirect-drive targets,
- support and inspect those targets,
- contain the target yield,
- diagnose experimental parameters,
- recover diagnostic data,
- assure staff and public safety,
- limit damage from the target yield, and
- meet environmental requirements.

The experimental rate required is of order of one to two complex target experiments per day, plus simple supporting experiments for diagnostic work and driver set-up and testing. High-yield and full-yield (up to 1000 MJ) experimental requirements identified are as follows:

- High-gain target development
  - at least 100 experiments of 100 to 1000 MJ
  - at least one full-yield experiment every 10 days
  - at least 1400 total experiments including diagnostic alignment and calibration
  - at least 300 experiments per year

- Weapon physics applications
  - a full-yield experiment per week
  - at least 5000 total experiments including diagnostics alignment and calibration
  - at least 500 experiments per year

- Weapon effects applications
  - at least 10 source development experiments per year (100 to 1000 MJ)
  - at least 50 exposure experiments per year at high yield
  - at least 100 lower yield exposure experiments per year
  - over 200 total exposure experiments at over 100 MJ
  - over 4000 total exposure experiments of 10 to 100 MJ.

A 30-year facility lifetime is projected, limited mainly by technological obsolescence. Multiple target chambers (experiment areas) may be required to meet the experimental needs because of the following factors:

- diagnostic differences for different users;
- experiment and diagnostic set-up times;
- manned access limitations due to induced radioactivity after high-yield experiments.

The experiment area is expected to dominate the facility's safety analyses and operating procedures. Additional conceptual design details, to be developed in the Phase II study, will be required to assess the siting, safety, and environmental issues associated with achieving the LMC.

Most driver issues are driver-dependent and are to be addressed in Phase II of this study. The driver must meet fundamental requirements of energy, power, pulse duration, and alignment accuracy and stability in order to drive ICF targets. Pulse shaping and beam focusing requirements may be driver dependent. Flexibility to deal with a variety of target and diagnostic geometries is highly desirable. The driver technologies being considered for the LMC are the following:

- neodymium-glass lasers,
- light-ion accelerators,
- krypton-fluoride excimer lasers, and
- induction-linac heavy-ion accelerators.[3]

The driver energy required to provide 1000 MJ of energy yield is estimated to be about 10 MJ for indirect drive, and may be greater. A more precise determination of driver energy requirements will be made in Phase II of this study. Once burn propagation is achieved in laboratory targets, the driver energy requirement uncertainty will be reduced. The uncertainty in driver requirements is one of the major risk factors for the LMC. This risk will be addressed not only with the LMF, but with current and near-term capabilities of the ICF program. Although there are unresolved technical issues in all of the candidate driver technologies, the overwhelming driver issue is anticipated to be cost. Indeed, the major LMC issue identified in Phase I is the demonstration of a credible, affordable driver technology.

6. Target Fabrication Requirements

ICF targets to achieve the LMC performance goals are expected to be similar to those now in use. Thus the fabrication technology required is expected to be an extrapolation of that presently being developed. The areas of target fabrication technology that require continuing R&D are:

- Capsule fabrication
    - foam development
    - high-quality shell fabrication
- Cryogenics
    - solid, liquid, and gaseous state fuels
    - elimination of capillary tubes and shell seams
    - fueling techniques
- Characterization
    - opaque capsule characterization
    - surface smoothness
    - non-destructive inspection

The target fabrication requirements to supply two or ten complex targets per day have been estimated. It is recommended that target fabrication capabilities to support operation, and supporting R&D activities, be substantial at the facility constructed to provide the LMC, that is, the Laboratory Microfusion Facility (LMF).

7. Siting, Safety, and Environmental

Environmental and siting activities will consume a large share of the project's resources during its early phases. Early attention to environmental and safety issues allows for more innovative solutions, greater inherent safety, and more flexible project management. Neglect of them leads to costly add-on fixes that are inherently less satisfactory than proper original designs. The project must conform to the requirements of the National Environmental Policy Act (NEPA). Preparation of Action Description Memorandum level of documentation should begin as early in the conceptual design process as possible.

There are sound arguments for locating the LMF convenient to the existing ICF laboratories. Convenience, R&D synergism, and better focus and control of R & D efforts are positive factors. The recruiting and retention of the facility staff are also eased by siting the facility near existing DOE organizations. These factors must be weighed against waste transport and disposal, land use, accidental releases to the environment, and decommissioning costs. Only thorough evaluation of safety and NEPA issues can support an objective evaluation of these potentially conflicting factors. Although such factors are at present secondary to the selection of the driver technology, wrong choices may delay the project or degrade its usefulness.

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3. The heavy-ion accelerator development program, under DOE's Office of Energy Research, is currently envisioned as a power plant driver. It could be a candidate for the Laboratory Microfusion Facility only in the long term.

8. Staffing and Management Approach

A moderately aggressive management approach is recommended for the LMF, including construction of selected full-scale prototypes appropriate for the selected driver technology, in order to maintain realistic control of cost, risk, and schedule. Personnel requirements are estimated to vary between 150 and 550 people during the project's life cycle. Annual operating costs are estimated to be 10 to 20 percent of the total construction cost. An annual capital equipment budget of 5 to 15 percent of the operating budget should be anticipated.

Three alternative project schedules have been examined. They trade off time for cost and risk in the solution of problems; the lower risk option allows adequate time to select and evaluate design options so that the facility is assembled and tested smoothly. Conversely, the faster option requires parallel development of alternatives, and the solution of unanticipated problems with money and man-power. All three options begin with the commitment to construction (that is, the driver technology has been selected and the conceptual design exists). They have the milestone schedules (in years after commitment to construction) shown in the following table:

Alternative Milestone Schedules

Milestones	Risk: Intermediate	Lower	Higher
Initial Design Complete	2	3	1
Construction Completion	6	9	4
Gain of One Achieved	7	12	5
Yield of 100 MJ Achieved	9	15	6
Decommissioning	30	30	30

(Years from Construction Commitment)

9. Cost Factors

Identification of the major cost factors of the LMF project is difficult prior to selection of the preferred driver technology. It is important, however, since this information is critical in structuring an optimal R&D effort. A generic work breakdown structure (WBS) has been prepared; driver-specific WBS's will differ from one another at lower WBS levels. As more is learned about the LMF's conceptual design, it will be possible to refine the WBS and to fill it in to greater depth, until it is an adequate master document for assignment of project responsibilities.

10. Conclusion

In conclusion, the DOE ICF program is in a position to define the specific requirements for a high-gain target facility. These requirements derive their credibility from the ICF laboratory results, progress in design, target performance, and driver development, and the results of the ICF experimental program. Further progress during the next few years will reduce the uncertainties in these requirements, increasing their credibility.

The program also is able to define the additional requirements for a high-gain facility which will provide laboratory access to weapon-like test conditions for DOE weapon physicists, complement existing laboratory simulation facilities for nuclear weapon effects for the DOE and DOD systems designers, and enhance the possibility of the application of ICF for energy production. This document is a step in the process, defining the driver-independent requirements for a laboratory microfusion capability. It leads to the difficult task of defining driver-specific facility designs that meet these requirements. The ultimate goal of this effort is the identification of the technology that will provide the maximum LMF utility to ICF target designers, weapon designers, weapon effects testers, and civilian power reactor designers at the least cost and risk.

II INTRODUCTION

II.A THE ICF PROGRAM: BACKGROUND, MISSION, AND GOALS

1. Historical Perspective

The first demonstration of a laser in 1960 led scientists working on advanced nuclear weapon concepts to consider the laser as a means to compress deuterium and tritium fuel to thermonuclear ignition and burn. This concept was proposed in a briefing for visiting scientists at the Lawrence Radiation Laboratory, Livermore, in March, 1961. Besides weapon research, the briefing mentioned possible application to Project Sherwood, the controlled thermonuclear reactions program of the Atomic Energy Commission (AEC). The potential of laser driven fusion and plans to pursue that potential were reported in 1963 to the Director of Military Application of the AEC. A patent application for electrical power generation based on "laser ignited thermonuclear explosions" was made in 1964. The possible application of particle beam accelerators as fusion drivers was not pursued until the early 1970's, when Sandia Laboratories, Albuquerque, adapted their pulsed power technology to produce beams of electrons, and later, ions, for fusion experiments.

Laser fusion program expenditures were recorded as early as 1963, when Livermore reported a 200,000 dollar expenditure. Congress authorized and appropriated inertial fusion operating funds as a separate budget line item for the first time in Fiscal Year 1976 (FY1976). At that time the Joint Committee on Atomic Energy (JCAE) stated, "The objective of the laser fusion program is to determine the scientific feasibility of laser and electron beam initiated thermonuclear reactions using principles of inertial confinement."[4]

In 1979 a review panel chaired by Dr. John S. Foster, Jr., endorsed expansion of the classified Halite/Centurion program[5] and of heavy ion fusion research and development. The heavy-ion fusion program first received ERDA support in 1977. At the direction of the Congress, however, the accelerator R & D portion of the heavy ion effort was transferred from the DOE's Defense Programs to the Office of Energy Research in 1984, and the advanced laser research effort managed by the Office of Inertial Fusion was no longer funded. Efforts were authorized by DOE at Los Alamos and Livermore to determine the prospects for cost effective short wavelength lasers.

In 1985 Congress requested initiation of a review of the Inertial Fusion program, oriented toward the military applications of ICF and focusing on the technical state of health of the program and its prospects for the future. A National Academy of Sciences (NAS) panel, chaired by Dr. William Happer of Princeton University, reviewed the entire ICF program. Among the conclusions of the committee were (1) the program should be maintained at the current level of funding for about five years, in order to resolve critical issues of ICF feasibility, and (2) the current experimental capabilities should be used to resolve these issues. The program hence has proceeded at nearly constant level of effort as an experimental campaign, with no new major facility construction starts since the first quarter of 1981.

2. Mission and Goals

Though the emphasis and priorities of the ICF Program have shifted through the years, the mission of the program has remained essentially constant. Official statements of program mission have come to be more specific than the 1976 Congressional authorization language, and the military applications of ICF have been stressed. The House Armed Services Committee authoriza-

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4. The JCAE's direction that the Energy Research and Development Administration (ERDA) consider and report on the management organization of the program led to the creation of a separate laser fusion division in ERDA.

5. The Halite/Centurion program involves ICF experiments in underground nuclear tests.

tion language for FY1981 stated, "The major near-term goal of the ICF program is to develop the full potential of inertial fusion for nuclear weapon technology applications. A long-term goal is the development of an energy source." According to the Inertial Fusion Program Plan:

> The objective of the Inertial Confinement Fusion (ICF) Program, since its inception in the early 1970's, has been to obtain a high yield (up to 1000 megajoules or nearly a quarter-ton TNT equivalent) microfusion capability in the laboratory.

It is envisioned that well-diagnosed thermonuclear micro-implosions will be produced in the laboratory for the purpose of increasing our understanding of nuclear weapon physics, simulating nuclear weapon radiation environments for vulnerability, hardening, and effects testing, and establishing the feasibility of ICF for power generation. The feasibility of ICF for applications such as space propulsion, fissile fuel production, and synthetic fuel production also can be explored.

3. Technical Evolution

The early program years were concentrated on laser development. By 1967 Livermore was irradiating targets with 20-joule pulses of 10-nanosecond duration from a 12-beam laser, and a 4-beam laser at Sandia Laboratories, Albuquerque, was used in 1969 to investigate Soviet claims of thermonuclear neutron generation in laser experiments. The Soviet claims stimulated further interest in ICF, and US efforts were expanded in the late 1960's to include the Battelle Memorial Institute and the University of Rochester's Laboratory of Laser Energetics (LLE). Patents were applied for in 1969 by Dr. Keith Brueckner (University of California) on target designs and laser fusion energy system concepts; KMS Fusion, Inc., formed to exploit Professor Brueckner's concepts, was granted a patent filed for in 1973.[6] The Los Alamos Scientific Laboratory (LASL) established an effort to develop large-aperture electron-beam-pumped carbon dioxide lasers for ICF, and the Naval Research Laboratory (NRL) made significant contributions to short pulse, high power neodymium glass laser development based upon technology developed by the French Atomic Energy Commission (CEA), including the fundamentals of disk amplifier and system design, and development of reliable mode-locked oscillators.

In addition to kilojoule carbon dioxide laser development, the early 1970's Los Alamos effort included calculations and experiments using neodymium glass lasers. Sandia adapted pulse power technology to generation of electron beams for ICF experiments; this program was later expanded to encompass beams of light ions (e.g., protons or lithium ions) as drivers. All of these efforts were focused on understanding the physics of ICF (non-classical absorption, non-equilibrium plasmas, microscale hydrodynamics) and identifying an effective means of producing laboratory thermonuclear micro-implosions.

During 1975 and 1976 laser fusion laboratories were completed at Livermore and Los Alamos, and the first two prototypes of an electron beam fusion accelerator were built at Sandia. The first ICF five year program plan, for FY 1976-80 (Wash-1363, 15 July 1974), provided for construction of a 10-kilojoule (kJ) neodymium glass laser (later named Shiva) at Livermore, a 100-kJ carbon dioxide laser (called HEGLF, later Antares) at Los Alamos, and an electron beam fusion accelerator (EBFA) at Sandia. Later converted to an ion beam accelerator, EBFA was renamed Particle Beam Fusion Accelerator I (PBFA I). The plan recognized the need for more powerful ICF drivers and projected a 100- to 1000-kJ short wavelength laser fusion system (later called Nova) at Livermore and a megajoule-class machine (later called PBFA II) at Sandia. The Sandia facility would specifically address Sandia's charter to provide weapon effects simulation facilities.

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6. "Method of Achieving the Controlled Release of Thermonuclear Energy," US Patent 4,608,222, filed July 10, 1973, granted August 26, 1986.

The plan also proposed an advanced fusion facility and a reactor component development laboratory, which were not started. In addition to these planned facilities, ERDA contracted with the University of Rochester for construction of a 10-kJ laser system to be operated, in part, as a national laser users facility, and with KMS Fusion for continued target development and ICF experimental work. KMS Fusion, Inc., convincingly demonstrated thermonuclear neutron production in a laser-driven ICF target on May 1, 1974.

Experiments in the 1974 to 1979 period utilized laser energies of 100 joules to 10 kilojoules (kJ) per pulse, and grappled with the two tenacious problems: poor target absorption and excessive target preheating. Absorption was low--typically 10 to 25 percent for the 10-micrometer wavelength light from carbon dioxide lasers and about 45 percent for the 1-micrometer wavelength of neodymium glass lasers. Prohibitive fractions of the absorbed energy were converted to suprathermal (hot) electrons in the target plasma. These electrons easily penetrated the mass of the target, either escaping as a loss, or worse, depositing their energy throughout the volume, preheating the target and precluding subsequent compression of the fuel to useful densities. Again the problem scaled as a function of the inverse of wavelength, 1-micrometer light was better than 10-micrometer light, but not good enough. Theoretical studies had indicated the desirability of shorter wavelength laser light; the experimental data showed that it was not only desirable, it was necessary. Low absorption decreases the scale of experiments that can be done with a given laser, or increases the cost of the laser required for a desired result. Though preheating does not prevent achievement of the necessary temperature, it precludes achievement of the necessary density for thermonuclear ignition and burn, thus precluding significant target gain.

The problems in laser-target interaction physics were addressed by shifting attention to laser drivers operating at shorter wavelengths. On one hand, resources were directed to the development of excimer lasers operating in the ultraviolet (UV) portion of the spectrum. Neodymium doped glass lasers continued to show their flexibility; the University of Rochester invented and demonstrated efficient techniques for conversion of their 1-micrometer output light to the second, third, and fourth harmonics at one-half, one-third, and one-fourth micrometer in the visible, near-UV, and hard-UV regions of the spectrum. The 1985 National Academy of Sciences (NAS) committee report stated, "...(this work) now forms the basis of all the world's ICF glass laser programs and is certainly a major cause of the present upswing in ICF technical results and prospects."

The fuel preheating problem was not confined to laser-driven ICF. Sandia abandoned electrons in the beam-driven ICF program in favor of ions. With their shorter penetration depths into matter, ions produce less preheating and better implosion efficiency than do electrons. Based on pioneering results of new ion generation techniques developed at Cornell University and NRL in the mid-1970's, Sandia demonstrated efficient generation and acceleration of ion beams by 1979, and electron beam driven ICF went the same way as carbon dioxide laser driven ICF. Both were technologically attractive, especially for the long term goal of energy production because of their higher efficiencies and lower costs, but they were not scientifically viable because of unacceptable target physics considerations. The ICF program shifted completely to shorter wavelength (one-half to one-fourth micrometer) lasers and ion beam drivers.

Through the early years of the ICF program the focus was on development of higher energy laser and ion beam drivers. Laser output energies increased from about ten joules to about ten kilojoules. But with the loss of support for advanced laser research and the growth of the Halite/Centurion program, the emphasis in the early 1980's shifted to target development, at the expense of advanced drivers. The prospects for demonstrating thermonuclear ignition were poor with the driver systems being built, and the characteristics required of follow-on higher-energy systems were uncertain. No new construction funds could be projected until experimental results were to provide the basis for technical reassessment of ICF in the later 1980's. The draft 1988-1992 program plan, based upon experimental results through 1987, provides for decisions on the future direction of the program.

In its 1985 review of the ICF program, the Happer panel concluded that "... the current program has the essential structure and capabilities to permit a fairly reliable estimate of cost and specification of the required driver and targets in about five years, if the program is funded at about the current levels." Recommended priorities were (1) the Halite/Centurion program, (2) Nova and PBFA II experiments, (3) utilization of the smaller supporting laboratories, and (4) a modest exploratory effort on laser development. Recent successes, achieved by following the priorities prescribed by the panel, have led the program to increasing its emphasis on a larger-scale follow-on laboratory capability.

The body of data and understanding built up significantly bolsters confidence in the technical feasibility of the ICF concept, and the specifications for advanced drivers to reach significant target thermonuclear yield and gain can now be written. It is anticipated that these driver and other facility requirements, delineated in this Phase I study report, can be achieved in the 1990's.

Drivers and target physics have been explored in the laboratory at drive energies below those required for thermonuclear ignition and burn; the current results from this program are described in Section II.B, "ICF Technical Achievements."

II.B ICF TECHNICAL ACHIEVEMENTS LEADING TO THE LMC

1. Introduction

Steady progress has been made in understanding the fundamental physical and technological issues in ICF; including driver technology, driver/target interactions, target fabrication, and target capsule performance. The ICF program will be working over the next several years to improve target performance, increase the understanding of driver/target coupling, improve target fabrication and characterization, refine experimental diagnostics, and develop more cost effective driver systems. These efforts will reduce the risk and allow for refinement of the requirements for the first experiments on the LMF. This section discusses past progress in hohlraum physics, capsule implosion understanding, and target fabrication, and anticipated progress with present and near-term experimental facilities.

The objective of the LMC is to achieve yields of 200 to 1000 MJ in order to provide high utility to weapon physics experiments, weapon effects simulations, and ICF civilian energy development. The current experimental program is an effective effort to gain understanding of target phenomena, using our current and near-term experimental capabilities in order to minimize the time and resources required for achieving high target gain after completion of the LMF. The current ICF program also has provided the weapons program with both experimental data and computational tools previously unavailable, and has supported the development of new diagnostic instruments and techniques.

This study concentrates primarily on driver-independent issues. Detailed consideration of driver-dependent LMF technical and cost issues will be undertaken in Phase II of the study.

2. Progress to Date

Current experiments are exploring hohlraum physics, direct-drive issues, hot-spot ignition, symmetry, and implosion dynamics. An encouraging aspect of the current results are that they are being obtained under less than the near ideal conditions of pulse shape, symmetry, and low preheat that would be obtained with an LMF driver, and that the results are in excellent agreement with calculations.

The Nova laser has achieved fuel capsule environments approximating LMF requirements using 20 kJ of 0.35 micrometer wavelength laser light. Excellent capsule drive uniformity and negligible fuel preheating are routinely demonstrated in short pulse experiments. A fuel density in excess of 100 times liquid D-T density, an ion temperature of 2 keV, and a capsule convergence ratio of up to 35 also have been measured in separate experiments without pulse shaping on Nova.

Experiments have converged toward LMF target requirements of radiation flux, flux uniformity, and compressed fuel capsule areal density (ρr) . Figure 1 shows the trend in target capsule drive flux over the last decade. The capsule drive flux in laser-driven laboratory experiments has increased steadily, with Nova now achieving the drive flux desired for high-gain targets suitable for the LMF.

Current implosion experiments require the same level of drive flux uniformity as high-gain, high-yield targets will, a few percent maximum non-uniformity. The procedure used to achieve the required level of flux uniformity at the fuel capsule is to use the LASNEX and other computer codes as design tools. Experimental results show that this technique has become increasingly successful and useful.

For high gain to be achieved, it is critical that only a small fraction of the compressed fuel mass be heated to ignition by the driver. The bulk of the fuel mass is heated by the propagating burn. The introduction of capsules with cryogenic fuel has been an important contribution to this progress into the high-gain regime. An important additional factor in efficiently obtaining high target gain is the areal density (ρr product), which can be improved by careful pulse shaping. With sophisticated pulse shaping, Nova is predicted to achieve pusher areal densities of about 10 percent of the ρr desired for LMF targets with about $1/1000^{th}$ the driver energy. Since the ρr achieved with optimal pulse shaping scales as the cube root of the absorbed energy, the Nova experiments adjusted for pulse shaping will scale directly into the region of interest for high-gain LMF experiments.

Direct-drive target experiments at the smaller research facilities have contributed much to the ICF target progress being made. Cryogenic target implosions have been done at University of Rochester's LLE Omega laser facility, with compressions of capsules to 100 times liquid D-T density. NRL has developed techniques for spatially smoothing (or tailoring) laser beams that meet the uniformity requirements for successful direct-drive implosions. NRL is also developing techniques (called induced spatial incoherence, ISI) for inhibiting the onset of growth of Rayleigh-Taylor instabilities in directly driven capsule implosions. Detailed high-resolution computer calculations predict that with the use of ISI smoothing thin-shell direct-drive targets can be imploded with sufficient inhibition of Rayleigh-Taylor instabilities to achieve 1000-MJ yields, using a minimum of laser energy at short wavelength. Sophisticated diagnostic techniques and target fabrication processes are being developed by KMS Fusion, Inc., to support the increasing experimental demands of the ICF program.

Driver technology is advancing in parallel with the understanding of target physics. The Particle Beam Fusion Accelerator II (PBFA II) is a reliable and powerful light-ion accelerator. Timing synchronization of all 36 modules is now within 15 ns, and beam generation and focusing experiments are now in progress at the rate of about one shot per day. Efficiency of conversion of electrical power at the diode to ion beams now routinely exceeds 70 percent, with the total energy delivered to the ion beam being 500 kJ. The specified focused beam size has been demonstrated with 5-MeV protons. The Aurora KrF laser is under development at LANL. LLNL is examining designs to lower the cost of glass lasers.

Experimental diagnostic developments have kept pace with the increased needs of the ICF program, including improved backlighting and increased spatial and temporal resolution. It is expected that the diagnostic requirements for the near-term targets will be more stringent than for the high-gain targets in the LMF except for the increased nuclear environment. This issue is discussed in Section V.C, "Experiment Area Requirements."

3. Anticipated Progress

Progress will continue with the existing ICF research facilities. Additional target physics requirements to be addressed include target performance with pulse shaping on Nova, and issues of ion energy deposition and transport with PBFA II. A more quantitative understanding of ablation-driven hydrodynamic instability and of fuel-pusher mixing will also be obtained on Nova. Numerical models have accurately predicted recent experimental results, but further refinement and testing against laboratory experiments are expected. Valuable experience with cryogenic targets will be gained on the Omega and Nova facilities.

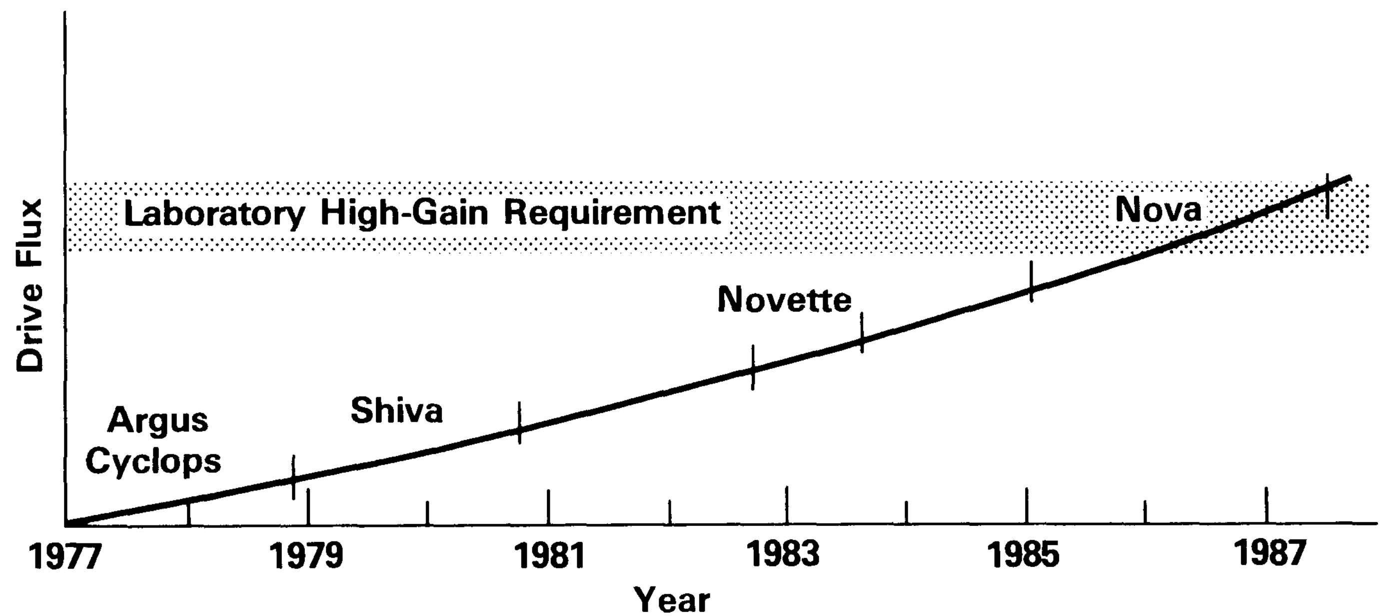

FIGURE 1. HISTORY OF CAPSULE DRIVE FLUX LEVEL
Historical trend of capsule drive flux in LLNL indirect drive laboratory experiments.

After demonstration of a well-focused ion beam on target, PBFA II will carry out experiments (without pulse shaping) at about 10 times more energy than Nova, contributing to the data base for all ion-driven ICF alternatives.

Cryogenic target fabrication capabilities will be extended beyond those demonstrated to date, including advances in techniques to produce a more optimum D-T fuel state, and cryogenic demonstrations on Nova.

4. The 1990's ICF Program Decision

The NAS Happer panel's review of the ICF program recommended that a decision "to continue the program vigorously or not" be made in the 1991 time period. The program achievements of the last few years, as well as those expected over the next few years, greatly strengthen the technical basis for that decision. The decision could well be whether or not to commence with construction of an LMF. The experimental and computational achievements described in this section are needed for a decision to proceed, but they must be supplemented with a credible demonstration of a technical approach for a multi-megajoule driver that can be built at an affordable cost. Phase II of the LMC study will address that task. The ICF Program Plan is structured to ensure that all the information required for that decision is available by then.

II.C THE NEXT STEP

1. Current Plans

The history of the ICF program shows continuing advances in driver technology and the understanding of target physics issues. The program emphasis has periodically shifted, in response to advances in experimental data and theoretical understanding. First the drivers were the center of attention, until adequate driver technology was in hand to perform meaningful target development experiments. Through the early and mid 1980's, emphasis on target physics grew with use of the newest driver facilities and with exploitation of the Halite/Centurion target program. Positive results from these experiments are now leading the program to shift its emphasis back toward the driver technologies, in the search for thermonuclear ignition with significant yield and gain, large scale laboratory applications, and new capabilities for determining the feasibility of civilian applications of ICF. This has been a bootstrapping process of developing experimental capabilities (drivers, targets, and diagnostics), using these capabilities to deepen understanding of the relevant science (driver-target interaction physics and implosion hydrodynamics), then using that understanding to define new driver requirements. At the same time, ICF experimental and computational capabilities of value to the weapons physics program have evolved. Slowly diminishing returns from current experimental facilities can be foreseen, but a rational approach for expansion of the program's capabilities can be defined, thus increasing its ability to take on new, pertinent applications. The strategy in this approach must maximize the benefit to the ICF program, the weapons program, and to the understanding of the energy production potential of ICF, since the scale and cost of any next generation facility will be commensurate with its increased capability.

The current program plan is to identify the technical issues which must be addressed in order to achieve these capabilities. The technical data base must support an early 1990's decision on the construction of a new facility, and then construction could begin in the mid-to-late 1990's.

2. Future Prospects

Section II.B discussed the significance of recent achievements in demonstrating the extent of current knowledge of target physics in the ICF community. Experimental results have given cause for considerable confidence that a well-bracketed range of driver requirements can be defined for thermonuclear ignition and high gain in the laboratory. Results obtained in the next few years should serve to define these requirements even more sharply. Figure 2, which depicts past and projected ICF driver energy output capabilities, shows the region of required LMC energy and also indicates the time frame in which the LMC driver capabilities could be available, provided a focused period of driver development begins soon. The LMC requirements are derived from a survey of conditions which would provide optimal potential benefits to the weapons program. The trend of driver development over recent years and in the near future indicates the feasibility of attaining the energy requirements of an LMC by the late 1990's.

For the next step in increasing ICF capabilities, two reasonable distinct options are available: (1) develop the LMC, or (2) develop a less ambitious, lower energy capability (perhaps a 1-MJ or less driver). Certainly with the lower energy option there is information to be gained in the areas of driver technology and target physics. There are also potential benefits to the weapons program, so indeed this is a viable option. It is also possible that with a high degree of irradiation symmetry (asymmetry certainly no greater than 1 percent) and a carefully shaped pulse, targets may be coaxed to thermonuclear ignition with driver energies of about 1 MJ. But this is a risky option in the near term; the confidence level of achieving it is low. Also, it is generally believed that the likelihood of attaining high target gain under these conditions is slim, as insufficient fuel could be compressed to achieve efficient burning even if ignition were achieved. Under conditions in which 200- to 1000-MJ target yields are judged to be feasible, a whole new realm of experimental capabilities that do not exist with lower target yields is entered. Unique capabilities for performing weapon physics experiments, and nuclear hardening and survivability tests, become feasible, making the LMC far more attractive. Chapter III and Appendices A and B discuss the utility of an LMC.

In either case (the LMC or a lesser intermediate capability), the cost will be significant. The intermediate capability will cost far more than any previous ICF facility, and the LMC will likely cost yet even more. Either option will be a step closer to achieving the goals of weapons program support and fusion energy production, but the far greater utility of the LMC, cited above and elsewhere in this report, makes it the far more attractive option. Both options are means to the same end, ultimate energy production, but the LMC is also an end in itself, a unique and valuable weapons program experimental facility. The LMC is a necessary step in the development of ICF. Developing an intermediate facility is a more conservative approach with respect to the evolution of the driver, but one which will push the LMC into the next century. Not only would an intermediate facility be very costly in monetary terms, it could move the LMC out of the time frame when it would be of the greatest benefit to the weapons program.

The LMC will provide extensive new capability and utility for many years into the future, but the magnitude of the effort to develop an LMC requires a lead time of several years. In order to achieve an LMC by the desired time, the program must begin now to direct its efforts toward that capability.

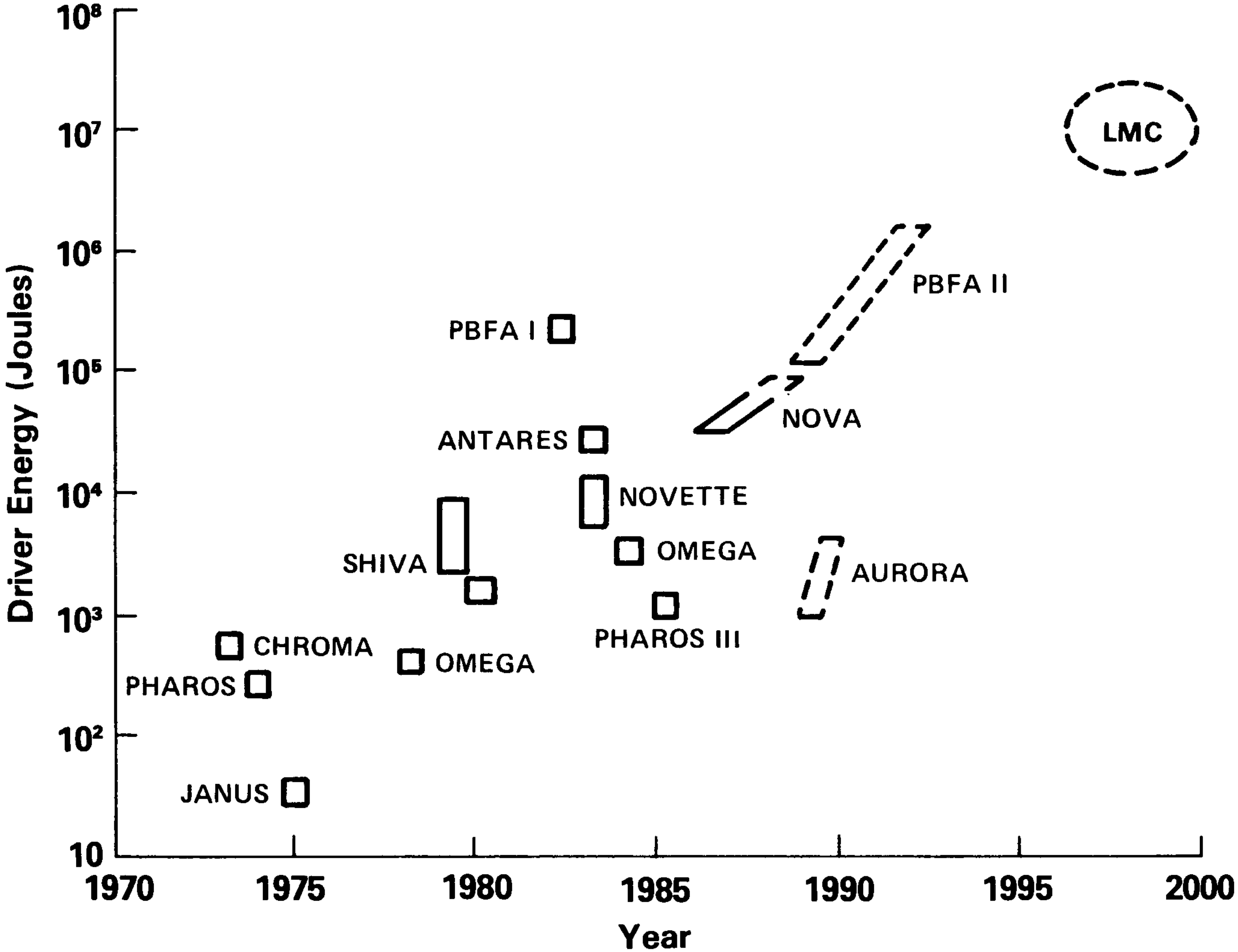

FIGURE 2. ICF DRIVER DEVELOPMENT TREND

III UTILITY OF AN LMC

III.A INTRODUCTION

The LMC will possess utility which is both immediate--making major contributions to military applications--and longer term--demonstrating feasibility in the energy, space, and biological disciplines. An LMC with a yield of 200 to 1000 MJ (energy equivalent to almost 1/4 ton of TNT) can produce high temperature and pressure conditions in the laboratory. Such a facility also will provide the technical development necessary to demonstrate scientific feasibility for production of fusion energy, space propulsion, and biological diagnostics.

Figure 3 indicates the focus of the inertial confinement fusion program which has had, since 1970, as its major near-term objective the operation of a high-yield ICF capability in the laboratory. Recent progress, reported in Section II.B, "ICF Technical Achievements," gives encouragement to the technical community that the LMC is attainable within reasonable extrapolation of present technologies and scientific understanding.

III.B WEAPON PHYSICS

A laboratory ICF facility that produces 200 to 1000 MJ of fusion energy per explosion will create conditions that are in many ways unique in the laboratory. Obviously these ICF experiments cannot address all the issues important to nuclear weapons, as discussed in Appendix A, "LMF Weapon Physics Applications." The ability to produce experimental data on high temperature and density physics under laboratory conditions would be of great value to the many areas of nuclear, atomic, plasma, and radiation physics. Having the capability to replicate many experiments each year would noticeably advance the understanding of weapon physics and effects, and encourage invention. In addition, this capability would attract new talent to weapon research that is important for national security.

A laboratory facility such as the LMC will not be enough by itself to assure the development of nuclear weapons or radiation hardness testing. Many interesting experiments require spatial or time scales larger than achievable with the LMF. Obviously weapon designs cannot be confirmed, nor can design reliability be assured, with laboratory experiments. However, the LMF represents a new, important capability to advance weapon technology.

Specific weapon applications stem from the expected performance of high-yield targets to be developed for the LMF. Experiments can take advantage of high temperature and density conditions to measure opacities, equation of state (EOS), and mixing in materials. However, ICF capsules will have limited energy, so the LMF will complement, not replace, other experimental facilities.

As discussed in Appendix A, LMF ICF source outputs can be tailored for testing of certain physics aspects of advanced weapon concepts.

These advanced weapon physics experiments require a range of capsule yields between 100 and 1000 MJ. Yields of 100 MJ represent the threshold above which there is sufficient specific energy or flux density to do realistic experiments. Approaching 1000 MJ, virtually all of the laboratory-scale experiments can be done.

In addition to the specific experiments that an LMC can perform for weapon development, an LMF laboratory will enhance the ability of the defense effort to attract competent technical personnel and to maintain the quality of work that has been characteristic of the ICF program.

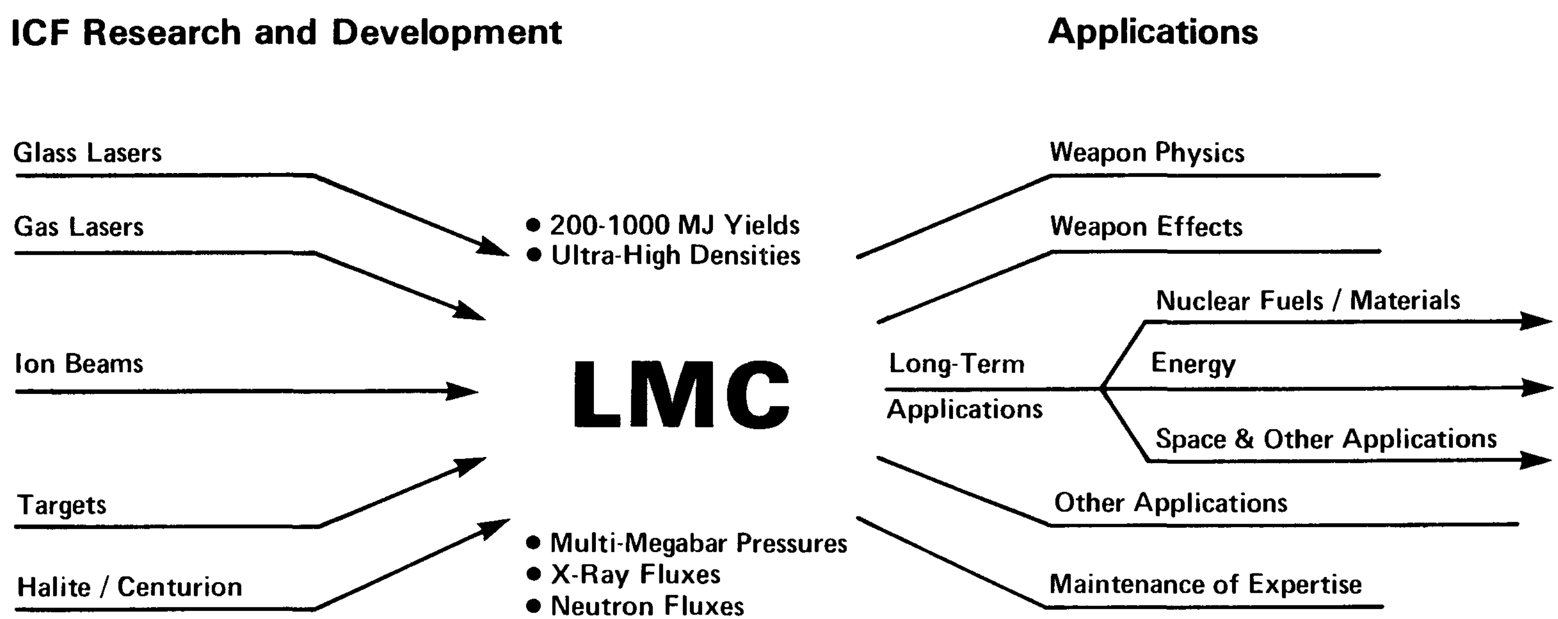

FIGURE 3. ICF PROGRAM FOCUS

III.C WEAPON EFFECTS STUDIES

In addition to valuable contributions in weapon physics (discussed in Appendix A), the LMF can play an important role in testing weapon effects, as discussed in Appendix B. With yields of 200 to 1000 MJ, the LMF will complement present and projected test facilities used for nuclear weapon effects simulation. These consist of the underground testing (UGT) facilities at the Nevada Test Site (NTS) and at laboratory (AGEX) simulators. Of the three principal radiation output components of nuclear weapons (neutrons, gamma rays, and x rays), the x-ray environment is the most difficult for AGEX simulators to duplicate. ICF could complement other facilities in the simulation of existing and advanced threats.

There are several reasons why improved AGEX capabilities are needed for future weapon effects experiments: 1) present military strategy dictates smart and flexible systems, 2) most military systems are becoming more complex, 3) more systems are using active electronics during threat encounters, 4) missions and threats are becoming more complex, and 5) potential new UGT limitations may require more reliance on AGEX's.

All the above require AGEX facilities to enhance the effectiveness of UGT's. Newer electronics technologies have smaller sizes, are more complex, and are potentially more sensitive to radiation threats. Even with the present level of UGT activity the requirement for improved AGEX sources will be driven by the need for better understanding of the technical issues of radiation effects. AGEX sources are capable of repeated testing and are very useful in preparation for UGT's. Finally, if problems arise in an UGT, AGEX's are needed to resolve the problem before the additional UGT's are performed.

III.D ELECTRIC POWER FEASIBILITY

As stated earlier (Section II.A.2), Congressional authorizations have consistently identified "the development of an energy source" as one of ICF's long-term goals. The demonstration of high gain in the LMF would be a major contribution towards establishing the feasibility of ICF for this application. Once high gain is achieved, several necessary energy-related experiments will be possible.

The energy application requires high gain at the lowest possible drive energy, so there will be a target development program. The LMF could address some reactor system tradeoffs, like illumination geometry versus drive energy, and reactor design issues like the first wall problem. The LMF could be used to establish the basic technical feasibility of the energy option for ICF.

III.E ADDITIONAL UTILITY OF THE LMF

In addition to the near-term application of the LMC for weapon physics research, nuclear radiation hardening and effects simulation, and electric power production, the LMC will have utility for other applications. Potential research areas include the production of special nuclear materials (SNM) for weapons, production of fissile fuels for light-water reactors, propulsion for space travel, and nuclear radiation for biological processes, sterilization, and diagnosis. As a scientific tool, the LMC will be unique, able to produce matter in states of very high density, temperature, and pressure never before available in the laboratory. It will contribute substantially to the overall strength of the U.S. scientific community in areas such as cosmology, biomolecular dynamics, laser-matter interactions, intercellular structure, and nuclear matter under extreme conditions.

IV LMC DEVELOPMENT ISSUES

IV.A THE DRIVING FACTORS

The predominant LMC development issues as they are currently envisioned, and a strategy for addressing them, are discussed in this chapter. The factors from which these issues derive are (1) the intended purpose of an LMC, which in turn dictates the physical requirements, (2) the state of development of the required technologies, (3) the degree of understanding of the pertinent physical processes, and (4) the political and economic scenarios of the time, including the perceived need of an LMC. The technical issues will grow out of the first three factors, but will likely be influenced peripherally by the fourth. The programmatic issues (including the budget) will be heavily influenced by the fourth factor which is the most difficult upon which to speculate. The programmatic issues will include the acceptable degree of risk and the credibility required in addressing the technical issues. They will also reflect how affordable the prescribed strategy is, and will fix the budget, hence the time scale, for carrying through the strategy. Possible scenarios which would dictate the programmatic issues are (1) a comprehensive test ban, (2) imminent energy crisis, (3) a particular public attitude toward nuclear processes, and (4) the national economic outlook. Since there is no way of predicting the scenarios from which the programmatic issues will emerge, only technical issues will be taken up in this chapter.

In Chapter VII, various programmatic alternatives are addressed. The ICF Program Plan considers the implications of different programmatic issues as well. Chapter VII describes the phases that occur in execution of an LMF line item, assuming that the driver technology selection and the decision to proceed have been made. This chapter considers program activities leading to the driver and construction decisions, and those program activities that would occur in parallel with LMF design and construction.

IV.B THE PRIMARY STAGES OF DEVELOPMENT

Most of the technical issues of LMC development are identified in other parts of this document, together with supporting rationale. They are presented here, however, from a unique point of view, intended to elicit a rational means for advancing toward the goal of an LMC with full utility. The strategy presented here allows for reasonable advancement of driver capabilities in concert with necessary research and development in other areas, such as target development.

The dominant milestone in the LMC development plan is the authorization to proceed with construction of the LMF. In the strategy presented here, the overall campaign is divided into three primary stages, the first being the period leading up to the construction authorization milestone, the second the period of LMF construction and activation, and the third the period of LMF operation and application. These stages are shown in Figure 4, which depicts the overall strategy of development of the LMC. The following discussion addresses each of these stages in order. In parallel with the first two stages is an LMF optimization program, which is also discussed below.

In addition to the development issues identified in this section, definition of the LMF project requires completion of two fundamental design studies. First is a quantitative analysis of target yield versus application benefits. The Phase I study presents sufficient data to support Phase II efforts, but this subject is sufficiently important to merit a separate, well-reasoned study based upon detailed design calculations that can be available early in the project's definition. Secondly, sound systems analyses will be required, concentrating particularly on the many systems in the experiment area (target chamber and room). Section V.C discusses many

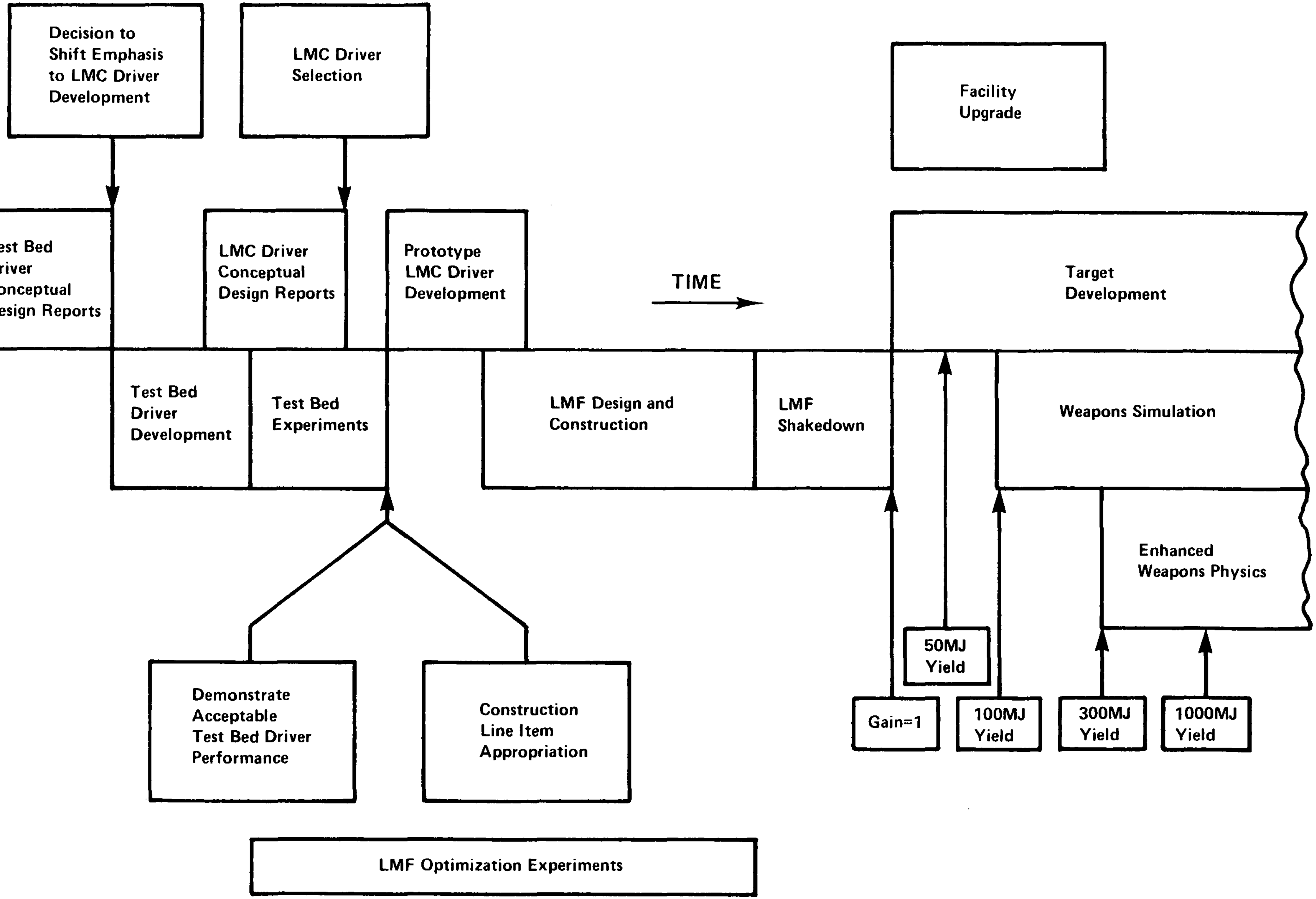

FIGURE 4. LMC DEVELOPMENT DIAGRAM

of the complexities of the systems located there, but adequate systems analyses must grow out of the design concepts that will form the backbone of the Phase II studies.

The fundamental premise of the LMC study, as well as of the ICF Program Plan, is that selection of a driver technology is the paramount prerequisite to the LMF construction authorization milestone. Thus, the overwhelmingly critical development task is the establishment of a credible driver technological base and the development of LMF cost estimates and development issues. Phase II of this study is almost entirely dedicated to that issue.

IV.C THE FIRST STAGE

The first stage in the strategy is one of building technical competence by demonstrating capabilities and deepening understanding of pertinent physical phenomena. For driver development, the major questions are:

> What technologies are available for cost-effectively enhancing driver capabilities to the LMC's scale?
>
> What target scaling relationships faithfully predict the LMC's required driver design parameters?

Each alternative driver technology is at a different level of maturity and requires a unique set of technical milestones in order to define and meet the LMC requirements. Neodymium-glass lasers, which represent the most advanced of ICF driver technologies, are being advanced by investigations of innovations for building multi-megajoule systems at acceptable cost. One goal is the demonstration of about an order of magnitude increase in efficiency over the current Nova efficiency. The PBFA II light-ion driver development effort is committed to irradiating of the order of a 1-cm diameter target with one megajoule of energy in 10 nanoseconds. The KrF laser effort is concentrating on development of the Aurora laser and on the scaling of KrF technology to the multi-megajoule level, pulsed power, optics, and kinetics R&D for KrF lasers. Heavy ion fusion accelerator research involves experiments in the Multiple Beam Experiment (MBE-4) apparatus, wherein four separate, space-charge dominated, low-energy ion beams are simultaneously accelerated in a single accelerator structure; the goals are demonstration of a current amplification and mapping the beam stability realm under MBE-4 experimental conditions. Other technical milestones will be required for each driver alternative. In order to be viable, candidate LMF alternatives must demonstrate the ability to meet LMC requirements at an acceptable cost and risk. That means that internal and independent reviewers should agree that a concept's scientific and technological issues have been demonstrated at or sufficiently near full LMC scale, and that the cost scaling relationships are established. The development programs to accomplish this for each driver alternative will be defined in Phase II. Demonstration tests will need to address the appropriate issues of each driver alternative. The appropriate test beds may vary substantially in complexity (from component size to whole driver modules), depending upon the technical issues that each must address.

In addition to driver technology cost and risk issues, all required scaling relationships must be established and verified. Environmental and safety issues need to be resolved, and specific plans for performing experiments in the LMF experiment area radiation environment must be defined. Establishment of pulse shaping techniques and criteria, and refinement of symmetry/uniformity requirements (hohlraum and direct drive) are also necessary.

System cost is the primary concern in LMC development. Driver cost scaling relationships must be credibly established as part of LMF design studies. The selected LMF driver technology base must support estimation of the line item construction project with realistic indirect costs. Other design questions that must be resolved are, for example:

What unique requirements are placed on the overall system by the selected driver technology?

How will the target chamber design assure the survival of the driver final optics (if any) and the target diagnostics?

How will the target area be operated and maintained, consistent with the design radiation environment?

What environmental and safety issues are there, and how will they be handled?

What are the required and highly desirable experimental capabilities, and how will they be provided?

What are the appropriate design safety margins for assured containment of target yields throughout the design lifetime of the facility?

What are the most likely facility upgrades during its lifetime, and what level of flexibility to accommodate them is affordable?

The LMF conceptual design must convincingly provide for the volume, area, fluence, spectrum, and temporal characteristics required by the users of the facility. No critical design issues requiring experimental verification have been identified in the target experiment area. LMF design concepts must adequately demonstrate the capability to sustain the experimental rate called for in Section V.C, in order to produce a flow of experimental data commensurate with the anticipated national investment.

The LMF target area radiological environment will not be directly comparable to that of any previous ICF facility. Series of scientific experiments will be performed en masse in an experiment area subject to intense energetic neutron activation. The conceptual design must convincingly demonstrate that the facility will be usable with practical operation and maintenance requirements. Critical technologies requiring hardware demonstration may be identified in the experiment area during the LMC conceptual design effort. Preconceptual design efforts must identify how the radiological environment will be dealt with, and then appropriate development and demonstrations must be completed.

There are no unique safety issues in the LMF. However, prior to construction, it must be demonstrated that the design adequately deals with all safety and environmental issues. No development issues are anticipated.

The experiment area will be a significant cost center of the LMF. Prior to construction authorization, design uncertainties must be reduced significantly to allow costing with realistic indirect costs.

It is the purpose of Phase II of this study to identify for each driver/facility alternative those issues that must be resolved before a favorable decision could be made for that alternative. Also to be identified are those issues which could be resolved in demonstration milestones during the construction phase.

IV.D LMF OPTIMIZATION PROGRAM

The emphasis of the first stage of LMC development will be on the driver technology, where the greatest advances are needed. Despite this focus, and while recent experimental results have supported the technical feasibility of ICF (see Section II.B), a number of important questions in other areas remain to be answered, such as:

What target and driver energy deposition configurations offer the greatest probability of early achievement of high gain?

What type of experiments will need to be done to determine if the most desirable configurations have been obtained?

What are the best alternative configurations to serve as backup options?

Are there likely to be technology improvements occurring during the construction phase that can be incorporated to upgrade the facility capability?

What does this imply for requirements on target fabrication?

What is the dependence of target performance on beam quality, alignment, synchronization, etc.?

None of these issues must be resolved before construction authorization; but achievement of high target gain is anticipated to require a lengthy development effort on the LMF; thus a continuous target development effort in parallel with driver development is prudent. Target advances will refine the driver requirements, reduce the required project uncertainty, and reduce the period of target development after LMF construction, thus making the LMF available for weapon applications at the earliest possible time. This target development effort is part of the parallel LMF optimization program shown in Figure 4.

The optimization program includes a number of LMC development efforts. In target fabrication, foam machining and bonding must be pursued, along with continued development of characterization capability. In the target design area, continued demonstrations of ignition, burn, and high gain at decreased absorbed energy are desirable, as are exploration of alternative target designs and driver energy deposition schemes. Additional advances in the spatial and temporal resolutions of target diagnostics on the LLNL Nova program are expected, as well as continued development of x-ray backlighting techniques. Cryogenic target capabilities will be substantially advanced if added to Nova and PBFA II, and if techniques for characterizing target fuels are demonstrated.

During LMF construction and activation, the suite of target experimental diagnostic instruments would be designed, and target fabrication techniques would be developed for the first LMF targets. Consistency between experimental data and computational predictions would continue to be improved in the multidimensional space of pulse shape, hydrodynamic mixing, yield, and absorbed energy. Driver beam energy-to-x-ray conversion efficiency and energy absorption efficiency would be measured. Accurate hohlraum temperature measurements throughout the shaped-pulse drive would be highly desirable.

IV.E THE SECOND STAGE

The issues discussed above are precursors to authorization of LMF construction. The second stage issues, also shown in Figure 4, should be addressed during the period of construction and shakedown. As time and resources permit, a low-risk strategy would begin construction and testing of prototypes of all important driver, target area, and control hardware and software. A number of major system and integration issues could be addressed at this point. Many of these will have been defined in prior and ongoing design efforts. The safety analyses and systems will be finalized, and required target mounting and other target support systems will be developed. Specialized target area systems are also required for initial operations in the radiological environment produced by low-yield targets.

This stage focuses on the detail design issues of construction, the facility shakedown, and the execution of the initial experimental series.

IV.F THE THIRD STAGE

An experimental campaign of target development will begin during the facility's shakedown, with demonstration of a target gain exceeding one anticipated early in the effort. The capability to perform at least one complex target shot per day should be demonstrated by the end of the facility shakedown.

The first need to be satisfied is necessarily that of target development, which is necessary to the weapon applications as well as the civilian applications of ICF. An anticipated target development program is described in Appendix C. The target diagnostic suite will need to be developed in parallel, keeping pace with the experimental needs and target developments. Also, as the target yields increase the systems required to cope with the radiological environment around the target chamber will need to become fully functional and achieve a high degree of versatility and reliability. The driver system may require both planned upgrades and correction of design or construction deficiencies. Specific development issues in these areas will be identified as the design process progresses. A facility upgrade effort is provided in the third stage (see Figure 4) to accommodate planned upgrades and needed alterations identified during facility shakedown and early experiments.

IV.G SUMMARY

The program must accomplish four things. First, it must identify the requirements; this has been accomplished in Phase I. Second, it must have a viable technical approach; that is, a driver, target, and experiment area concept with all show-stopping issues identified and addressed. Third, it must have a credible cost estimate, including realistic, acceptable indirect costs. Lastly, it must have a strategy with cost-risk-schedule options available which are responsive to external political and economic realities, recognizing that those realities change more rapidly and are less predictable than the technical issues.

This chapter has identified the development issues that must be resolved during the stages of development of the LMF. Driver-specific issues will be detailed in Phase II. Additional areas where other issues will arise are also identified. These additional issues will need to be addressed along the path from authorization to completion of LMF construction and achievement of the full LMC with the facility.

The rate of progress of the program is dictated by both the technical issues and the programmatic issues (probably more the latter). For this reason no time scale is depicted in Figure 4. Alternative project time scales are examined in Chapter VII, "Staffing and Management Issues."

V LMC REQUIREMENTS

V.A INTRODUCTION

LMC requirements derive from the basic experimental goals that are to be accomplished in the facility. These, in turn, follow from the ICF Program Mission and from the potential utility of the LMC, whose missions can be divided into five categories: 1) obtain high gain--gains greater than ten are needed to begin most applications, gains greater than about 100 are ultimately desired; 2) conduct advanced weapon physics experiments--yields above 100 MJ are required, yields up to 1000 MJ are desired; 3) conduct nuclear weapon effects and vulnerability studies--yields above 100 MJ are required and yields up to 1000 MJ are desired; 4) assess ICF's potential for electric power generation; and 5) assess ICF's potential for other military and civilian applications.

The matrix in Figure 5 shows one way to consider these requirements. In the sections that follow, the requirements necessary to obtain high gain are discussed first. Then requirements that follow from high-yield weapon physics and weapon effects experiments are discussed. Requirements that stem from the long-term goal of determining the feasibility of ICF as a viable electric power source are discussed next. Finally, other applications of high-gain ICF technology are discussed, but these very-long-term potential desires are not translated into specific requirements.

Figure 5 shows the features needed to accomplish each goal further divided into those that are required and those that are merely desired. A capability is required if it is deemed necessary in order to achieve even the minimum statement of a goal. It is placed in the desirable category if it is not necessary for the stated minimum goal but would enhance the flexibility of the facility, would expand the range of applications experiments that could be done, or would allow exploration of the feasibility of facilities beyond the LMF. Obtaining high gain, doing weapon physics and vulnerability experiments, and determining ICF's electric power potential were judged to be fundamental, required ICF goals for the LMF. Thus, these goals have both required and desirable associated features.

The ICF applications beyond these (e.g., materials production, space propulsion, etc.) are not considered fundamental. Therefore, capabilities needed to accomplish goals for these applications are classed as desirable rather than required. The third axis of the matrix is time. Some of the required or desirable capabilities will be needed as soon as the facility construction is complete and experiments begin. Most of those associated with first obtaining high gain are in this category, although some may be deferred. Other capabilities are not needed until high gain is demonstrated. To the extent possible, these differences are noted in the sections that follow.

This chapter on LMC requirements first discusses those requirements that stem directly from the need to make the target perform properly from the physics standpoint (Section V.B). Surrounding the target are many structures which collectively comprise the experiment area (EA), as distinguished from the driver and the target fabrication facilities. These structures include those necessary to establish the pre- and post-experiment conditions (except for the driver) that will make the experiment a success. Section V.C discusses the requirements of the EA, while Section V.D discusses general driver requirements. Finally, Section V.E discusses the target fabrication facilities necessary to build the number and types of targets required. All of these sections attempt to make the requirements non-driver specific, i.e., the LMF will have to satisfy the requirements independent of its driver technology. In some cases, however, some requirements are cast in different, but equivalent, forms for alternative driver technologies.

Goal / Level of Desirability	Obtain High gain	Weapon physics	Weapon effects & vulnerability	Electric power	Other applications
Required	Minimum requirements to obtain high gain	Minimum yield to do contained, significant experiments	Minimum yield to expose objects to realistic fluxes	Demonstrate sufficient gain for an economically feasible reactor	None required
Desired	Ability to achieve high gain sooner	Expanded range of realistic weapon physics expts.	Expanded exposure capability to do larger objects	Expanded capability to explore reactor design issues	Capability to investigate other applications of ICF

FIGURE 5. LMF CHARACTERISTICS GROUPED INTO CATEGORIES
The third axis is the time that the capability is needed.

V.B TARGET PERFORMANCE RELATED REQUIREMENTS

1. Introduction

The driver requirements that must be met to achieve a given level of target performance have often been specified as ranges of acceptable values for a few gross beam parameters such as energy (E), focal spot radius (r), power (P), and intensity (I). For example, one often sees statements that the beam energy must lie between 1 and 10 MJ, the focal spot radius between 1 and 10 mm, the power between 100 and 1000 TW, and so on. While these order-of-magnitude requirements are useful for orientation, they are not sufficiently precise to define the LMF requirements. For a given driver, the energy yield (or equivalently gain) of a target can depend strongly on a large number of variables. For purposes of discussion, we divide these variables into four categories:

a) Gross quantitative beam parameters such as E, r, P, and I. In general, P and I are time dependent and target gain depends strongly on the pulse shape. For lasers the wavelength, λ, and for ions the range, R, are also important parameters.

b) Beam quality and precision factors, such as beam shape and smoothness, bandwidth or energy spread, energy imbalance among beams, alignment precision, pulse shape precision, shot-to-shot reproducibility, level of contaminants (e.g., protons in a Li beam) that might cause preheat, etc.

c) Illumination geometry, which includes the following:

- one-sided;
- two-sided (target is illuminated by two diametrically opposed beams or beam clusters occupying relatively small solid angles);
- conical (beams arrayed in two or more cones as in the Nova facility);
- equatorial (including barrel diodes, spoke geometries, HIBALL, etc.);
- nearly spherical (many beams oriented normal to surfaces of regular polyhedra, etc.)

d) Sophistication and precision of target fabrication technology.

Ideally, in giving the target requirements for the LMF one would simply express target yield as a function of all the variables described above. Then for a given yield (Y), say 200 MJ or 1000 MJ, the driver designers would be free to choose the set of variables that in some sense optimizes the driver, for example, the set of variables that minimizes driver cost or technical risk.

Although several attempts have been made to give target yield as a function of some subsets of the variables given above, the task is not yet complete. Moreover, there are still some uncertainties in target theory so that different target designers and different institutions incorporate different levels of optimism in their work.

2. Methodology

The LMC study must evaluate several drivers and two types of target drive, direct and indirect. It is therefore necessary to develop a methodology that treats the various options on an equal basis. If it is assumed that all alternatives can implode fuel on the appropriate adiabat and at the appropriate velocity, then all options can be treated on an equal basis by specifying the kinetic energy (K) required to get the desired yield. The driver energy (E_d) is then related to K by the equation $K = \eta E_d$, where η is the efficiency with which the driver energy is converted to the kinetic energy of the imploding fuel. The efficiency can be factored into several parts. For direct drive it is convenient to express η as a product of absorption efficiency (η_a) and hydrodynamic efficiency (η_h) so that $\eta = \eta_a \eta_h$. For indirect (radiative) drive, there are two additional factors, the driver energy-to-radiation conversion efficiency (η_x), and the fraction of radiation that is transferred to the capsule rather than lost (η_c). Thus, for radiative drive $\eta = \eta_a \eta_x \eta_c \eta_h$. The three factors η_a, η_x, and η_c are driver dependent; however, to a good approximation the factor η_h is not. Thus, for radiatively driven targets, the various driver concepts can be put on an equal basis by specifying how much drive energy $E_a = K/\eta_h$ must be delivered to the capsule to get the desired yield. Specifying E_a rather than K and η_h separately is convenient since it eliminates one variable and also eliminates some minor ambiguities regarding the precise definition of the imploding fuel and the time at which K is measured. Moreover, the designers of radiatively driven targets more commonly communicate in terms of E_a rather than K and η_h. For these reasons, E_a is chosen here as the fundamental quantity. Of course, E_a must be delivered to the capsule with acceptable spectrum, pulse shape, symmetry, and preheat. These topics will be discussed later in this section. Choosing the capsule drive energy E_a as the fundamental quantity slightly complicates the comparison between directly and indirectly driven targets, since different values of E_a must be specified for direct and indirect drive; however, the two values of E_a are simply related because $E_a \eta_h = K$ for both types of drive.

In response to a request in March, 1987, the three laboratories studying radiatively driven targets gave their best estimates of the values of E_a for thermonuclear yields (Y) of 200 MJ and 1000 MJ. After discussions and several iterations, an agreement was reached on the value of E_a for radiative drive that should be adopted to produce, with reasonable confidence, a nominal yield of 1000 MJ within a few years after the completion of the facility.

The technical risk of target failure increases as E_a decreases. For example, at lower values of E_a, the target fabrication, diagnostic, and pulse shaping requirements are all more stringent, and the targets are more sensitive to preheat and uncertainties in physics. At lower values of E_a, a longer, better funded operating program would be required to achieve success. Thus, there is a tradeoff between construction costs and operating costs; however, even with an enhanced operating program, the risk of failure is higher at values of E_a lower than the consensus value selected in this study.

In order to put directly driven targets on the same basis as radiatively driven targets, ICF target designers were asked to provide values of the ratio of efficiencies, η_h, for direct and indirect drive. If a consensus had been reached on this ratio, it would have been possible to give a value of E_a for direct drive corresponding to the specific goal agreed upon for radiative drive. The uncertainties are currently too large to reach a consensus. Even for a single driver, a 1/4 micrometer laser, estimates of η_h for direct drive differed by 50 percent. More fundamentally, η_h for direct drive is almost certainly driver dependent. One would not expect η_h to be the same for 1/4 and 1/3 micrometer laser light wavelengths or for ion ranges (R) of 0.03 and 0.01 grams/cm^2. Therefore, determination of η_h for direct drive belongs in Phase II. The value of η_a for direct drive is also driver dependent, and together with η_a, η_x, and η_c for indirect drive, must be determined in Phase II. However, η_h for indirect drive is driver independent. Currently, Nova experiments confirm that the calculations of η_h are reliable.

In summary, it is possible to determine the relative energy requirements of the various driver alternatives and types of drive by determining η_a and η_h, and where appropriate, η_x and η_c, for each option. Factor-of-two estimates are presented at the end of this section.

The consensus value of E_a for Y equal to 1000 MJ assumes conventional pulse-shaped targets and low preheat. Some driver technologies may be able to deliver very energetic pulses to minimize or eliminate concerns about pulse shaping and preheat; the present PBFA II configuration is an example of such an approach. These options do not fit into the methodology described above and any such alternatives must be considered individually.

It is interesting to ask if advances in target theory and design might lead to smaller values of E_a for the same yield. As long as the target design remains approximately as currently envisaged, dramatic energy breakthroughs are unlikely. Performance estimates given by various laboratories approach limits set by conservation of energy and momentum. Advanced concepts such as polarized fuel and magnetic insulation might lead to better performance, but physics uncertainties at this time are large enough that the LMF cannot be based on such concepts.

The above methodology using absorbed energy (E_a) in the target as the primary parameter is useful for the target designers and for comparison of alternative target concepts. However, ICF facility design and costing efforts are strongly driven by the magnitude of the driver energy. With the present uncertainties in the various coupling efficiencies described here, the pulse shape, the illumination uniformity, etc., this methodology using an E_a for 1000 MJ of yield translates into 10 to 20 MJ of laser or light-ion driver energy for indirectly driven targets and 6 to 12 MJ for directly driven targets.

3. Conventional Pulse-Shaped Targets

The following is a more complete description of the conventional pulse-shaped target on which the energy requirements in Section V.B.2 are based. This description is semiquantitative and is given to illustrate important target issues and the relationships among variables. Detailed LMF target requirements will be given subsequently in Section V.B.4.

Spectrum and Pulse Shape: In modeling targets, the drive pulse usually consists of a low power foot followed by a peak power pulse. The dynamic range of driver power needed to supply the foot and the main drive pulses is different for different drivers.

The specifications for the foot follow from the requirement that the compressed ρr product of the fuel must be large enough to give high gain. In order to achieve an adequate ρr product (typically greater than 3 g/cm^2), the pressure in most of the fuel must be within a factor of a few of the Fermi-degenerate adiabat, i.e., the pressure must be less than 2 megabars at ρ equal to 1 g/cm^3. Excessive power in the foot usually generates strong shock waves that lead to higher adiabats. Also, the radiation spectrum must be such that transport into the fuel is at a low enough level to achieve the proper adiabat.

The peak drive requirement is based primarily on considerations of fluid instabilities. In the simplest approximation, the Stefan-Boltzmann law gives that E_a is proportional to r^2T^4t, where r is the target radius (area is proportional to r^2), T is temperature, and t is the implosion time. Ignition requires a definite implosion velocity that is relatively independent of r; thus t is proportional to r so that if E_a is fixed then T is proportional to $r^{-0.75}$. Therefore T decreases with increasing r. Unfortunately, the shell thickness (Δr) also decreases with increasing r, and thinner shells are more subject to disruption by fluid instabilities than are thicker shells. Setting the capsule aspect ratio, $r/(\Delta r)$, during the implosion to a maximum value of 25 to 30 determines the peak power requirement of roughly 1000 TW often seen in the literature.

There are requirements on the precision of the pulse shape. Typically the driver must be able to deliver the pulse such that the power is within roughly five percent of the desired value throughout the pulse. Also since different target designs require somewhat different pulse shapes, significant pulse shaping flexibility is a requirement of any LMF driver based on pulse-shaped targets. In addition, the required pulse must not be preceded by a deleterious prepulse.

For directly driven targets, the requirements are comparable. The power ratio is such that directly driven targets require a foot that is roughly two orders of magnitude less powerful than the main pulse. The intensity and wavelength (or ion range) must provide adequate hydrodynamic stability and an acceptable fuel adiabat.

Symmetry: Both directly and indirectly driven targets typically require a fluence uniformity of about two percent or better. Requirements on flux uniformity at a particular time are more relaxed, but the limits have not been fully explored. Directly driven targets rely on the overlap of a large number (over 30) of smooth beams as well as beam smoothing techniques.

Specific target design and performance requirements impose stringent requirement on the alignment and spot sizes of driver beams.

The considerations just discussed can be used to illustrate the relationships among the various variables listed in Section V.B.1, "Introduction", above. If the effective pulse length is 15 to 20 nanoseconds, corresponding to the value of E_a selected for the LMF, the beam focal radius must be less than about 1 mm and the alignment accuracy must be better than a small fraction of a millimeter. Furthermore the beam shape is an important issue. If the peak power requirement is 1000 TW, the target must be illuminated by approximately 100 beams.

It is clear that one cannot simply specify gross beam parameters. There are tradeoffs among energy, focal spot radius, beam shape, alignment tolerance, wavelength, number of beams, etc.

Beam misalignment can lead to reduced efficiency and implosion asymmetries. Detailed calculations are required to determine which of these leads to tighter alignment tolerances.

For direct drive, symmetry requires that the beam radius is roughly equal to the target radius (usually a few mm at 7 MJ). Alignment tolerances are also set by symmetry considerations. These tolerances are currently believed to be 1 to 3 percent of the beam radius for 32 beams and are expected to scale as the square root of the number of statistically independent beams. Systematic errors among the beams have not been fully investigated.

For all targets the tolerance to energy imbalance among the beams is determined by symmetry considerations. The allowable imbalance is strongly dependent on target design, illumination geometry, and number of beams.

Preheat: In addition to the conditions on spectrum and prepulse described above, the beam must be free of any properties (contaminants or other characteristics) that can raise the fuel adiabat above the acceptable level or that precondition portions of the target to the point that they don't function properly. Processes that may be important in lasers include stimulated Raman scattering, the two plasmon decay instability, filamentation, and ion turbulence. For ion drivers, collective processes, atomic and nuclear excitation, and beam contamination may be important.

4. LMF Target Requirements

The discussion of Section V.B.3 gives the motivation for the detailed requirements given in this section. In giving target requirements, the word demonstrate will be frequently used. In this context "demonstrate" means to show experimentally or with state-of-the-art calculational methods that have been validated by experiments. Clearly not all things can be demonstrated experimentally or there would be no need to do target development on the LMF. However, whenever practical, experiments must be done. The experiments and calculations must be convincing to the ICF community and to any DOE designated review panels.

The following specific requirements are recommended:

Energy: Each LMF driver alternative must be costed for delivery of E_a equal to the consensus value for 1000-MJ yield for indirectly driven targets, or the equivalent kinetic energy to the fuel mass of a directly driven target. Details of absorption fraction, conversion efficiency, losses, etc., must be given. That is, evaluations of driver alternatives must include a detailed energy accounting from beam to fuel. It is emphasized that the value of E_a selected equals that which corresponds to a target yield (Y) of 1000 MJ, the LMF design goal. The value of E_a required to achieve the minimum acceptable LMF yield of 200 MJ is almost certainly smaller than this value. The final choice of E_a will depend upon tradeoffs among capital cost, operating expense, technical risk, target development time on the LMF, etc. At present there is not enough information to make this choice. Since the costs of the various driver alternatives are unknown, these tradeoffs must be addressed in Phase II.

Fluid Instabilities: All high-gain ICF capsules, driven by pressures which can be achieved in the laboratory, rely on the assumption of growth rates for hydrodynamic instabilities which are below that for the classical Rayleigh-Taylor instability. It is therefore essential that all LMF concept alternatives convincingly demonstrate that the targets are sufficiently stable against shell breakup and mixing during all phases of the implosion.

Spectrum and Pulse Shape: All driver evaluations must demonstrate sufficient pulse shaping to drive targets giving yields of 1000 MJ. The evaluations must demonstrate that the spectrum, pulse shape, and target design satisfy the constraints on fluid instabilities and preheat. All potentially important plasma, atomic, and nuclear processes must be considered. The driver must demonstrate sufficient pulse shaping precision to satisfy calculated tolerances. Since the driver should be capable of driving a variety of targets, pulse shaping flexibility is required. Note that specification of energy and pulse shape determines the power requirement.

Symmetry: All evaluations must determine the capsule symmetry requirements and demonstrate that the illumination geometry, energy balance among beams, alignment precision, beam smoothness, shot-to-shot reproducibility, etc., are sufficient to achieve the symmetry requirements. Flexibility in focal spot radius may be important. Motion of the absorption region due to the interaction of the beams with the hydrodynamic motion of the target must be evaluated. The latter effect could be important for both direct and indirect drive.

Beam quality: All evaluations must demonstrate that the beam is free of contaminants, hot spots, etc., that cause unacceptable preheat. Beams must not have temporal (prepulse) or spatial components that could destroy the target or lead to detrimental effects. Effects of bandwidth or transverse and longitudinal energy spread must be evaluated.

Target fabrication: Target designs must be capable of being fabricated.

Integrated Target Design: To satisfy the six requirements given above, target designs must be developed that are consistent with all known experimental and theoretical knowledge. Such designs are referred to as "integrated target designs." Each driver technology concept explicitly must include at least one such design having the required value of E_a or K, and at least the required yield.

These seven requirements address all the variables listed in Section V.B.1. They provide the basis for the Phase II of the LMC study, but may require modification, clarification, or expansion before the LMF is built.

V.C EXPERIMENT AREA REQUIREMENTS

1. Introduction

The structures, equipment, and diagnostic instruments in the experiment area (EA) must establish the proper pre-shot target conditions; provide the interface between the driver and the target, satisfy pre-shot target needs, diagnose target performance, quantify the experimental results, and protect the public, facility personnel, instruments, and data from the effects of the energy release. They must accomplish these functions in the hostile environment created by the target. This section first discusses general characteristics of the environment created by the target and then discusses requirements for structures, equipment, and diagnostic instruments of the EA. For this discussion, EA functions are divided into four specific groups: 1) intra-chamber target support structures; 2) diagnostic instruments and systems; 3) structures and equipment necessary to establish the pre-shot environment, provide the interface between driver and target, and contain post-shot effects; and 4) general requirements applicable to all parts of the EA.

2. Description of Experimental Environment

LMF designs must consider the many effects associated with release of up to 1000 MJ of thermonuclear yield. The direct, prompt effects of the emitted x rays, neutrons, gamma rays, charged particles, and debris must be calculated. These direct emissions interact with surrounding material to produce electromagnetic pulses (EMP), shrapnel, ablation, shock waves, spall, pressure pulses, and thermal stresses. Delayed effects such as those associated with hot vapors, liquid metals, induced radioactivity, unburned fuel, toxic materials, corrosion, and condensation may impact both the experiment and the ability to do future experiments.

In moderate- to high-vacuum target chambers (lower than 0.1 Torr), the inner surface of walls will be ablated by the x-ray energy absorbed there. The ablation causes shock waves, and the ablated materials (on the order of a kilogram) cause a pressure pulse. The ablated materials then recondense on nearby surfaces. In chambers with pressures of 1 to 10 Torr of gas (as with a light ion driver) the chamber wall ablation may not occur (depending upon the gas and pressure used) since the x rays are deposited in the gas instead of on the wall. However, in this case a blast wave will be created in the gas that will have to be dealt with. In either case, solid material within a meter of the target (such as parts of the target support apparatus) may be heavily ablated. Large momenta are imparted to structural pieces, high-velocity shrapnel may be created, and ablative shock waves crossing density discontinuities may spall material.

The emitted neutrons also cause a variety of effects. Personnel and electronics must be shielded from the prompt radiation dose. In addition, the design must account for the degradation of material properties (like yield strength) by the pulsed neutron dose, the creation of electromagnetic pulses in electronic instruments (system generated EMP), and the induced radioactivity. Induced radioactivity can limit the experiment turn-around time by restricting human access or by increasing instrument background; and it determines the amount and type of radioactive waste that must be handled and disposed of, including the containment and removal of radioactive debris and unburned tritium from the target chamber.

Shielding and the handling of induced radioactivity must be addressed in the earliest phases of EA conceptual design.

3. Experiment Area Requirements for Achievement of High Gain

Target Support Systems: The target and its associated support, manipulation, alignment, and documentation hardware are among the most important items in the EA. This combination of units occupies a unique location within the chamber, namely the working point to which the driver beams are focused and the diagnostic instruments are pointed. The target support equipment is highly specialized and has three purposes: to position the target for the experiment, to maintain the target's local environment until shot time, and to verify the target's location and configuration at shot time. The equipment's preferred location is not easily compromised, and it must be designed as an integral part of the chamber.

Requirements:

- Handle cryogenic and non-cryogenic targets, with and without tritium
- Handle indirect- and/or direct-drive targets
- Handle non-implosion targets

Desirable Features:

- Handle direct drive targets
- Handle hazardous materials

The most important part of the target unit is the target itself. Its construction and environmental requirements dictate the design and operation of the target support apparatus. An integral part of the target is the mounting system, which may consist of a stalk, a film web, or thin filaments.

Because there can be six degrees of freedom in positioning the target, the alignment must be accomplished with fixtures or other aids. These are usually precisely affixed to the target during fabrication and interact with the alignment and diagnostic instruments.

Many experiments will use non-cryogenic targets for basic studies of driver energy conversion efficiencies, hohlraum characterization, and dud implosions. However, most complex LMF targets will employ cryogenic fuel with substantial amounts of tritium in the capsule, producing significant target self-heating. Until shot time, this heat must be removed from the capsule.

The complex targets will be fragile and of high value. They will require careful handling so the risk of damage during insertion and positioning is small.

Target Handling Apparatus: The following are eight primary functions provided by the target handling apparatus:

- -- Transport to working point
- -- Target positioning and orientation
- -- Target fill
- -- Cryogenic target protection
- -- Target inspection
- -- Recovery or disposal of target debris
- -- Monitoring and control system
- -- Remote handling inside target chamber

The target must be transported from the entry access port at the chamber wall to the working point, perhaps several meters, and the path must avoid other equipment inside the chamber. Fueled targets likely will require that their specialized environments be maintained during this handling.

The target must be positioned to high precision at the working point with the proper orientation to diagnostic instruments, driver beams, and secondary structures for target support. Alignment aids will be required with many targets.

The fuel (gas or liquid) must be placed into the target. This may occur during fabrication (before insertion) or at the working point, depending on the target design.

A target with cryogenic fuel must be protected between the time when it is filled and the shot time. A protective shroud may have to remain in place, blocking the paths of the driver beams, until within a few tens of milliseconds before shot time. Preservation of the fuel state is accomplished by flowing helium gas around and perhaps through the target, so the cooling gas must be brought to the target and removed if it cannot be exhausted into the ambient background of the chamber.

Inspection, verification, and documentation of the target configuration prior to the shot is vital to analysis of target performance. The position and orientation of the target must be verified, quality of the cryogenic fuel must be ascertained, and all information must be recorded outside the chamber. The majority of data are likely to be optical. Some electronic signals may be generated near the target and relayed to the outside.

Even though the target itself and perhaps several tens of centimeters of supporting material are vaporized during the shot, some of the remaining hardware will be melted, torn, or bent, but still attached to the positioning equipment. This will have to be removed before the next target can be inserted and aligned.

There must be electronic links between the target handling apparatus and the master control system. In addition to the alignment verification signals discussed above, removal of protective shrouds at the last instant before the shot, go/no-go target verification signals, and any other signals required during the shot sequence must be synchronized with the driver.

Because of nuclear activation of the chamber and nearby structures, much of the maintenance of target handling hardware will be accomplished by remote manipulation. This will be the case for most interior components, and needs to be treated in detail during the LMF design process, starting in the earliest phases of the EA conceptual designs.

Special Considerations During Facility Start-Up: During the one or two years immediately following the facility activation, there will be operational development and debugging. The ICF program has considerable experience in these activities and a variety of simple targets will be required to accomplish these tasks. Many targets will be of the non-implosion variety, such as discs and diagnostic hohlraums. Some targets will have room-temperature (non-cryogenic) fuel capsules. These have simpler target support requirements, including minimal need for remote handling capabilities; hence, the target support apparatus will be simpler. There is always the need to provide alignment verification and documentation consistent with experimental requirements.

During early operational development there will be opportunities to refine the designs and procedures of inserting and manipulating the advanced cryogenic targets to be used later. Several iterations of some components could be required, and this check-out phase will prove to be important for efficient routine operation.

Diagnostic Requirements: The diagnostic requirements are those measurements needed to assess high gain target performance. The diagnostic requirements are divided into four groups of measurements: 1) driver performance at the target; 2) energy transfer to the ablation surface; 3) capsule implosion dynamics; and 4) burn performance. Diagnostics for addressing these classes of measurements must be addressed in EA conceptual designs, and some diagnostics may be useful for more than one application. This list is intended to be the minimum set of measurements for diagnosing high gain ICF targets and additional diagnostics may be pertinent.

Many target performance diagnostics will be driver independent. However, in cases where the driver dictates specific laboratory diagnostic systems, the diagnostics and their operating requirements (including vacuum, x-ray or optical lines-of-sight, and shielding) need to be identified.

The relationship between diagnostic operation and the target chamber environment needs to be evaluated, including the diagnostic's survivability and susceptibility to damage. For example, if a pinhole aperture will be destroyed on each shot, the effect of its debris on the chamber, and its replacement and fielding costs may have significant operational implications. Diagnostics need to be evaluated in terms of both radioactivity produced by the target and residual radioactivity in the chamber, for diagnostic operation (e.g., sensitivity) and for its contamination potential.

Diagnostics for target burn experiments will face a more hostile chamber environment than the first three groups of diagnostics outlined earlier. It is expected that many diagnostics in the first three groups will not be fielded during burn propagation studies. EA conceptual designs need to address how the measurements of the first three groups will be related to burn experiments. Also, the facility should have the flexibility to change between doing burn experiments and doing experiments in the first three groups in a reasonable time.

In addition to individual diagnostics, support systems will be required for operating the diagnostics. These include data acquisition and analysis systems, vacuum support systems, electronic timing and fiducial systems, and mechanical support systems.

The driver performance diagnostics characterize the incident driver conditions to allow evaluation of their effects on target performance. Driver diagnostics include the following: incident driver energy, driver pulse shape, driver symmetry, driver synchrony, spectral content, and beam spatial profile.

Energy coupling diagnostics are designed to evaluate the efficient transfer of the incident driver energy from the point of deposition to the ablative surface of the imploding capsule. These diagnostics are more driver-specific and depend upon whether the target is directly or indirectly driven. The following are included in this group: transfer efficiency, symmetry, capsule drive characteristics, and fuel preheat.

Diagnostics for capsule implosion dynamics are designed to measure capsule implosion performance and to assess quality of fuel assembly. These measurements can be done without producing high fusion yields from burning by using dudded fuel. The following are required: pusher position versus time (r-t), implosion symmetry, instability and mix, fuel density (ρ) and areal density (ρr), and fuel temperature (non-burning).

Fuel burn diagnostics measure burn performance for high gain targets, including low performing targets as well as normal performance. Since these targets may produce significantly more energy than dud fuel, debris and radioactivity requirements of these diagnostics will be more severe. The following must be measured: ignition time, target emissions, burn temporal history, fuel temperature, and spatial distribution of burn.

It is envisioned that initially all experiments at the LMF will be in the first three categories above. Required instrument sensitivity will be easier to achieve in a chamber environment that has not been exposed to high thermonuclear yield. Once high gain experiments are done, the chamber background will change dramatically. However, it is likely that even after high gain is initially obtained, experiments requiring instrument sensitivities like those achievable in a quiescent chamber will have to be done. That is, even after a burn experiment there will be a requirement for additional experiments that fall into the first three categories above.

Environmental and Protective Systems: These structures and systems include those that support beam delivery systems and diagnostics; create the necessary pre-shot environment; and protect data, equipment, or people from the effects of the exploding capsule. The structures must do the following:

- Establish pre-shot vacuum, temperatures, and background noise levels necessary for beam transport, target data collection, and cryogenic target support;

- Contain stresses of 1000 MJ design yield;

- Meet health and safety requirements for prompt dose, residual dose rate, waste disposal, routine releases, accidental releases, and toxic hazards;

- Protect diagnostics against loss of data and avoid large dollar losses;

- Be able to begin cleanup one month after worst case accident; and

- Be capable of the following shot rate and lifetime for achieving high gain:

  -- At least 100 experiments at 100 to 1000 MJ
  300 experiments at 10 to 100 MJ
  1000 experiments at below 10 MJ

  -- Allow at least 300 target experiments per year (over 600 desirable)

  -- Allow at least 1 maximum yield experiment per 10 days (1 per week desirable)

Resolution of issues of fatigue, radiation damage, activation, waste quantities, etc., requires information concerning the total integrated fluence that structures will be exposed to during the facility lifetime. At least 1400 experiments with the relative yields listed here will be conducted in order to reliably achieve high gain. This information, combined with the design maximum-yield shot rate and overall shot rate, will dictate a facility lifetime for the attainment of high gain. This may not be the effective life of the facility. After high gain is achieved, military applications experiments (weapon effects and physics experiments) may be conducted at this same facility (perhaps in multiple chambers). Potentially, the high gain development goals may be met with one or multiple chamber(s) with designated yield limits for each chamber. There is opportunity for creative engineering and cost-benefit analysis in optimizing the EA's configuration to meet LMC objectives.

Appendix C outlines a possible specific series of target design experiments to achieve high gain. The number of experiments (at various yields) that will be required, and the time period required, evolved from an accounting of the contingencies and from the desire to achieve high gain within 5 years.

Achieving a gain of 100 or more will require a variety of target types for parametric studies. Experiments will focus on a variety of phenomena (implosion symmetry, temperature, convergence ratio, etc.) and each will be diagnosed in the way that best measures the pertinent data. Some experiments will require larger yields than others, and many can be dud targets, allowing use of the maximum diagnostic capability. Therefore, three hundred target experiments per year, each a step toward high gain, is expected to be the average annual requirement until high gain is reliably demonstrated. If twice as many experiments (600) can be done per year, the time required to achieve high gain will be significantly reduced; this is considered quite desirable. Achieving an experimental rate approaching 600 per year may require two or more target chambers.

The required frequency of high yield shots will be an important variable for design of the EA structures. The facility goals are that it be capable of sustaining an average of one 1000-MJ shot every ten calendar days. An average of one every seven calendar days will significantly enhance the facility's capabilities and is therefore desirable, but not required.

The time required to complete all experiments designed to achieve high gain (1400 shots at 300 per year) is less than 5 years.

Additional Structures Capabilities for High Gain: The following capabilities enhance the utility of the LMF:

- One day manned access to instrumentation outside the chamber is required;

- All waste produced from the facility, to include the decommissioning of the facility itself, should meet shallow burial requirements as outlined in 10CFR61 or other applicable standards;

- It is desirable not to preclude the use of materials having superior driver energy conversion efficiencies; and
- Provide rapid (1 day) manned reentry inside the target chamber.

4. Experiment Area Requirements for Weapon Physics and Effects Experiments

Target Support Systems: Requirements outlined in the preceding section (for achievement of high gain) are equally important in the applications areas discussed here. The target mounting and alignment accuracies are essentially the same as before. However, the source will often be much larger in mass and dimensions; this has significant implication in the EA.

There are added requirements for each of the two application areas. For weapon physics experiments, the experiment package is likely to be distinct from the thermonuclear source but in close proximity to it. They may or may not be fabricated and installed as a single unit. If they are separate units, the experiment package must be supported and aligned with both the source and the diagnostic instruments. Portions of diagnostic instruments may be mounted directly on the experiment, and external power, gases, fluids, etc., may be required. Equation-of-state (EOS) experiments using special nuclear materials will require special handling, safety, and clean-up procedures.

Other weapon physics experiments will require large structures more distantly located from the source. Access ports are required for these large structures, and unique alignment problems may be presented. In the case of x-ray laser development, the lasing medium will probably be closely coupled to the source, but auxiliary structures could be at some distance (e.g., cavity mirrors). Alignment of x-ray laser experiments and diagnostics may be very difficult challenges.

Weapon effects simulations present different problems. Although the source insertion and alignment problems are essentially unchanged, the experiment package may be quite large and have a large number of detectors and associated data recording circuitry. Furthermore, in contrast to the weapon physics experiments, the device under test will be of high value and must be recovered intact. The test objects will be located some distance from the source. Most likely, the source insertion will be the last step before conducting the experiment.

Diagnostics for Weapon Physics Applications: Weapon physics experiments include those which utilize just the driver energy and those which utilize the output of the medium- to high-gain capsule as an energy source. Diagnostics for the former class of experiments are expected to be similar to those used to characterize target environments to achieve high gain. Diagnostics for the latter class must be sensitive to the higher temperatures and pressures characteristic of high-yield capsule sources.

Experiments to study mix, hydro instability growth, projectile acceleration, and EOS will require techniques similar to those used to characterize capsule implosion dynamics. They will also require adequate characterization of drive conditions (i.e., energy coupling diagnostics). Positions of interfaces must be tracked in both one and two dimensions as a function of time. Spectroscopy, radiography, and/or other methods should provide the capability to ascertain the condition (density, temperature) of interfaces as a function of time. If x-ray backlighting is proposed, the facility requirements implied by the required x-ray energy, flux, and spectral, temporal and spatial resolution, will need to be addressed. Multiple laboratory diagnostic lines of sight may be required.

For experiments driven by capsule yield, measurement of drive environments will require diagnostic capabilities appropriate to the higher energy density available, in addition to the capsule burn diagnostics described earlier (section V.C.3). The drive characteristics (magnitude, spectrum, time history, and symmetry of drive on the experiment) as well as preheat mechanisms, must be addressed in this regime, and the effects of prompt capsule yield on the ability to diagnose weapon physics package parameters must be assessed.

Atomic physics, radiation flow, and opacity experiments will require diagnosis of drive environments as in the mix and hydrodynamics experiments. In addition, they require extensive keV and sub-keV time-resolved spectroscopy and imaging, possibly along multiple lines of sight or different lines of sight than the diagnostics used to support driver energy transfer to the ablator and capsule implosion. The state of the material being probed must be characterized. Typical measurements include the spectrum, as a function of time, both incident on and transmitted through a characterized sample, and radiation and density distributions through the sample as a function of time.

Measurements for experiments driven by capsule yield should take into account the effects of that yield on diagnostic systems as well as possible requirements for diagnostics to cover different regimes of energy or flux.

Diagnostics for Weapon Effects Applications: Diagnostics for these experiments need to characterize the source (a high-yield capsule), the effective (modified) radiation environment at the object under test, and ancillary environmental effects of the source. The following are required:

- Essential source diagnostics are the target output diagnostics discussed in V.C.2, including yield and spectra of the neutron, gamma, and x-ray output from the burning fuel capsule;

- Test package dose and source distribution diagnostics measure the effective radiation environment at the test package;

- Because of possible effects on system survivability and performance, EMP from the ICF target, its support structure, and the target chamber, must be assessed.

- Debris from target support hardware, shields, and filters can damage the test package and diagnostics, and must be accounted for in the diagnostic designs.

Experimental rate and number of experiments needed for high-gain and weapon physics experiments: The EA design must support the following experimental effort level for the closely related tasks of developing high-gain targets and weapon physics experiments:

over 500 target experiments per year (over 800 desirable);

at least 1 experiment per week at 100 to 1000 MJ (1 every 3 days desirable);

over 1000 experiments at 100 to 1000 MJ, 3000 experiments at 10 to 100 MJ, and 2000 experiments below 10 MJ.

Some source and technique development will have to be done for this application. Some variations in output can be adapted from the weapon effects program if that is concurrent. Each experiment to be done must be reviewed to determine the shrapnel hazard, complexity of structures needed to support the experimental platform, and implications for waste clean-up.

The capabilities expected to accrue from the LMF in the areas of weapon physics evolved as a consensus concerning a productive rate for acquiring data that would benefit the weapons program. Experience from UGT's and from Nova experiments in providing mix, opacity, and x-ray laser data to the weapons program provide the background for these judgments about the desirable experiment rates and the total number of experiments.

Within the range of required numbers of experiments at various yields, three times as many shots will be done at greater than 300 MJ than between 100 MJ and 300 MJ. At 500 per year, 12 years is required for 6000 shots. The high-yield shot rate of 50 per year for 1000 experiments gives a lifetime requirement of 20 years, which is greater. Retrofitting the high-yield target chamber (or chambers) during the lifetime of the facility may be an effective design alternative.

Desirable features: All requirements and desirable features for high gain apply here (since high gain is needed here, too) with the following added desirable feature: for beam pointing and focusing, all beams should be individually pointable so as to strike more than one object at a time in the chamber. The use of a portion of the driver may be a cost effective approach to meet pre-shot heating requirements in some physics experiments, reducing the complexity in the EA. Handling hazardous materials is desirable to maximize the LMF's utility.

Experiment rate and total number of experiments for Vulnerability/Effects Experiments:

- Source Development Experiments:
  over 10 per year at 100 to 1000 MJ;
  over 10 per year at 10 to 100 MJ;

- Exposure Experiments:
  over 6 per year at 100 to 1000 MJ;
  over 10 per year at 10 to 100 MJ;
  more than 100 total at 100 to 1000 MJ;
  more than 200 at 10 to 100 MJ

The number of experiments and shot rate shown here are based on past experience in AGEX facilities and on the recognition that the rate of data return needs to be substantially greater than from UGT's.

The vulnerability and weapon effects series of shots may not begin until after high gain has been reliably achieved, the proper source characteristics have been obtained, and the desired exposure configurations have been designed and tested. Complicating the characterization process, much hardware will be required to provide neutron shields, conversion schemes, blast or shrapnel screens, etc. and the incident x-ray fluence and spectrum will be modified from that emitting from the capsule. Since the chamber radius will be determined by the test object's size, designs should accommodate the maximum size objects and maximum exposure areas at the maximum yield. This provides the greatest utility for prospective users.

Source development experiments will be used to tailor or to characterize the output of target assemblies specially suited for exposure experiments. Allowance of 10 shots at 100 to 1000 MJ and 10 shots at 10 to 100 MJ per year is required. Six exposures should be done each year until the end of the initial exposure series of experiments. The ability to repeat the initial series with minimal repair is desirable.

Requirements for effects/lethality studies: The following requirements have been identified:

- Provide large solid angles and large areas for exposures in which test volumes, fluences, and uniformity are based on the needs for space-based asset vulnerability testing;

- Support of large masses with large dynamic loads, including assemblies surrounding the target to tailor its output;

- Collect data in exposure region since few diagnostics will be directed at the capsule and most will be on the test item and its environment;

- Be able to alter source spectra, energy partition, and pulse duration;

- Protect exposed items from collateral damage; and

- Removal of exposed items within 1 day.

Because of the long set-up and refurbishment times and the unusual configurations, a second target chamber would allow concurrent work on other applications.

5. Facility Requirements for Power Applications

Desirable Features

-- Larger variety of target types
-- Variable illumination geometry
-- Target injection and tracking
-- Capability to handle hot liquid metals

As included in the ICF mission statement, the primary long-term goal of the ICF program is to determine the potential of ICF as a commercial source of energy. Affordable power plants today are a few hundreds to a few thousands of megawatts. To compete in this environment, ICF will have to establish not only that high gain can be achieved, but that it can be achieved at low drive energy. Target physics considerations, however, make it much easier to obtain high gain at large drive energy than at small. It is expected, therefore, that the initial attempts to get high gain will first occur at the largest drive energy obtainable in the LMF. Thus, once high gain is achieved, study of the feasibility of the energy application will require further target physics experiments designed to obtain the highest gain at the lowest drive energy possible. This involves optimization of the target's utilization of drive energy as well as exploration of different target types.

Options like direct-drive targets and polarized fuel are possible types of advanced targets.

Another type of energy related study that must be done in the LMF involves quantifying some of the system cost tradeoffs that determine the practicality of an ICF power plant. For example, the cost of a reactor is minimized if all the driver beams can enter the reaction chamber from a small number of beam directions (i.e., one or two), preferably all in one horizontal plane. However, calculations show more drive energy is required for this configuration than one in which the beam directions are more uniformly spread over the surface of a sphere. Similarly, power plant costs will be reduced if some of the LMF's high precision requirements can be relaxed (for example, if the precision of the pulse shaping requirement could be relaxed). The initial high-gain experiments will undoubtedly have the target conditions that are most likely to give high gain. Therefore, it will be necessary to perform experiments that reveal the drive energy penalties incurred when other parameters are varied in ways that would save cost or increase reliability in other parts of the plant.

Finally, if the above studies indicate that ICF is indeed a promising energy source, then the way must be cleared for the design of future engineering test, materials test, and economic demonstration power reactors. While design of such facilities would probably be beyond the scope of the LMF charter, the LMF could perform experiments that would provide the data necessary to make the design of such reactors much easier--and the LMF would be the only place where such data could be gathered. Such questions as the feasibility of various proposed first wall materials could be examined. Target injection and tracking systems that had been developed off line could be installed in the LMF to demonstrate that a target could be ignited in such conditions before another large driver is built for the pulsed reactors.

LMF design requirements for performing a set of energy application experiments have been considered briefly. First, a wider variety of target types would have to be built and handled. The ability to vary the illumination geometry, pulse shaping, beam quality, focusing characteristics, and other such variables would be required. Flexibility in changing these variables quickly and inexpensively would be an advantage. The experiments needed to prepare for experimental reactor design would require the ability to handle hot liquid metals (before the shot), ceramic granules, and other material being considered as first wall candidates. Diagnostics that address the first wall vaporization and condensation issues would have to be developed. It would be desirable if the EA could be modified to test the target injection and tracking systems as well as any associated beam pointing systems.

6. Other LMF Applications

There are many potential applications of ICF technology other than those discussed above. Basic scientific studies of the conditions of matter at extremes of temperature and pressure would interest many scientific communities. The laboratory x-ray lasers that could be pumped with either the driver or the ICF capsule would be the brightest x-ray sources on earth. Biomedical and holographic applications would be inspired. ICF reactors could effectively produce plutonium and tritium for weapons or fissile fuel such as uranium-233 for reactors. ICF space propulsion engines and space power systems would have great advantages over nuclear electric or other advanced propulsion schemes for fast, large-payload interplanetary missions.

The LMF will be the only facility where large-yield ICF pulses can be observed in a laboratory setting. One would anticipate great demand to perform at least rudimentary experiments to allow basic assessment of ICF's potential in these other applications. Data from such endeavors would allow the proponents of these applications to decide if and when to build their own dedicated test facilities (perhaps as simple as an additional, separate experimental area at the LMF serviced by the same driver as the rest of the experiments) that would allow a complete evaluation of the application. While we have not placed any requirements or even desirable features on the LMF design specifically oriented toward these very long range applications, it would clearly be desirable if the LMF were adaptable at a later time to address these.

V.D LMC DRIVER GOALS AND REQUIREMENTS

The 1985 National Academy of Sciences review of the ICF program[7] stated that "...it is prudent to initiate design studies for larger ICF drivers now." The LMC driver requirements are dictated by the planned weapon physics and effects experiments, and by the target physics which maps desired target yield to required target drive. Although most of the driver characteristics are obviously driver dependent and must remain undefined at this time, this chapter provides a framework contributing to the objective cited in the NAS report and to the evaluation of alternate driver technologies by defining the goals, requirements, and desirable characteristics of the driver system.

The NAS report also stated that for the early-1990's decision, "A reasonable goal would be about 1 MJ of energy with good pulse shaping capabilities at a cost of $200 million or less." In order to determine the next major step in driver development, a clear view of the ultimate LMC requirements is needed. The LMC requirements, driven by recent advances in target performance and application needs, are more aggressive than this NAS estimate.

Currently there are four long-term driver candidates for ICF commercialization, two laser types (krypton-fluoride excimer and solid state) and two particle accelerator types (light-ion diode and heavy-ion induction linac). Driver selection criteria for the LMF will be weighted towards the near term goals of obtaining high target gain and supporting weapon physics, weapon effects, and vulnerability studies. However, care must be taken not to lose sight of those characteristics essential for long-term ICF reactor applications, such as high efficiency and repetitive operation.

The characteristics and requirements to achieve the facility's major goals are emphasized in Table 1, and remarks about other applications are also included.

V.E TARGET FABRICATION REQUIREMENTS FOR THE LMC

1. Introduction

This section describes the objectives, approach, conclusions, and recommendations for LMC target fabrication functions. Major fabrication issues are discussed, specifically fuel capsule technology, cryogenics, and characterization. The objectives of this section are to determine the target fabrication capabilities required by the LMC and to identify significant deficiencies in present target fabrication technology. Generally, the technical discussion is limited to that necessary to clarify the bases of the recommendations or conclusions.

2. Approach: Candidate Fuel Capsules

All four proposed areas of LMC application (ICF, weapon physics, weapon effects simulation, and other) require target fabrication support which, to varying degrees, exceeds that available at present. Unfortunately, since it is not possible to precisely predict the targets that will be required by the LMC, the fabrication requirements must suffer the same degree of inexactness. Nevertheless, enough information is available to anticipate the principal fabrication requirements.

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

TABLE 1 DRIVER REQUIREMENTS and DESIRABLE FEATURES*

	Item	Requirements	Desired	Remarks
1.	Adequate driver output energy	Must provide 200-1000 MJ yield		Driver dependent This is estimated to to be 10-20 MJ for indirect drive and 6-12 MJ for direct drive
2.	Large range of driver energies	Must be variable to meet all experimental requirements		
3.	Wide range of pulse durations	Peak power 3 to to 10 ns (typical) Total duration of a few tens of ns	0.1 to 50 ns	Laboratory x-ray laser expermts benefit from the "Desired" range
4.	Flexible pulse shaping	Meet target requirements Shot-to-shot reproducibility Acceptable prepulse	Rapid changes	Driver dependent
5.	Compatible with diagnostic requirements	Meet backlighting requirements Meet other diagnostic requirements		There are other alternatives to provide backlighting
6.	Efficient target coupling	Wavelength/ion range consistent with requirements Efficient coupling Low fuel preheating		Lasers typically 1/3 to 1/4 micron Ion range typically 0.02 to 0.2 gram per cm^2
7.	Adequate shot rate	See Section V.C. High availability		
8.	Pointing, focus and alignment stability	Meet target reqmts Stable longer than the alignment time		Direct drive, x-ray laser, and special targets have special requiremts

TABLE 1 -- continued

	Item	Requirements	Desired	Remarks
9.	Flexible illumination geometries		Indirect and direct drive Backlighters Targets for advanced weapons	
10.	Low capital and O&M costs		Minimize total facility cost Annual O&M < 15 % TEC	Recommend cost be the 2nd highest priority Priority TEC < $ 2B Prefer TEC < $ 1B
11.	Reliable operation	Perform within specification on 95% of high-value target shots		
12.	Short turnaround	Routine maint. less than 1 month/year Max. unscheduled maint. 1 month/year Few-hour shot recovery		Strongly design dependent Remote maint. may be critical
13.	Minimum technological advance	Minimal scaling from prior experience		Demonstrate critical technology before commitment
14.	Repetitive pulse operation		Burst mode for commercial applications	No requirement

* All driver parameters are dependent upon the driver technology and designers may have great latitude to trade-off driver performance, cost, and risk while remaining consistent with known target requirements. The entries in this table are representative of currently envisaged design approaches.

For the purpose of costing target fabrication requirements it is assumed that the preponderance of LMF experiments will employ radiation-driven targets.

Fuel capsules of current primary interest are the most likely focus of early LMC investigations. This enables identification of the capabilities required early-on and of the most pressing fabrication issues. However, the capabilities associated with alternative cryogenic designs, which may in fact prove more desirable, must be included.

Capsule fabrication difficulty increases with decreasing absorbed energy. This increase in difficulty results from a decrease in the dimensions. Some of the implications of these requirements are discussed further in the sections on cryogenics and fuel capsule fabrication.

Current designs may not be optimal for the LMF. Of course, as new target performance data are acquired, new target designs and modifications will evolve, resulting in new fabrication issues which will have to be addressed as part of a continuing development effort. Therefore, in addition to identifying capabilities associated with specific capsule and target designs, the LMC's need to address continually changing R&D activities as they relate to target fabrication must be considered.

3. Physical Plant and Location

Fabrication personnel perform two functions, 1) direct support of the target experiments, and 2) R&D in the area of target fabrication. The support effort consists of fabricating targets, supplying support to the experiments (e.g., designing, testing, and fielding cryogenic equipment), and assisting in the acquisition and analysis of experimental data (e.g., documentation of pre-shot target conditions and post-shot physical and chemical analyses). Functions to be performed in the LMF are shown in Table 2.

These target fabrication direct-support group functions can be organized into the following component groups:

Shell fabrication and assembly
Photolithography
Target chamber support
Analytical chemistry
D-T filling facility
Polymer chemistry
Cryogenic support
Metallurgy
Characterization
Machine shop facilities
QA/documentation
Health physics support
Mechanical design
Hohlraum/special target assy.
Electronic design
Electronic maintenance

Based on the present status of target technology the R&D group's activities will probably lie in 5 main areas:

Cryogenics
Shell fabrication and assembly
Characterization
Special target fabrication

Special target fabrication includes targets for diagnostic development, x-ray lasers, certain weapon effects simulations, and some potential weapon physics experiments. It is worth noting that the development group will need to use all of the components of the direct-support group with the exception of target chamber support, QA, and cryogenic support. Locating the two groups at different sites will require duplication of some personnel and equipment.

Table 3 identifies the current target fabrication issues. The LMC target development group will likely still be addressing the majority of these issues.

Two cases are estimated; a realistic scenario of two complex hohlraum targets per day is presented in the following discussions, and a maximum credible scenario of 10 complex targets per day was also examined.

Table 4 lists the major instruments and equipment required for these activities, assuming that the direct-support and R&D groups are co-located on-site at the LMF. The confidence to list equipment requirements reflects the belief that the major portion of the target fabrication capabilities to be needed are techniques which are fairly well defined and presently used routinely, e.g., hohlraum fabrication, tritium handling/filling, etc. Although there is fair confidence in the types of equipment needed, there is less confidence in the numbers of particular instruments or

TABLE 2

LMC Target Fabrication Requirements

1. Fuel capsule fabrication
2. Hohlraum fabrication
3. Cryogenics
4. Capsule fueling and tritium handling
5. Characterization: Fuel and shell uniformity and sphericity
6. Targets for weapon effects studies
7. X-ray laser and other special targets

TABLE 3

Current Issues in Target Fabrication

1. Seamless/plugless shells
2. Elimination of capillary fill tubes
3. Cryogenic target fabrication, inspection, and thermal environment control
4. Solid, liquid, and gaseous fuel states
5. Fuel characterization
6. Capsule surface characterization
7. Cryogenic models

TABLE 4

LMC Target Fabrication Equipment and Laboratory Facilities Requirements *

	Cost (000's)
Characterization/Inspection Laboratory	
Optical Microscopy	$ 280
Interferometry	280
Scanning Electron Microscopy/ Energy Dispersive X-Ray Analysis	800
Radiography/Densitometry/Photometry	1,100
Image Analysis	120
Profilometry	30
Spectrometry	1,500
Chromatography	175
Acoustical Microscopy	200
Neutron Radiography	500
Wet Analytical Chemistry Facility	200
Microfabrication Laboratory	
Photolithography	475
Electron Beam Lithography	300
Ion Beam Implantation	500
Plasma Etching	140
Ion Beam & Reactive Ion Beam Etching	500
Ion Milling/Drilling	450
Vacuum Evaporation	240
Sputter Evaporation (RF, DC)	400
Plasma Polymerization	280
Polymer Deposition	240
Electroplating	100
Chemical Vapor Deposition	200
Cryogenics Laboratory	
Holographic Interferometry	1,700
Cryogenic Transfer Systems	800
Cryogenic Processing Systems	1,400
Organic/Inorganic Chemistry Laboratory	
Controlled Solvent Extraction System	210
Freeze Dried Processor	30
Shell Fabrication/Fueling	
Material Processing Systems	200
D-T Filling/Storage Facility	1,800
Tritium Monitoring Equipment	400
Hazardous Materials Machining Facility	900
Non-Hazardous Machining Facility	200
Clean Room Assembly Stations	500
Shell Processing Systems	200
Shell Facility	600
Health Physics Laboratory	750
Subtotal	$ 18,700
Miscellaneous (25%)	4,675
GRAND TOTAL	$ 23,375

(1987 Dollars)

* Table 4 assumes two shifts producing two complex targets per day.

machines needed; that would require an in-depth analysis of each of the operations to be performed. This lack of complete data also reflects in the confidence in estimating the size of the facility. Cost estimates are presented in 1987 dollars.

Fabrication of two complex cryogenic hohlraum targets per day leads to the conclusion that a minimum of 40 to 45 fabrication support personnel will be required in a structure of 23,000 to 30,000 ft^2. An additional 90 to 95 R&D personnel, with space needs of 25,000 to 35,000 ft^2, will be required. These estimates include design support personnel and radiation safety personnel, but do not include administrative personnel.

The amount of equipment required also depends on the number of shifts. If a single shift is presumed, the number of work stations for assembly and inspection somewhat exceed the number of targets required daily. The number of excess target stations depends on the downtime for equipment, the fabrication time per target, and the fraction of targets rejected during QA inspections. Table 4 assumes two work shifts, a rate of two targets per day, and an excess target fraction of 50 percent to determine the need for duplicate work stations for certain assembly and inspection functions.

The assumption that both R&D and direct-support target activities will be housed at the LMF site needs to be examined. It may be that physical separation of the two will allow for a more orderly development effort than has been witnessed in prior facilities that have housed both. It may also allow calling upon a larger community to be involved in the development efforts, e.g., university personnel. However, these factors must be weighed against the synergism and shortened response time that accrues from co-location of production and development activities. Current opinion is that keeping them together as much as possible is the better of the two options. A final recommendation will depend upon careful evaluation of the economic advantages in utilizing existing national facilities.

The direct-support personnel must be responsive to the changing needs of the experimental program. It is recommended that these personnel be located on-site, enhancing the interaction between the experimentalists and the target fabricators, and also promoting team effort.

Transport of some targets or components may be made difficult by radioactivity associated with the fuel. Generally, significant levels of fuel capsule radioactivity can be expected. Although transport of materials with much higher levels of radioactivity is common, the fragility of targets and other concerns (like maintenance of cryogenic temperatures) make LMF target transport a serious concern. In a number of cases filling and testing on-site after transport may not be possible.

The handling of radioactive materials does not present any special problems since techniques for handling much larger quantities of similar materials are well in place. However, processing fragile targets mandates that all operations after filling take place in controlled-environment glove boxes and transfer systems.

Locating much of the target fabrication on-site can also avoid the duplication of, or reduce the number of, certain facilities and services such as machine shops, engineering design, electronic maintenance, health physics, analytical laboratories, etc. However, not all of the fabrication support activities should be located on-site. For example, some of the targets for weapon physics and weapon effects investigations are expected to require fabrication of structures considerably larger than the ICF fuel capsules. Generally, when target component dimensions exceed about 10 cm, considerably different expertise and equipment is required for fabrication. Since facilities to fabricate these large components presently exist, it is recommended that components with dimensions greater than about 10 cm be fabricated off-site.

4. Capsule and Special Target Fabrication

ICF fuel capsules which produce high yields will generally be useful to the weapon physics and weapon effects experiments. However, depending upon the particular application, capsule designs will be varied to tailor the output spectra. Other than the introduction of new materials, these designs do not require a significant increase in fabrication capabilities over those needed for ICF fuel capsules.

The need to study weapon physics may increase somewhat the complexity of hohlraum fabrication by the introduction of materials for equation-of-state (EOS), radiation transport, opacity, etc., studies. However, there do not appear to be any major additional fabrication issues associated with them.

Several important issues associated with fuel capsule fabrication exist and continue to be addressed. Presently, smaller fuel capsules are fabricated as shells using vertical furnaces or microencapsulation techniques. Capsules with dimensions comparable to those required by the LMC have been fabricated either by coating a sacrificial mandrel and subsequently removing the inner materials, or by forming two hemishells which are subsequently joined. The perturbations to spherical symmetry caused by the seams at the joining of two hemishells, or the imperfections left by holes used for the removal of mandrels, have been seen. It is expected that the effects of these perturbations will be significant in high-gain experiments. Target specifications relative to these perturbations must be addressed, in order that these issues receive the appropriate priorities.

5. Cryogenics

Because of lower driver energy requirements, cryogenic targets will continue to merit thorough investigation, and further investigations into the improvement of fuel uniformity are warranted.

Eliminating the capillary fill tube will grow in importance as higher compression ratios are sought. Indeed, the sizes of the LMC capsules will severely limit the size, or perhaps even the use, of capillary tubes.

Thus, a need exists to investigate other possible fueling techniques; e.g., assembling and maintaining fuel capsules under high fuel pressure environments until later cooled to cryogenic temperatures, or fueling and assembling under cryogenic conditions. In the short term, techniques should be investigated for removing the capillary tube and healing the region from which it is removed so that no significant perturbation is presented to the required spherical symmetry.

There are several other issues, which, though difficult undertakings, employ techniques the majority of which are currently available. For example, cryogenic transfer may be required to place the target in the target chamber.

6. Characterization

It should be clear that the critical element in the cryogenic development efforts is the characterization of the fuel. Characterization is not only critical, it is also presently inadequate, in that it lacks sufficient precision and requires visible observation.

If visual inspection is impossible, and since the fuel is essentially transparent to x rays, other yet-to-be-defined probes must be relied upon. Alternatives to visual inspection are less precise and present additional difficulties.

The achievable fuel compression depends on the capsule's sphericity, uniformity, and surface smoothness, as well as the drive symmetry. Thus precise characterization of these capsule parameters is necessary.

There does not appear to be a complete set of specifications on which all target designers can agree. The different defects (i.e., deviations from perfect symmetry and smoothness) affect the implosion process in different ways, either by making the implosion non-symmetric or by generating fluid instabilities. Predictions of the degradation of target performance in terms of the magnitude of these defects for specific LMC targets are required before the required precision can be stated confidently.

There are generally accepted requirements for shell sphericity, thickness, uniformity, and surface smoothness. Some care must be taken in interpreting these specifications, particularly in the case of surface and interface smoothness. The need to characterize surface defects with high precision is anticipated.

Much has been accomplished in the area of uniformity measurements with optical interferometry, including holographic interferometry, and x radiography. Opaque systems can only be characterized by radiography and microdensitometry, although cursory investigations have been made of the efficacy of other techniques, such as acoustic microscopy. Unfortunately, even x radiography suffers when characterizing many material combinations of interest.

Some of these difficulties can be circumvented by characterizing the fuel capsule at each stage of fabrication. This procedure, although potentially satisfactory in resolving the uniformity measurements, generally degrades the shell surface as a consequence of debris which attaches itself during the inspection steps. No satisfactory techniques exist to completely remove this debris, which is evidently attached due to combinations of electrostatic attraction, welding, and deliquescent or other chemical forces. Thus the surface examination process itself will invariably degrade the surface of interest. It is wise to plan on component fabrication and assembly in class 100 clean rooms.

This situation is aggravated by the small dimensions of the capsule debris, which require resolutions usually available only by electron microscopy. Likewise, at present no satisfactory techniques exist to perform full (4π) surface or sphericity characterizations.

7. Conclusions and Recommendations

Among LMC target fabrication needs, cryogenics should be given immediate attention. Foam technology needs continued development and techniques for increasing the fuel densities in the central void should be examined.

Fuel, capsule, and foam characterization are additional areas of pressing need. The required characterization precision and the effects of various defects (such as surface debris, fill tubes, holes, seams, and material inhomogeneities) need to be investigated by the designers of LMC target fuel capsules.

The cost to equip the LMF's target fabrication facility is estimated at approximately 24 million dollars for a shot rate of two targets per day. A minimum of 40 to 45 fabrication support personnel will be required in a structure of 23,000 to 30,000 ft^2. An additional 90 to 95 R&D personnel, with space needs of 25,000 to 35,000 ft^2, will be required. These estimates do not include administrative personnel. Costs are also dependent on the amount of work which is done on-site. It is recommended that as much work as possible be done on-site.

VI SITING, SAFETY, AND ENVIRONMENTAL CRITERIA

VI.A INTRODUCTION

Siting, safety, and environmental (SS&E) criteria are presented in Phase I to identify those criteria that may be established now and to identify areas where future design studies need to provide additional data.

Siting, safety, and environmental factors are closely interdependent and are fundamental to the total project process. They are imposed by law, by presidential order, and by DOE policy, at the highest of priorities. They are as critical as technical criteria and must be met before construction or operation may commence.

DOE and its predecessor organizations have evolved well-proven site selection processes, and environmental requirements and review processes are well institutionalized. DOE Order 6430.1, Chapter V, provides site selection and general design guidance for DOE facilities. There should be no reason for the LMC/LMF project to fail in these areas. Indeed, they should be handled smoothly, so that the project team can focus on the technical objectives, cost, and risk. This section is in support of that objective.

VI.B SITE SELECTION

Major facility site selection is a multistep process, involving technical and program objectives, cost, environmental and safety requirements, and political considerations. DOE and its predecessor organizations have followed site selection processes that share a number of common steps, as follows:

1. Establish the siting criteria from technical, safety, and programmatic considerations.
2. Identify all suitable sites.
3. Perform a preliminary evaluation of sites and select those that appear acceptable.
4. Perform a technical and cost evaluation, creating the Best Qualified List (BQL).
5. Perform an in-depth evaluation, establish a ranking for the BQL, and select the preferred site.
6. Select the site.

Criteria are set as broadly as possible in step 1, so that no good candidate sites are excluded from step 2. The most painful siting experiences appear to have been caused by not searching out all suitable sites in step 2, rather than by use of poor selection criteria.

Step 6 is the proper place where political considerations enter. If the prior steps are performed correctly, then all of the technically acceptable sites are ranked in step 5; there are no unacceptable sites under consideration, and the merits and liabilities of each candidate site are established. DOE management then selects the final site, judging the technical and cost factors against policy, economic factors, and prejudice. Step 6 can be an embarrassment only if the prior steps are poorly done.

Siting criteria are categorized as qualification, technical, or cost criteria. Qualification criteria are those which are mandatory. Technical criteria are those which address the desirability of sites meeting the minimum requirements set forth in the qualification criteria. Technical criteria expand upon the qualification criteria and introduce additional factors for which there are no minimum requirements. Assessment of cost criteria requires estimation of the life cycle costs of the facility at the specific site, considering all site variables and their effect on design, construction, and operating costs. Technical criteria must be ranked in relative importance, and there must be an a priori assignment of the relative importance of technical merit versus cost. Although the specifics are not important here, the rules of the selection process must be established in advance to maintain the credibility of the rankings when step 6 of the selection process is entered.

Actual site selection criteria will be established by the LMC project team when initiating the selection process. However, the following have been identified to date.

Qualification Criteria: The mandatory criteria identified in the selection process are called qualification criteria. The following are probable LMF siting qualification criteria:

a) The site must be located within the United States.

b) The site must provide at least the minimum required area suitable for LMF siting, which is driver dependent. The required land may be of the order of 80 hectares (200 acres).

c) The site must lie above the local Probable Maximum Flood (PMF) level (as defined by the US Army Corps of Engineers), with additional allowance for concurrent failure of upstream dams.

d) The site must be located on existing federal lands.

e) There must be no unacceptable environmental impacts.

f) The site must meet population center distance and population density requirements consistent with radiological safety standards.

g) The site must have adequate power and water available.

h) The site must provide critical fire protection and emergency services.

<u>Technical Criteria</u>: Technical criteria are used, along with cost, to rank the attractiveness of sites meeting the qualification criteria. The following have been identified as probable technical criteria; additional technical evaluation criteria and their relative weights will be established as the LMF concept develops.

a) Transportation lines should produce minimal ground vibrations consistent with driver and target alignment criteria.

b) Site seismology also should be consistent with target and driver alignment criteria.

c) Adequate construction resources should be available.

d) Transportation and security provisions of the site should be consistent with the desire to have visiting scientific staff participate in the LMF's research efforts.

e) Housing, social services, educational facilities, and recreation should be consistent with the need to hire and retain qualified personnel.

f) Existing environmental documentation is desirable in order to reduce risk and cost. This includes, but is not limited to, an existing DOE environmental survey (ES) and/or an existing site Environmental Impact Statement (EIS) which encompasses most or all LMF operations.

g) There should be an adequate emergency preparedness plan in place.

h) The site should be currently under the control of DOE, be transferable to DOE's control, or have an established history of satisfactory joint tenancy between DOE and another federal agency.

i) The site should have an established infrastructure of security, personnel, plant maintenance, safety, health, payroll, accounting, purchasing, waste disposal, and other required services.

j) The site should have established waste disposal facilities, or it should have established waste packaging and transport facilities and permits, adequate to handle LMF waste requirements with minimal or no upgrading for normal, hazardous, and radiological wastes.

k) Local political support should be favorable and required local permits available.

l) The land should be relatively level with at most gentle slopes consistent with a complex of research buildings.

m) Electric power, potable and cooling water, steam, and sanitary sewerage should be available to meet LMF requirements with minimal upgrading.

n) Environmental requirements and LMF impacts upon the site should be minimal, and required mitigation should be minimal using well accepted methods.

o) The site should offer an established meteorological monitoring service.

p) The site should be consistent with LMF decommissioning requirements.

<u>Cost Criteria</u>: The LMF cost evaluation, including both construction costs and operating costs, is discussed in Chapter VIII, "Major Cost Factors." The relative weights applied to cost and technical factors must be determined prior to commencement of site selection.

VI.C SAFETY

Each LMF structure must be classified in accordance with the requirements of DOE Orders. Relevant classes include nuclear (as the experimental building might be), accelerator (as a heavy ion driver building would be), and non-nuclear (as a laser driver building would be). Structures are also classified as critical (essential to weapon production or of high value) or non-critical (non-essential and low value). Siting, safety, and design requirements are determined by these classifications, and are significant cost factors.

All applicable federal, DOE, and site safety requirements shall be met. Proposed designs must be evaluated to assure that the facility will meet established safety requirements while providing the required experimental capabilities. The design safety analyses must assure that the emission of radionuclides, and the staff and public exposure doses, conform to requirements under operating and accident conditions.

Aspects of the safety analyses, for example, definition of the design basis earthquake (DBE) and design basis tornado/extreme wind (DBT), will be site specific. The design basis fire is not expected to be site specific, although the consequences will be. The following are needed as early as possible in the design cycle in order to begin defining the design basis accidents (DBA's).

Structural activation, radiation dose management for maintenance personnel, and consequences of accidents wholly contained within the target area need to be addressed as described in Section V.C.

Unusual fire risks must be identified. The risk of fire concurrent with external events, like earthquakes, should be addressed.

Although the magnitude of the DBE will be site specific, the cost of hardening designs to withstand various levels of DBE will be design specific. An attempt should be made to identify those features of the design that either significantly increase, or significantly decrease, these costs with respect to alternative approaches.

Critical safety systems required to assure containment and monitoring of radiological releases must be identified.

In addition to identification of preliminary design basis accidents (the worst credible events), worst case accident scenarios should be identified, independent of their calculated probabilities of occurrence. Examination of such accident scenarios often provides much insight into the inherent safety of a design.

Unusual hazards (those other than common industrial hazards) that occur routinely during operation should be identified.

Radiological containment is strongly interactive with the siting process. DOE Order 5480.1A, Chapter I, provides as a recommended standard appropriate portions of 10 CFR 100, issued specifically for siting stationary light water reactors. Siting criteria in 10 CFR 100 have been the authoritative guidance, and have been applied by the NRC, AEC, ERDA, and DOE to nonreactor facilities. DOE Order 5480.1A, Chapter V, establishes safety requirements for all DOE nuclear facilities except reactors and accelerators to assure:

> ... that nuclear facilities are sited, designed, constructed, modified, operated, maintained, and decommissioned in accordance with generally uniform standards, guides, and codes that are consistent with those applied to comparable licensed nuclear facilities.

The siting decision process can be summarized as answering the following relevant questions:[8]

> Does the proposed site meet the siting guideline doses?
> Is the proposed site more suitable than alternative sites...?
> Can emergency planning requirements be met...?

Both immediate and long-term release consequences must be considered, so the potential for extensive ground decontamination must be considered, if necessary.

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8. LA-10294-MS, "A Guide to Radiological Accident Considerations for Siting and Design of DOE Nonreactor Nuclear Facilities," Los Alamos National Laboratory (January, 1986)

VI.D ENVIRONMENTAL

The project (called an "action") must conform to the requirements of the National Environmental Policy Act (NEPA), implementing regulations of the Council on Environmental Quality, DOE policies and procedures, related state and local requirements, and numerous other environmental acts per Executive Order 12088.

The NEPA Process: The first step in the preparation of NEPA documentation is the preparation of an Action Description Memorandum (ADM) in accordance with the requirements of the DOE operations office having jurisdiction over the site being considered. This is the highest level of NEPA documentation that may be prepared without specific DOE authorization. Because of the importance of the NEPA documentation to the timely execution of the project, ADM level documentation should begin as early in the conceptual design process as possible.

The various states have statutes equivalent to the NEPA. DOE policy is that environmental documentation be prepared in as broad a manner as possible to encompass both state and federal requirements with a minimum number of separate documents. Because state requirements are site dependent, they cannot be addressed in detail until specific sites are being examined.

Permits: The following are the major possible permit requirements. Approval to construct by the EPA Administrator may be required for the LMF as a radioactive air emission source. If so then notices of intent to start up and of actual start-up must be submitted; and annual reports to the EPA are required. Applicable state and local permits, including an air quality permit to construct, underground tank permits, and possibly water use and waste water treatment permits may be required. EPA and state permits are required for generation and disposal of wastes regulated under the Resource Conservation and Recovery Act (RCRA), and additional permits are required if RCRA regulated wastes are to be stored on site in excess of 90 days (storage permit applications must be submitted two years prior to commencement of construction), unless the site already has adequate existing permits. Unless the LMF is covered by existing site permits, EPA permits and notifications for radioactive mixed wastes will be required.

Permit requirements vary greatly, depending upon the state and locality of the selected site. DOE policy requires conformance to applicable state technical requirements, as well as all federal requirements.

An emergency preparedness plan is required. Existing DOE sites should have adequate approved plans in place.

Environmental Requirements: Project environmental assessments require documentation of the preexisting environment including wildlife, archaeological and historical artifacts, geology, seismology, hydrology, terrestrial and aquatic ecology, meteorology and climatology, background radiation sources, population distributions, and social services. Current environmental documentation must be assessed for proposed sites and alternatives, and the cost of required additional surveys (and their associated risk) estimated.

In addition, the existing environmental baseline must be documented in a DOE environmental survey. This survey should begin two years before facility start-up, and must begin at least one year before start-up.

The availability of reliable data improves the quality of accident analyses and reduces dependence on extreme conservatism; hence, it is a positive factor in the consideration of a site. Earthquake, tornado, and extreme wind hazard curves for major DOE sites have been published.

The site hydrology data, the minimum of one year of valid site meteorological data, and regional climatology data are available for most major DOE sites, and their availability should not require consideration at this time in the LMC study.

VI.E SUMMARY

Environmental and siting activities consume a large share of the project resources during its early phases. Postponing consideration of these factors can lead to gross cost estimate errors, project cancellation, or major redesigns. Environmental hurdles can be insurmountable for a project wedded to one site. Early attention to environmental and safety issues allows for more innovative solutions, greater inherent safety, and more flexible project management. The issues identified in this section should be explored as completely as data, resources, and the status of the project definition allow.

There are strong arguments for locating the facility convenient to the existing ICF laboratories, including: convenience, R&D synergism, better focus and control of R&D efforts, and the recruiting and retention of the facility staff. These factors must be weighed against waste transport and disposal, land use, accidental releases to the environment, and decommissioning costs. Only thorough evaluation of safety and NEPA issues can support an objective evaluation of these conflicting requirements.

VII STAFFING AND MANAGEMENT ISSUES

VII.A INTRODUCTION

This chapter specifies a reasonably complete sequence of events required to deliver the LMF and recommends methods for implementing necessary tasks, starting with the commitment to construct the LMF and ending with the completely operational facility. Some planning depends on the driver technology, lead laboratory, and schedule selected for the project. Experiences from earlier ICF projects and other DOE programs have been surveyed and applied here with assumptions about LMC project priorities to generate LMF staffing and management recommendations.

Driver-dependent (Phase II) studies are expected to include additional details and recommendations as well as to address LMF project cost, performance, and schedule. These then can be incorporated into the technology evaluation process.

Awareness of management and staffing issues during the early phases of the LMF project definition helps identify and resolve problems. Should the project suffer from poor or inadequate planning and design during its early phases, it is most likely that everything following will be more costly, more difficult, and less satisfactory.

DOE must address two major management and staffing issues: the management reporting structure for LMF design, construction, and operation; and the decision making processes. A formal set of decision making processes is required to establish the top-down management structure; and thereafter that management structure will be tantamount to the decision process. Delay in addressing these issues can contribute to less than optimum use of the resources available within the ICF program. DOE will need to guide the operating management philosophy of the LMF; i.e., whether it operates with its own scientific agenda or operates strictly as a user's facility.

VII.B PROJECT PHASES

Previous large ICF R&D facilities have progressed through a typical series of evolutionary elements from inception to full experimental use. These elements, shown in Table 5, can be grouped into four major life-cycle phases: Planning and Design, Construction, Operational Development, and Applications. This chapter provides descriptions of these elements, management implementation approaches, and estimates of staffing and support resource needs including estimated operating costs. Implementation of the LMC will be the major (but not the sole) activity of the ICF program during the 1990's. This chapter does not address the program's technical base and other non-LMC activities.

1. The Planning and Design Phase

This phase of the LMF life cycle defines in detail the scope of the LMF project, how the construction project will do business, and what will be delivered. These constitute one element which the Phase II alternative driver studies will expand on. A formalism for managing the start-up, planning, implementation, and closeout phases of the project is needed. A matrix form of project management should be employed to optimize the use of DOE resources, allow utilization of multiple laboratories and contractors, and provide the opportunity for distributed participation. Core and extended project teams need to be formed, and a base line configuration, including site selection, needs to be established. A work breakdown structure for accomplishing all tasks is needed, and accountability for work, schedules, and estimated resources must be established. Roles of DOE laboratories, other support laboratories, and industrial contractors should be firmly established. Planning and design offers an early opportunity to involve an industrial contractor to assist in LMF implementation. The extent of the involvement should be decided early in the project. Prototype R&D efforts, criteria, and initial and some final designs for the facility, components, and subsystems are established during this period.

The project priorities of performance, cost, and schedule must be established consistent with the constraints. For the LMF to be a user facility, it must meet its technical specifications for high target gain early in its lifetime. It is recommended that performance criteria be fixed to at least a minimum assured value and be of first priority. Construction cost will be second priority; overall project schedule will be third priority and will be the variable most likely allowed to slip should major problems arise. Of the numerous requirements, some of the most essential are a large target yield capability, an acceptably low technical risk, and acceptable capital and O&M costs.

The operating philosophy needs to maximize the total learning rate and to minimize the cost of obtaining data. The design approach taken during the early phases ultimately dictates the operating approach during the applications phase. The recommended engineering philosophy is a balanced and conservative fast-track approach to design, with operating criteria and issues (i.e., efficiency, reliability, turnaround time, O&M costs) addressed during the earliest phases of the project. Strong operational input is recommended during planning and design.

Prototype construction and testing is recommended as an integral part of the LMF effort; there are two distinct roles for constructing prototypes of major components. One is the reduction of technical uncertainty required before a driver technology can be considered for selection, involving demonstration of critical technologies at essentially full scale before a commitment is made to a driver technology. The second, the testing of designs early in the design and construction phases prior to commitment to quantity production, applies to virtually all of the special hardware in the facility. Development of full-scale prototypes of components and subsystems to satisfy both of these roles is strongly recommended even though this approach may appear to make the LMC project more costly and longer in duration. Numerous examples exist in which the failure to construct and test prototypes of critical technical elements has contributed to the project missing significant objectives or failing completely. Risk reduction experiments are necessary to identify deficiencies as early as possible, allowing their resolution prior to fabrication of production hardware.

TABLE 5

TYPICAL ELEMENTS IN THE DEVELOPMENTAL LIFE CYCLE OF A LARGE R&D FACILITY

PLANNING/DESIGN PHASE
* Formation of the Project Team
* Selection of a Management Methodology
* Establish Conceptual Design Criteria
* Preliminary Design
* Preprototype Development
* Final Design

OPERATIONAL DEVELOPMENT PHASE
* Development of Standard Operating Procedures
* Planned Upgrades and Deficiency Corrections
* Fully Operational Status

CONSTRUCTION PHASE
* Construction of Buildings and Major Support Systems
* Procurement/Fabrication of Components
* Design, Construction, and Test of Prototypes
* Procurement, Acceptance, and Inventory of Components
* Subsystem and System Assembly
* Checkout and Facility Integration
* Full System Testing
* Facility Characterization and Optimization

APPLICATIONS PHASE
* Mature Operational Procedures
* Efficient Multi-User Capability

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2. The Construction Phase

This phase is concerned with the construction and occupancy of the site and buildings, and the fabrication, assembly, and installation of most components and subsystems. Most of the construction funds are spent during this period. Alternative driver studies should include details on several construction phase management issues: the role of major contractors; methods for controlling costs, delivery schedules, fabrication quality, and inventory; implementation and management of the assembly and testing of components and subsystems; and configuration control and interface/integration management.

For building construction, user criteria are typically needed 12 to 18 months before the start of detailed design. Selection of the A/E firm can take 6 months, and detailed design may last 9 months. Procurement requires 2 to 3 months, and construction takes 12 to 24 months. The total duration for this activity is 3 1/2 to 5 years.

In construction management the roles of DOE and its field offices and laboratories are specified by DOE. For a project of this size the DOE would designate a special office and a lead laboratory to oversee the major contractors.

Quality assurance (Q/A) programs must be established throughout the life of the LMF to address methods of furnishing experimental hardware, software, subsystems, and buildings of the highest quality commensurate with cost and schedule constraints. Q/A programs should include elements of control and of assurance/audit. Control elements provide methods to evaluate and control particular project aspects; assurance/audit elements provide the evidence needed to demonstrate confidence that quality functions are being performed. Methods to assure the quality of critical systems must be established early in the design cycle.

3. The Operational Development Phase

This phase achieves the objectives and milestones of the LMF, and develops reliable and efficient operating modes for the applications phase. Facility upgrades may occur during this period in accordance with the original project implementation plan. Prior consideration should be given to smoothing the transition from construction management to LMF operation, since construction project funding and management formalities normally end at this point in the life cycle.

Developing the full LMF capabilities requires specifying a number of management issues, e.g., operating logistics, methods for characterization and optimization of driver and target performance and coupling, chain of command, scheduling and facility use, development of operating documentation from construction project closeout information, target area and diagnostic upgrades and retrofits to handle the rising target yields and radiation environment, and utilization of the increasing target yields for larger scale weapon physics and effects experiments. The methods and logistics for handling the radiation environment produced by high-yield shots need to be addressed in evaluation of alternative designs.

Achievement of the LMC's objectives and full potential entails more than putting hardware on the floor and firing the first shot. There needs to be adequate planning for the capital equipment and operational funding requirements of the LMF as driver difficulties are resolved, target yields increase dramatically, and the experiment area becomes fully capable of dealing with the evolving requirements and radiation environment. Also, a smooth transition across the funding boundary at the closeout of the line item must be planned, not only in funding but in personnel, to assure that the facility achieves peak performance throughout its life cycle. The construction project team should be accountable for demonstrating that all systems are in place and working, perhaps by achievement of early performance objectives, e.g., demonstration of a target gain of one at an acceptable shot rate and operating cost. Planning should also accommodate an upgrade cycle which will be driven by the increasing target yield, will allow correction of deficiencies, and will allow for phased completion of the driver system if the selected technology is amenable to that. Details covering the evolution from construction project management to integration into the R&D program management need to be planned well in advance to ensure continuity of effort across the line item-to-operational boundary.

The level of effort required for early and rigorous characterization and optimization of the major systems and subsystems is frequently underestimated. One to two years may be required to exercise the driver (including diagnostics), target support (insertion, alignment, cryogenics, etc.), and target diagnostics systems; establish characterized operating modes; and identify items requiring resolution. An adequate period for system shakedown should be reserved prior to a major commitment to applications use. During this period, brief experimental campaigns will exercise the total facility, acquire performance data in a minimum time, and facilitate preparation for the heavy experimental campaigns to come. Characterization experiments optimize subsystems and identify those requiring the greatest additional development. Target production, handling, and diagnostics systems will also receive their shakedowns during this period.

The Operational Development phase blends into the early part of the Applications Phase, since applications experiments will begin as soon as the driver, diagnostics, and experiment areas are ready. Here we define the transition point to be the achievement of a target yield of 100 MJ. It is anticipated that the operations during this time will include a significant upgrading or reconfiguration of the facility late in the Operational Development phase. This upgrade will complete the shielding installation, install the remote handling equipment, and expand the target diagnostics suite to accommodate the increasing target yield. Final driver improvements may be added at the same time, as part of a planned phased installation or improved operational efficiency. Optimal planning will integrate these activities to minimize the impact on the facility operation, but realistic planning may include up to one year of downtime for these activities.

4. The Applications Phase

This last phase in the LMF life cycle (except for decommissioning) involves two operating modes: single user (also called baseline) and multiple user. Baseline operations management must handle experiments from laboratories and agencies familiar with ICF technology and the LMF, i.e., DOE and some DOD users. Multiple user operations management must successfully interface between LMF provided services and outside users employing the LMF radiation environment. Descriptions of the experimental services, standard operating procedures, procedures for establishment of user support and maintenance schedules and priorities, and cost center documentation and control will be required.

VII.C STAFFING AND RESOURCE ESTIMATES

Staffing needs for the four life cycle phases of the LMF have been estimated from historical manpower needs of prior DOE projects, and personnel categorized into the labor types (skills, disciplines, capabilities) required to develop the LMF. The actual numbers of personnel and the mix of talents will be driver dependent and must be addressed in Phase II. However, the labor and functional support requirements (space, services) are included here to assist in scoping future LMC requirements studies.

Estimates have been made by reviewing manpower needs for prior ICF projects. Figure 6 shows trends in the total project staff, management, the engineering disciplines, and O&M personnel throughout the PBFA II project life cycle at Sandia National Laboratories, Albuquerque. Total staffing increased slowly through design and construction, then tapered off to an intermediate level when construction, component fabrication, and assembly/testing were completed and the facility began to support experiments.

1. Annual Operating Costs

These staffing trends have been applied to the LMF. Total personnel requirements for the functions considered are estimated to vary from about 150 to 550 FTE's during the LMF life cycle. A significant fraction of the work force is likely to be contractor-provided. Prior projects have utilized contractor personnel for as much as one-half to two-thirds of the work force in their later phases.

LMF operating costs during the operational development and applications phases will depend on a number of factors, some driver specific and some driver independent. Factors include the design philosophy, design effectiveness, shot rate, operating hours, required technical capability of work force, number of personnel required to sustain a high level of operational efficiency, etc.

Desirable operating characteristics of the LMF, discussed in Chapter V, include a shot rate from a few complex targets per week to a few per day, high reliability, high availability (limited downtime for major routine maintenance and refurbishment between shots), and total annual costs not to exceed perhaps 10 to 15 percent of the construction cost.

Operating cost breakdowns will be driver and design specific, and will need to be prepared as part of the evaluations of driver technology alternatives. A consistent methodology will be needed for these estimates, categorized two ways: by driver systems, target systems, and special structure/systems requirements; and by labor, procurements, and capital equipment.

Operating costs are estimated here from reviews of prior ICF projects. Figure 7 illustrates the scaling of total operating costs with the stated construction costs for past and present ICF facilities. The 10 percent operating budget (annual cost/construction cost equals 0.1) indicated by the dashed line in Figure 7 appears to be a lower bound for extrapolation to an LMF operating cost. Table 6 shows the estimated operating costs as a percentage of the capital cost (total estimated cost, TEC) of the facility, broken down into categories of labor and procurements, for the PBFA facilities. Target fabrication costs are not included in Figure 7 or Table 6.

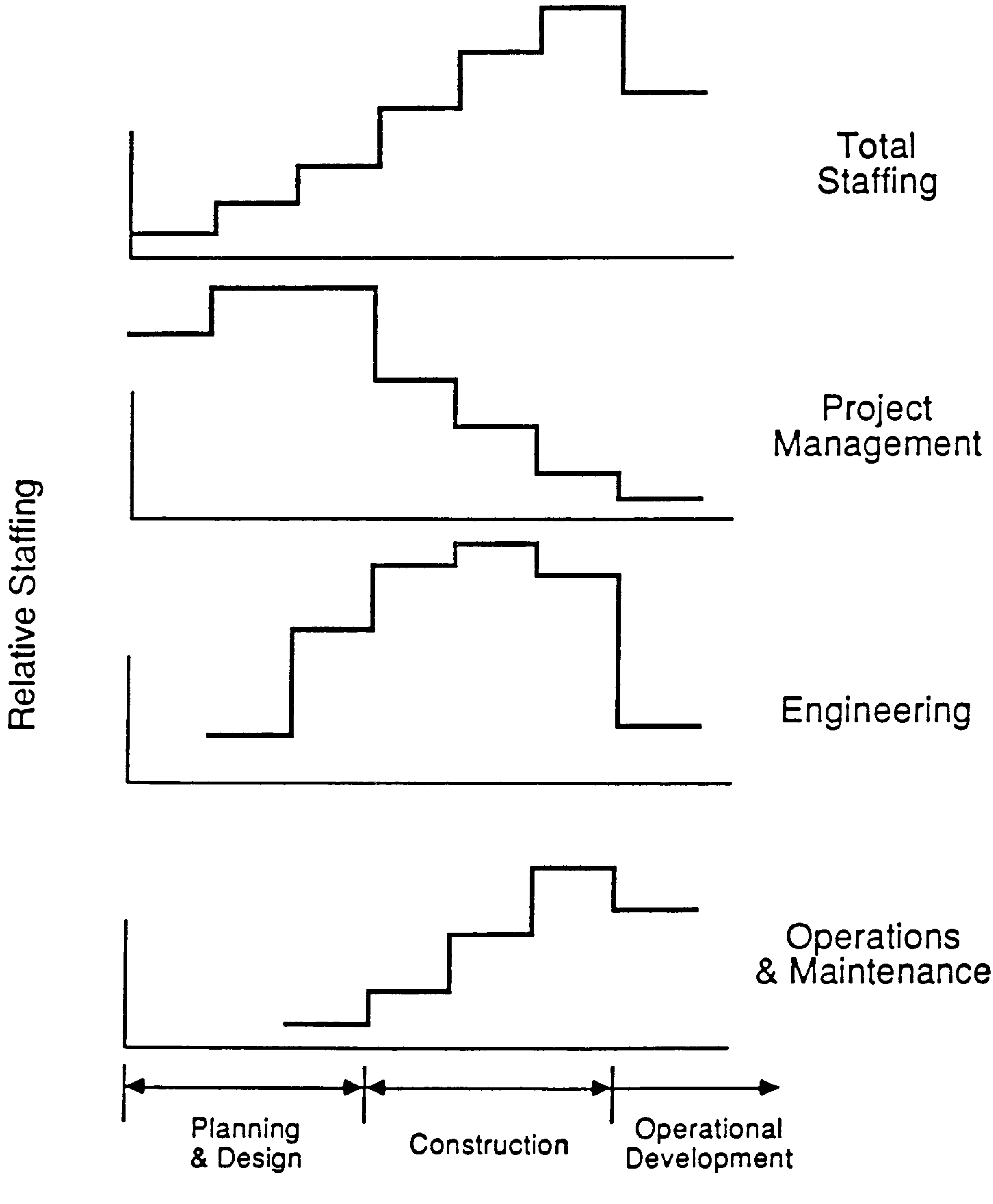

FIGURE 6. RELATIVE STAFFING OF VARIOUS DISCIPLINES OF THE PBFA II PROJECT

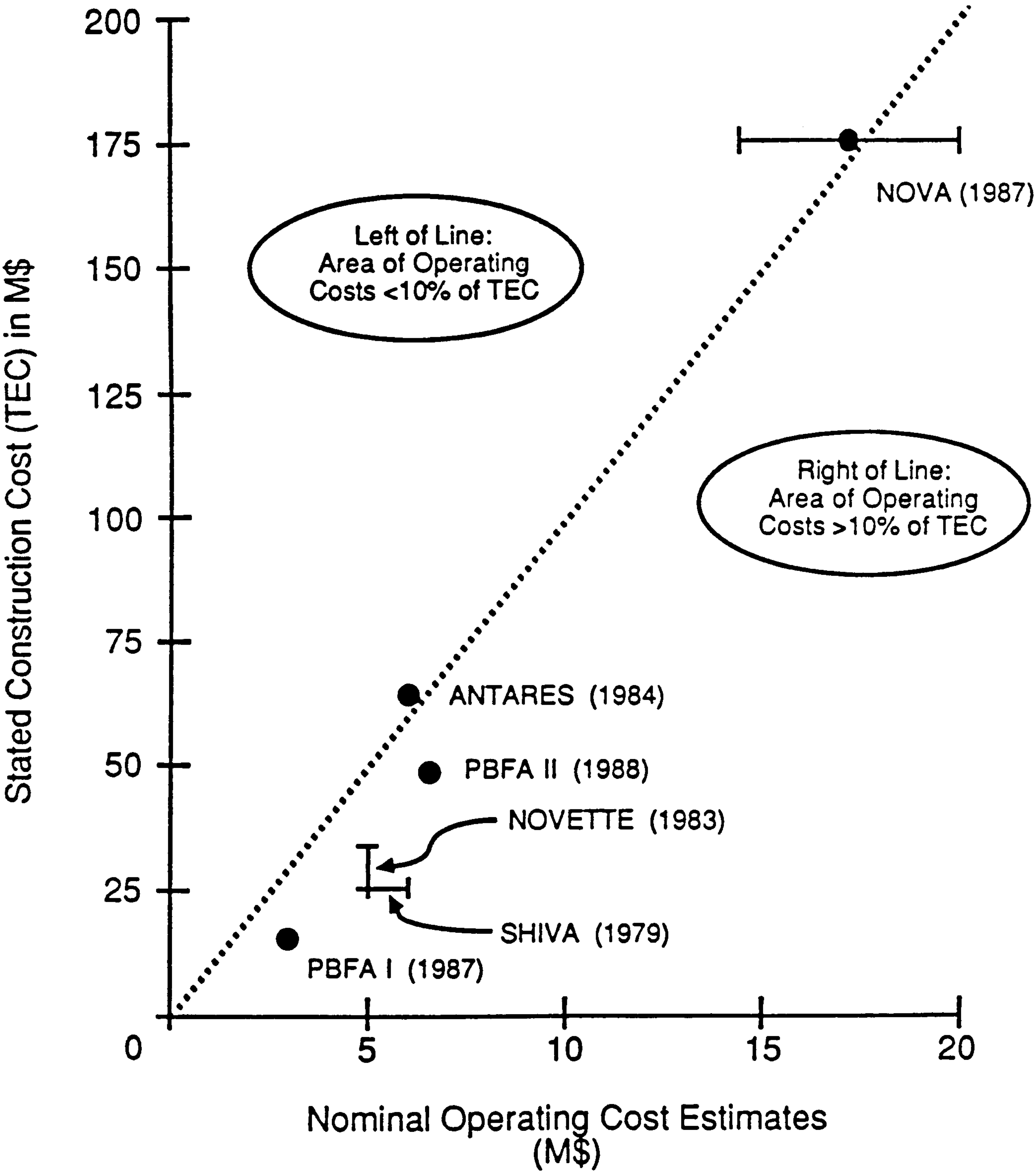

FIGURE 7. SCALING OF OPERATING BUDGET WITH TEC

Labor costs depend on the level of training (staff, technician, trades, etc.) and the balance between contractor and laboratory personnel. PBFA I and II employed about a 3-to-1 contractor-to-laboratory personnel ratio and required more technician-level individuals than professional staff for operations.

Table 6 shows total labor costs ranged between 7 and 13 percent of the TEC for the PBFA programs. If labor for major projects scales linearly with the TEC, and if the LMF TEC is $750M, this range corresponds to an annual labor cost of $53M to $98M.

Costs of consumables in Table 6 range between 5 and 7 percent of the TEC. If consumable costs also scale linearly with the TEC, a $750M LMF would require $37M to $52M annually for operating supplies. Actual operating expenses will depend on the design philosophy and the funding.

From Table 6 the total annual operating cost (labor and consumables) is estimated between 12 and 20 percent of the TEC, or from $90M to $150M annually for a $750M project, not including target fabrication costs.

Capital Equipment is included for one upgrade early in the LMF's lifetime and for continuing operations. The cost of the upgrade is estimated to be from 4 to 8 percent of the TEC ($30M to $60M for a $750M TEC). A research facility has a continuing need for new capital equipment. Extrapolating from the present ICF program, an annual capital budget between 5 and 15 percent of the LMF operating budget (i.e., $5M to $22M) will be required. The upper amount applies especially during early operating years.

2. Space and Services Requirements

Many functional requirements for supporting LMF implementation and operation are cited in Chapter VIII, "Major Cost Factors." The accommodations for supporting work certainly will change through the LMF life cycle, with support for a peak work force of more than 500 persons anticipated.

During the planning and design phase, emphasis will be in the areas of communication and documentation. Sufficient office building(s), parking lots, eating facilities, conference and meeting rooms (both classified and unclassified), communications, word processing, and computing support (personal, mini, and mainframe) required to execute this activity must be functional early in this period. For the various schedule options proposed, it is likely that site preparation and construction of the LMF complex will not be completed during this phase; it therefore will be necessary for the project team to form and to commence its work at an existing DOE facility, and then move to the LMF site after occupancy of offices and labs. Low bay and medium bay space for component fabrication will be required at existing laboratories for prototype construction and testing activity and for design modeling.

During the construction phase, low-bay, medium-bay, high-bay, and warehouse space are required to house driver component and subsystem assembly and testing. The requirements for space, etc., are estimated in Chapter VIII, "Major Cost Factors."

During the operational development and applications phases, the facility will house the largest group of people. It likely will require multiple-shift and six- or seven-days-per-week operations, needing services from shops, computing, maintenance, and support functions. Adequate cleared and uncleared office space for both long-term project/operations personnel and transient users must be provided. Work space should be tailored to the activity of the individuals. Persons supporting driver, experiment, or target functions should be located close to their work areas and have office space available whenever possible.

TABLE 6

ESTIMATED LMF ANNUAL OPERATION COSTS
based on PBFA facilities at SNLA

	ESTIMATED PERCENTAGE RANGE OF TEC	$ RANGE FOR $750M TEC
LABOR:		
Lab Staff	2 - 6%	$ 15 - 45 M
Contractor	5 - 7%	38 - 53 M
Total Labor	7 - 13%	$ 53 - 98 M
CONSUMABLES:		
Direct Support	1 - 2%	$ 7 - 15 M
Direct Charges	4 - 5%	30 - 37 M
Total Consumables	5 - 7%	$ 37 - 52 M
TOTAL ANNUAL OPERATING COSTS	12 - 20%	$ 90 - 150 M

VII.D SCHEDULES AND MILESTONES

The schedule and associated technical risk are driver dependent. However, the following three generic schedule options for LMF implementation have been examined, each covering the time period from the decision to build to the facility decommissioning. The options are termed intermediate, lower, and higher risk.

The first schedule is the intermediate risk option, providing a balanced approach between schedule and risk. It is a fast-track, moderately aggressive approach to achievement of the LMC. The second schedule is a lower risk option. The schedule is fast-track, but less aggressive. The third schedule is more aggressive and higher risk, having the shortest construction time considered realistic, and a larger associated risk. Adoption of this schedule requires careful assessment of the risk.

The three schedule options are summarized in Table 7 and the underlying assumptions and logic each are given. Although applications experiments may begin early in the operational development of the facility, the applications phase of the facility's life cycle is defined to begin with the achievement of 100 MJ of target yield. A facility lifetime of 30 years is assumed, limited by technical obsolescence.

1. Intermediate Risk Option

Assumptions

- The funding cycle for authorizations and appropriations is two years.
- A fast-track construction approach is executed with a finite risk of cost and schedule growth or performance reduction accepted.
- Prototypes are built where possible, but initial hardware commitments do not wait on prototype results.
- Intensive applications experiments are delayed until the full yield is reached.
- One major upgrade occurs when 50 MJ yield is achieved.
- The construction program is success oriented.

TABLE 7

LMF SCHEDULE OPTIONS

OPTION:	#1 INTERMEDIATE RISK		#2 LOWER RISK		#3 HIGHER RISK	
PHASE	Duration	Cumulative Elapsed Time	Duration	Cumulative Elapsed Time	Duration	Cumulative Elapsed Time
Decision to Construct		0		0		0
PLANNING/DESIGN	2	2	3	3	1	1
CONSTRUCTION	5	6	6	9	4	4
OPERATIONAL DEVELOPMENT	2		5		2	
Gain = 1		7		12		5
Yield 50 MJ		8		14		6
APPLICATIONS	22		16		25	
100 MJ		9		15		6
300 MJ		10		16		7
1000 MJ		11		18		8
Decommission		30		30		30

Note: Design and construction phases overlap.
These estimates are in years.

The clock starts running when the commitment to construction is made. The assumed starting point is when: (1) one technology option is selected and the conceptual design is approved, (2) site studies and the initial engineering design begin immediately, and (3) Congressional authorization occurs in the first year, with major appropriations in two years. The core project team is formed immediately to begin the initial engineering design. The site selection is completed in one year, and the extended project team is formed. The initial engineering design is accelerated, requiring one year after formation of the extended project team. During this time, some prototype work is done, but hardware commitments do not wait for prototype results or risk reduction experiments. Designs are completed with acceptance of risk of redesign and slippage. The design of the major facility is frozen at the completion of the final design period, and accelerated hardware orders are placed. All hardware not previously ordered is fabricated and assembled within two years. The facility shakedown requires one year and major experiments begin. A target gain of unity is achieved in the first year of major experiments. A target yield of 50 MJ is obtained in the second year of major experiments. A facility upgrade, based on assumed success, is completed in the same year to provide the capability of achieving a yield of 1000 MJ. In the subsequent three years, yields of 100 MJ, 300 MJ, and 1000 MJ are attained. Weapon effects simulations and weapon physics experiments are performed until decommissioning.

2. Lower Risk Option

Assumptions

- The usual funding cycle for authorizations and appropriations applies.
- A fast-track construction approach is adopted.
- Prototype-based hardware commitments are made.
- Applications experiments are performed at each level of performance.

The clock starts running when the commitment to construction is made. The assumed starting point is when: (1) the conceptual design, based upon a program decision to pursue one option, is complete, (2) sufficient funds are available to begin site studies and the initial engineering design, and (3) Congressional authorization of the project occurs with major appropriations in three years. A core project team is formed immediately to begin the initial engineering design. The site selection is completed in one year and the extended project team is formed. The initial engineering design takes two years after formation of the extended project team. During this time, the initial and final designs of driver prototypes are completed, and prototype hardware is ordered. Major facility construction starts in the first year of appropriations. Prototype construction takes three years, followed by three years of risk reduction experiments. After the first year, the design of the major facility is frozen and hardware orders are placed. All hardware not previously ordered is fabricated and assembled within two years. Major experiments begin after two years of facility shakedown. A target gain of one is achieved a year later. Limited applications experiments are performed in the same year. Two years later a target yield of 50 MJ is achieved. At this point, the promise of the facility is clearly demonstrated, the problems and deficiencies are also understood, and the first major facility upgrade is done to provide the capability of achieving a yield of 1000 MJ. The upgrade takes less than one year. The following year, a yield of 100 MJ is achieved, enabling the first substantial weapon effects simulations to be done. Then 300 MJ yield is achieved. The full yield of 1000 MJ is achieved two years later, bringing the facility to a mature operating state for applications work.

3. Higher Risk Option

Assumptions

- Immediate Congressional action is taken to provide construction appropriation within 90 days.
- The fastest credible construction approach without assured failure is adopted.
- Prototypes are built where possible, but no hardware commitments wait on prototype results.
- Existing technology is used where acceptable, without cost constraints.
- Applications experiments are delayed until substantial yield is reached.
- No major upgrades are needed. Everything desirable is put in at the beginning.
- Time is the critical resource.
- The construction program is success oriented.

The clock starts running when the commitment to construction is made. The assumed starting point is when: (1) one technology is selected and the conceptual design is approved, (2) the site is chosen immediately and the extended project team begins initial design immediately, and (3) appropriations are available within 90 days. The initial design is accelerated, taking one year from the beginning of the project, and construction is started in parallel. Some prototype work is done, but no hardware commitments wait for prototype results or risk reduction experiments. Parallel design approaches are taken where necessary to reduce risk, but with increased cost. The major facility design is frozen at the completion of the accelerated final design period, and accelerated hardware orders are placed. All hardware not ordered previously is fabricated and assembled within two years. Major experiments begin after a one-year shakedown, achieving a target gain of unity in the first year. Target yields of 50 MJ and 100 MJ are obtained in the second year of experiments. A target yield of 300 MJ is obtained in the third year, and 1000 MJ is obtained in the fourth year. Weapon effects simulations and weapon physics tests are performed until decommissioning.

VII.E SUMMARY

There are significant management issues to be addressed in the LMF project. In particular, the top-down management structure and decision-making process must be established in order to coordinate the ICF program resources toward achievement of the LMC. Additionally, the level of acceptable risk must be established and combined with budget estimates, to establish schedule goals for the project. Three possible risk-schedule options are presented in this chapter; the final determination must await driver technology selection.

It is recommended that DOE establish the following priority for the LMF project: performance first, cost second, and schedule third.

Design and construction of the LMF will be a challenging effort. With the establishment of a sound decision making process, application of established management techniques, and creation of a central project office that has both the authority and the responsibility to succeed, the task is a reasonable extension of prior large ICF R&D facility experience and should achieve its objectives. Extensive construction and testing of prototype hardware is recommended, both to reduce risk as decisions are made and to refine designs during construction.

A significant hurdle in the LMF's life cycle will be the transition from a construction line item to an operating facility. This involves major shifts in funding, personnel, and responsibilities and authorities. Planning for this transition should begin in the earliest phases of the project in order to maximize the utilization of the facility's capabilities.

Based on prior ICF experience, the operating costs can be estimated as a percentage of the construction cost. These cost estimates will require refinement as alternative design concepts are developed for the LMF.

Unlike previous large ICF R & D facilities, the LMF will have continuing utility to outside users. A total lifetime of 30 years is assumed, based on continuing applications work and balanced against technical obsolescence.

The relative priority of the various applications will require decisions as the LMF begins operation. Many useful experiments can be performed with low target yields, and doing them will necessarily delay the achievement of higher yields. Thus the rate at which target designs are improved to increase the available yield will be inhibited by extensive low-yield applications experiments, causing commensurate delays in high-gain ICF target development and high-yield weapon physics and weapon effects applications. Scheduling LMF time will become easier after high-gain targets are developed; that is, after the first several years of operation.

VIII MAJOR COST FACTORS

VIII.A INTRODUCTION

1. Purpose

The LMC's cost and cost breakdown will be important factors in decisions of when (and if) the LMF will be built, and in the driver technology selection. This section examines and categorizes the costs associated with construction of the LMC, while operating costs are estimated in Chapter VII, "Staffing and Management Issues." Only the driver-independent costs are specified here. Cost areas that are driver dependent are identified without estimates being made for the cost; these cost estimates will be part of the evaluations of driver alternatives.

It is difficult to estimate costs without detailed designs. Indeed, in some areas, the solutions to technical issues have not yet been identified. At issue is the following question: How can costs be specified without a conceptual design or when technical solutions for construction and/or operation of required components have not been identified? Additionally, under these uncertain conditions, to what accuracy can the cost estimates be made? Unfortunately, some costs can be specified only with large uncertainties. However, it is important to define rough estimates for each system, subsystem, and component in order to identify the high-leverage items. Then increased technology development work may reduce costs in key areas. Also, it is important to provide a uniform framework for comparison of alternative driver concepts. For example, it is inappropriate to compare LMF cost estimates if one conceptual design includes a target fabrication facility and another does not, or if one assumes a 5 percent contingency (too low) and another assumes 20 percent (more reasonable). Lastly, it is important to define a standard costing methodology suitable for all driver alternatives and inclusive of all the systems of the LMF. The driver-dependent cost uncertainties will be reduced when the alternative drivers are examined in detail.

Simplistic comparisons fail for the reason that the different drivers have historically had significantly different costs. The two drivers with the highest energy currently available are the Nd:glass laser, Nova, and the light-ion accelerator, PBFA II. Nova became operational in 1984, has been reported to cost $167 million, and is expected to be capable of 50 to 70 kJ of frequency-tripled laser light[9], while PBFA II became operational in 1985, has been reported to cost $48 million, and is expected to be capable of 1 to 2 MJ delivered to target[10]. This simplistic comparison fails to reveal the differences between the two projects in terms of target experimental capability, nor does it address the relative driver requirements for equivalent performance. LMC driver alternatives must be evaluated in terms of equivalent systems, where the equivalency is established in target yield, rather than raw driver performance. This section provides the basis for the generation of comparable cost estimates.

Discussing costs in units of dollars per joule is misleading because: (1) the total cost does not scale linearly with driver energy, (2) costs stated in units of dollars per joule are ambiguous as to what is included, (3) the total facility includes

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9. "1984 Laser Program Annual Report", LLNL UCRL-50021-84, June, 1985. Note--The line-item cost cited is less the Building 481 office complex.

10. J. P. VanDevender, "PBFA II and Inertial Confinement Fusion," Bull. Am. Phys. Soc., 31, 9, 1413 (1986).

substantial non-driver costs, and (4) equal target yield may require different performances from alternative driver technologies. Additionally, there is often confusion on what exactly is included in the driver cost, e.g., are the driver building, the target chamber, target diagnostics, driver control system, etc., included? To avoid this confusion the costs of the LMF and its components will use dollars, not dollars per joule.

Determination of the driver-independent high-cost-leverage components of the LMF is complicated by possible significant differences in the total cost. For example, if the total cost of the LMF is $500 million, then $50 million of target diagnostics represents 10 percent of the total cost, and is clearly significant, whereas $50 million is a less significant 2.5 percent of the total in a $2000 million project. Thus, identification of the high-cost-leverage components may be driver dependent. However, estimation of the cost of the driver-independent LMF systems and components is important regardless of the total cost.

2. Effect of Differences Between Drivers

There are currently four driver technologies being considered: KrF and solid-state lasers, and light- and heavy-ion accelerators. Also, both direct and indirect drive target concepts are being considered. The differences between the alternative drivers are profound, and these differences cascade throughout the entire LMF. For example, the targets required for ion accelerator drivers are different from those for lasers, possibly requiring different target fabrication techniques, insertion mechanisms, diagnostics, etc. The target chamber vacuum requirements also differ; three of the drivers operate with a high vacuum while the other requires a few torr background pressure. These driver differences complicate determination of the major cost factors for the LMF.

System, subsystem, and component costs can be classified into three categories. The first includes items whose costs are either totally or strongly driver independent, e.g., certain types of target diagnostics and fabrication equipment, the office building, experimental laboratories, and hot cells for handling radioactive materials. For items in this category, direct capital costs are specified. The next category of cost items are those that are moderately driver dependent, e.g., the target chamber, target assist functions (target insertion, cryogenic capability, and verification of the state of the target in the chamber), and site improvements. For items in this category, either an estimate for the direct capital cost is made (with larger uncertainty), a unit cost is estimated, or the cost is left to be calculated as a function of the driver design. In the third category of cost are items with a strong driver dependence, e.g., the driver, its control and alignment subsystems, driver diagnostics, and the driver building; the costs of which will need to be estimated in driver-specific design efforts.

3. Basis of the Cost Estimate

It is necessary to categorize the LMF into systems, subsystems, and components in order to estimate the driver-independent costs. The work breakdown structure (WBS) in Figure 8 illustrates this structure.

Some items may be different or nonexistent for different drivers or different designs. For example, target fabrication may be placed in its own building, or may be a part of another laboratory. A light-ion driver will almost surely be located in the same building as its target chamber. The hot cells may or may not be located with other experimental equipment in the same laboratory building. These potential variations mean that driver-specific cost estimates will need to customize the formalism presented here.

The cost estimation procedure is organized by system, subsystem, or component in the WBS. The cost of each item is the sum of the base cost; mark-up; project management cost; engineering, design, and inspection (ED&I) cost; and contingency. The costs are in 1987 dollars. Because a construction date and schedule have not been defined, no attempt has been made to include the effects of future escalation and inflation on the cost estimate. This will need to be done in order to prepare the line-item cost estimate for the LMF. Only non-driver costs can be estimated now, and no overall total costs are given.

SITE IMPROVEMENT	BUILDINGS	SPECIAL STRUCTURES	SPECIAL EQUIPMENT	UTILITIES	STANDARD EQUIPMENT
Clear and grub site	Office building	Driver building	DRIVER SYSTEMS	Sewerage	Furnishings
Roads	Target fabrication	Target building	Prototype module	Potable water	Communications
Parking lot	Shops	Oil handling	Laser or accelerator	Cooling water	Computation main/mini personal
General land improvements	Laboratories	Water handling	Driver diagnostics	Electrical	Scientific equip
	Support buildings	Radiation waste handling and storage	Vacuum system	Heating	Mechanical equip
			Alignment system	Waste disposal	Electronic equip
			Control system	Liquid nitrogen	
			Gas handling system	Liquid helium	
			TARGET SYSTEMS	Compressed gases	
			Target chamber		
			Target diagnostics		
			Target fabrication equipment		
			Target assist system		
			Vacuum systems		
			Remote maintenance systems		

FIGURE 8. UPPER-LEVEL DRIVER-INDEPENDENT LMF WBS

VIII.B WORK BREAKDOWN STRUCTURE

A work breakdown structure (WBS) has been developed (Figure 8) to ensure that all elements of the LMF are included in the cost estimate, and to establish a common costing methodology. This WBS lacks detail in the driver-dependent areas. Many of these details may be filled in during Phase II of this study. The WBS is organized into the six major sections defined below:

1.1 Site Improvement includes clearing the site and preparing for construction of the buildings, roads on the site, a parking lot on the site, and all general land improvements. A road to the site is not included.

1.2 Buildings consists of an office building, shops, laboratories, a building for target fabrication, and support buildings. Support buildings include a warehouse and a fire/security facility.

1.3 Special Structures includes the driver and target buildings, because of the special construction and/or safety requirements. Additionally, a radioactive waste storage facility is included in this category. Other facilities in this section include some driver-dependent facilities, such as for handling and storage of deionized water and transformer oil.

1.4 Special Equipment is where the driver and target systems are categorized. Most of the items in this section are driver dependent. This section will be a major portion of the LMF's cost.

1.5 Utilities consists of sewage, water, natural gas, and electrical connections. Radioactive waste disposal must also be accounted for, as well as handling facilities for liquid helium. Only on-site utilities are included. The cost of bringing utilities to the site depends strongly on the site location and is not included.

1.6 Standard Equipment includes furnishings for offices, communications equipment, computers, standard laboratory and shop equipment, and other standard scientific equipment.

These sections of the WBS define the major systems, subsystems, and components in the second and third levels of the WBS for the LMF, as illustrated in Figure 8. Finer detail will be needed to accurately estimate the cost of the LMF, and a fine-detail WBS will differ significantly from the generic WBS, for example, in the target diagnostics area. The level of detail of the driver-dependent and driver-independent WBS, as well as the accuracy of the cost estimates, will improve as more is learned about the LMF design.

VIII.C COST ESTIMATE

1. Cost Estimating Procedures

The cost data developed for the driver-independent aspects of the LMF are presented in 1987 dollars. All estimates are developed according to the WBS format presented in Figure 8. More accurate estimates for the total cost (driver-independent plus driver-dependent costs) of the LMF for each of the driver alternatives will be required.

The cost estimates for the driver-independent systems, subsystems, and components have come from different sources. Prior experience has been used where available, and prior experience has been relied on heavily. These estimates will need to be refined as design details become available.

Many decisions about the LMF's details will be required. For example, the site selected has significant cost implications; utility installation and connection costs are strongly site dependent, as are labor costs. National average labor rates are assumed here, but construction costs can vary by a factor of two.

Escalation is not included in this document because the date and schedule for construction are not established. When the construction date and schedule are defined, then escalation can and will need to be estimated.

2. Assumptions for the LMF Cost Estimates

The following assumptions are used in these cost estimates. First, the site is assumed to be on existing federal land; the cost of land is not included. Next, the costs for bringing utilities and an access road to the site boundary are excluded.

The final assumption required concerns target manufacturing; there are two choices. The first option is that a complete target fabrication facility is located on site. This is probably the best situation with respect to convenience, but results in a higher LMF cost. The second possibility is to expand current target fabrication facilities, with a minimal facility located at the LMF site. This choice reduces the LMF's cost and may still provide adequate service for target fabrication. However, the second option is both misleading and inefficient. It is misleading in that a given level of target fabrication support is required for the LMF. In the second option the construction cost will be lower, but there will be additional cost for target fabrication at other sites. The program's total target fabrication costs could actually be higher with the second option because it requires transportation of targets, duplication of equipment and effort, and offers poorer response to experimental needs. Therefore, the first option, locating a complete target fabrication facility on site, is used here.

Values of mark-ups for the cost of construction needed to calculate the cost of the LMF are shown in Table 8. Variations from the standard mark-up values are allowable if done in a consistent manner for all of the driver candidates. For example, it is recognized that target diagnostics for high-yield shots will be difficult. It may be appropriate that diagnostics have a 30 percent contingency instead of the default 25 percent. The most important aspect of the cost estimates is that agreement is reached on the values, and that they be consistently used in the alternative design cost estimates.

3. Driver-Independent Cost Estimates

Table 9 shows the direct costs for the driver-independent items in the WBS. The default mark-up rates are adjusted for certain elements of the WBS based upon engineering judgments of the difficulty of construction and estimates of the required technology development. The direct cost of an item is the sum of the material cost; the labor cost; cost of rental, maintenance, and fuel for construction equipment; and a mark-up for a subcontractor. Cost estimates in Table 9 are qualified under the column called "Note." All the costs in Table 9 are site dependent as the labor rates vary in different locations. If a cost is judged to be site dependent by more than a factor of two an estimate is given with an indication of the uncertainty.

Other costs have been determined to be driver dependent. If the cost is judged to be driver dependent by more than a factor of five, the cost is not estimated here; these costs will need to be estimated later. Finally, an office building for 400 personnel is assumed.

The total cost of an item is the sum of the direct and indirect costs. As indicated in Table 10, the indirect costs consist of contractor mark-up; project management costs; engineering, design, and inspection (ED&I); and contingency. The values for these indirect costs are taken from Table 8, with some variations based upon engineering judgments about the specific item.

Each item of the example WBS has been defined in detail to assure that there are no significant overlaps or gaps. Cost estimates have been taken from related projects and from the judgment of experienced engineers, as appropriate.

The total of the costs estimated here, with all of the caveats identified above, is about $300 million.

TABLE 8

MARK-UP RATE FACTORS

Item	Factor	Item	Factor
Warehouse and handling rate	0.04	Labor fringes, taxes, and insurance	0.30
Subcontractor mark-up rate	0.03		
Equipment rate	0.04	Escalation rate*	0.00
Overhead rate	0.07		
Profit rate	0.04	Project management mark-up rate	
Gross receipts tax rate	0.05	Standard Equipment	0.03
Bond rate	0.01	Construction	0.03
Special engineering rate	0.02	Special facilities equipment	0.02
Engineering, design, and inspection rate:		Contingency	
Standard Equipment	0.00	Standard Equipment	0.15
Construction	0.15	Construction	0.20
Special facilities equipment	0.10	Special facilities equipment	0.25

* Future escalation is not included in this study as there is no assumed construction date.

VIII.D SUMMARY

Driver-independent costs of the LMF have been estimated and a work breakdown structure has been developed for these driver-independent items to organize LMF costs by systems, subsystems, and components. Detailed WBS's will be needed for the alternative driver concepts in order to estimate the total cost of the LMF; these will require preconceptual point designs for each alternative. Tables 9 and 10 list the cost estimates for the driver-independent elements of the WBS. The estimates are subject to change as details become known about the LMF design.

An attempt has been made to establish a common basis for costing alternative LMF concepts. Default values of indirect cost fractions have been defined; variations from these defaults are appropriate if they are consistent for all driver alternatives. The driver-independent costs are significant, estimated here to be almost 300 million FY87 dollars. However, the driver-dependent costs are expected to dominate. The driver-dependent costs must be estimated in future driver technology studies to estimate the total cost of the LMF.

TABLE 9 SUBSYSTEM-LEVEL DIRECT-COST ANALYSIS

WBS DESIGNATION	DESCRIPTION	NOTE	QUANTY.	TOTAL MATERIAL	TOTAL LABOR	CONSTRUCTION EQUIPMENT	SUBCONTR. MARK-UP	COMPONENT DIRECT COST
1.	LABORATORY MICROFUSION CAP.			k$	k$	k$	k$	k$
1.1	SITE IMPROVEMENTS							
1.1.1	Clear and grub	1,2						
1.1.2	Roads		2000 m	195	95	57	31	378
1.1.3	Parking lot		125 x 250 m	404	164	72	52	692
1.1.4	General land improvements	1,2						
1.2	BUILDINGS							
1.2.1	Office building	3,4	1	20,000	0	800	600	21,400
1.2.2	Target fabrication	4	1	14,250	0	570	428	15,248
1.2.3	Shops	4	3	3,000	0	120	90	3,210
1.2.4	Laboratories	4	3	8,000	0	320	240	8,560
1.2.5	Support buildings	4	2	4,000	0	160	120	4,280
1.3	SPECIAL STRUCTURES							
1.3.1	Driver building	2	1					
1.3.2	Target building	2	1 or 2					
1.3.3	Oil handling	2						
1.3.4	Water handling	2						
1.3.5	Rad. waste storage	4	1	5,000	0	200	150	5,350
1.4	SPECIAL EQUIPMENT							
1.4.1	Driver module prototype	2	1					
1.4.2	Laser or accelerator	2	1					
1.4.3	Driver diagnostics	2						
1.4.4	Driver vacuum system	2						
1.4.5	Alignment system	2						
1.4.6	Control system	2	1					
1.4.7	Gas handling	2						
1.4.8	Target chamber	2	1 or 2					
1.4.9	Target diagnostics		1	30,000	0	0	0	30,000
1.4.10	Target fabrication equip.		1	28,500	0	0	0	28,500
1.4.11	Target assist equip.	4	1		0	0	0	
1.4.12	Chamber vacuum system	2						
1.4.13	Remote handling equip.		1	5,000	0	0	0	5,000
1.5	UTILITIES							
1.5.1	Sewerage	1	1000 m	63	66	18	16	163
1.5.2	Water	1	1000 m	30	24	5	2	61
1.5.3	Electrical	1,4						
1.5.4	Natural gas	1	1000 m	13	23	4	4	44
1.5.5	Rad. waste disposal	3	1	25	0	10	8	43
1.5.6	Liquid helium	3	1	10	0	2	2	14
1.6	STANDARD EQUIPMENT							
1.6.1	Furnishings	3	400	800	0	0	0	800
1.6.2	Communications	4		1,600	0	0	0	1,600
1.6.3	Computers--mainframe	4	2	5,000	0	0	0	5,000
	Computers--personal	4	400	2,000	0	0	0	2,000
1.6.4	Scientific equipment	4		24,000	0	0	0	24,000
1.6.5	Mechanical equipment	4		7,000	0	0	0	7,000

Notes: [1] Site dependent, uncertainty factor > 2. [2] Driver dependent, uncertainty factor > 5. [3] Based on 250 people, may need scaling. [4] Labor included in material cost.

TABLE 10 SUBSYSTEM-LEVEL TOTAL COST ANALYSIS

WBS DESIGNATION	DESCRIPTION	PM	ED&I RATES	CONT.	COMPONENT DIRECT	MARK-UP	SUB TOTAL	PM COST	ED&I COST	CONTINGENCY	COMPONENT TOTAL
1.	LABORATORY MICROFUSION CAP.	%	%	%	k$	k$	k$	k$	k$	k$	k$
1.1	SITE IMPROVEMENTS										
1.1.1	Clear and grub	3.0	15.0	20.0							
1.1.2	Roads	3.0	15.0	20.0	378	95	473	14	71	95	653
1.1.3	Parking lot	3.0	15.0	20.0	692	174	866	26	130	174	1,196
1.1.4	General land improvements	3.0	15.0	20.0							
1.2	BUILDINGS										
1.2.1	Office building	3.0	15.0	20.0	21,400	5,350	26,750	802	4,012	5,350	36,914
1.2.2	Target fabrication	3.0	20.0	25.0	15,248	3,812	19,060	570	3,812	4,767	28,209
1.2.3	Shops	3.0	15.0	20.0	3,210	803	4,013	120	602	803	5,538
1.2.4	Laboratories	3.0	20.0	20.0	8,560	2,140	10,700	321	2,014	2,014	15,049
1.2.5	Support buildings	3.0	15.0	20.0	4,280	1,070	5,350	161	803	1,070	7,384
1.3	SPECIAL STRUCTURES										
1.3.1	Driver building	5.0	15.0	20.0							
1.3.2	Target building	4.0	20.0	25.0							
1.3.3	Oil handling	3.0	15.0	20.0							
1.3.4	Water handling	3.0	15.0	20.0							
1.3.5	Rad. waste storage	3.0	20.0	25.0	5,350	1,445	6,795	204	1,359	1,699	10,057
1.4	SPECIAL EQUIPMENT										
1.4.1	Driver module prototype	3.0	25.0	30.0							
1.4.2	Laser or accelerator	2.0	10.0	25.0							
1.4.3	Driver diagnostics	2.0	10.0	25.0							
1.4.4	Driver vacuum system	2.0	10.0	25.0							
1.4.5	Alignment system	2.0	15.0	25.0							
1.4.6	Control system	3.0	20.0	20.0							
1.4.7	Gas handling	2.0	10.0	25.0							
1.4.8	Target chamber	5.0	20.0	30.0							
1.4.9	Target diagnostics	4.0	25.0	30.0	30,000	8,100	38,100	1,524	9,525	11,430	60,579
1.4.10	Target fabrication equip.	3.0	15.0	25.0	28,500	7,695	36,195	1,083	5,429	9,049	51,756
1.4.11	Target assist equip.	4.0	20.0	30.0							
1.4.12	Chamber vacuum system	2.0	10.0	25.0							
1.4.13	Remote handling equip.	2.0	20.0	30.0	5,000	1,350	6,350	127	1,270	1,905	9,652
1.5	UTILITIES										
1.5.1	Sewerage	3.0	15.0	20.0	163	41	204	6	31	41	282
1.5.2	Water	3.0	15.0	20.0	61	15	76	2	11	15	104
1.5.3	Electrical	3.0	15.0	20.0							
1.5.4	Natural gas	3.0	15.0	20.0	44	11	55	2	8	11	76
1.5.5	Rad. waste disposal	4.0	15.0	25.0	43	11	54	2	8	11	75
1.5.6	Liquid helium	3.0	10.0	15.0	14	3	17	1	2	3	23
1.6	STANDARD EQUIPMENT										
1.6.1	Furnishings	3.0	0.0	15.0	800	0	800	24	0	120	944
1.6.2	Communications	3.0	0.0	15.0	1,600	0	1,600	48	0	240	1,888
1.6.3	Computers--mainframe	3.0	0.0	15.0	5,000	1,250	6,250	188	0	938	7,118
	Computers--personal	1.0	0.0	10.0	2,000	0	2,000	20	0	200	2,220
1.6.4	Scientific equipment	3.0	0.0	20.0	24,000	6,480	30,480	914	0	6,096	37,490
1.6.5	Mechanical equipment	3.0	0.0	15.0	7,000	1,750	8,750	263	0	1,313	10,326

Abbreviations: [PM] Program Management. [ED&I] Engineering, Design, & Inspection. [CONT.] Contingency.

IX CONCLUSIONS

Need for a Laboratory Microfusion Facility

The Laboratory Microfusion Capability (LMC) is defined here as the ability to produce single-shot experiments of 200 to 1000 MJ of thermonuclear yield within the laboratory. Such a capability has considerable payoff potential for the weapons research, development, and testing (WRD&T) program and for energy production. Some weapon physics applications exist at low yields, even well below target ignition: equation-of-state and opacity measurements, mix experiments, and atomic physics. Indeed, present ICF facilities are being used for such experiments. But these types of experiments take on new importance at high yields (100 to 1000 MJ). Opacity, EOS, atomic physics, and mix experiments are particularly important at yields above about 100 MJ. Other applications, such as x-ray laser pumping can be done when the flux densities are large enough. As target yield increases between 100 and 1000 MJ, more and more weapon physics experiments can be done with increasing realism. At yields approaching 1000 MJ almost all currently conceived ICF laboratory experiments can be done.

Within the nuclear effects category, the greatest application lies in the soft x-ray output of a Laboratory Microfusion Facility (LMF). This becomes significant at target yields of about 100 to 200 MJ, and continues to grow in significance at higher yields. The utility of the LMF becomes markedly greater as yields surpass 100 to 200 MJ, and continues to increase appreciably as the yield approaches 1000 MJ.

In addition to having immediate benefits to the weapons program, the LMC has long been recognized as a necessary step in the development of ICF for long-term applications of energy production and nuclear materials breeding.

National Academy of Sciences Review

The ICF experimental program of the 1980's has been addressing the issue of feasibility of inertial fusion. This issue has been articulated by the National Academy of Sciences' Committee for the Review of the Department of Energy's Inertial Confinement Fusion Program in its report of March 1986:

> It is not yet clear how hard it will be to bring the ICF Program to a successful conclusion. The main uncertainties are the nature and practicality of the driver needed to ignite high-gain pellets; the minimum mass of D-T fuel that can be imploded and efficiently burned, and how much energy is required to accomplish this; and the degree to which laser-plasma interactions and hydrodynamic instabilities such as Rayleigh-Taylor can be controlled. Will the cost of such a system be commensurate with the objectives and the potential benefits of ICF?

Recent Program Progress and Directions

Through recent experimental results, including Centurion/Halite tests, the ICF program has made significant strides toward answering these questions. Significant indirect-drive target physics issues are being addressed on the Nova facility at LLNL, with excellent agreement being achieved between experimental results and computer calculations. Direct-drive implosion of cryogenic targets is achievable at LLE, where compressed target densities of 100 times liquid density have been demonstrated. NRL has demonstrated techniques for smoothing laser driver beams and for inhibiting the onset of Rayleigh-Taylor instabilities in directly driven targets, an important step toward meeting the stringent requirements for successful direct-drive target implosions. Sophisticated diagnostic techniques and target fabrication processes are being developed at KMS Fusion, Inc., LANL, and LLNL, to keep up with the increased experimental needs of the advancing ICF research program. By the 1990 to 1991 time period, conclusive evidence should be available to answer most of the remaining questions posed above. A number of uncertainties will remain, such as actual target yield attainable as a function of driver energy and other parameters; but one of the primary purposes of the LMF itself is to address these issues. In order to address the predominant issue of driver capability versus cost, the ICF program is beginning to focus more on defining and developing the necessary driver technologies for a Laboratory Microfusion Facility. Driver development is currently underway at LANL, SNLA, LLNL, and LBL; and LLNL and LANL are investigating advanced concepts for cost-effective solid-state and KrF laser drivers respectively. LLE and NRL are beginning design efforts for increased direct-drive laser capabilities.

An LMF of greatest utility for the cost will need to produce a yield approaching 1000 MJ. Though target designers are reasonably confident that, under appropriate laboratory conditions (see Section V.B), a target can produce high yield, there remains considerable uncertainty as to the actual driver energy required. The LMF is required to determine accurately the energy input versus yield of an ICF target. The requirements and desirable features of an LMF driver for these experiments are given in Table 1 (Section V.D).

LMF Utility and Phase II Requirements

Each point design for Phase II of this study will be of a facility that is nominally capable of producing a target yield of 1000 MJ. For indirect drive, the target designers achieved a consensus on the energy required to be absorbed by the fuel capsule to meet this stipulation. For direct drive the required energy is less definitive, since hydrodynamic efficiency of direct drive is believed to be sensitive to the driver type. A number of target-related issues must be addressed, and present uncertainties and complexities of target physics examined. Each design must:

1. Give a detailed energy accounting from the primary energy source through the beam to the target fuel. This should include absorption fraction, conversion efficiency, hydrodynamic efficiency, losses, etc.

2. Address the stability against shell break-up and mixing during all phases of the implosion.

3. Include spectrum of flux, pulse shape flexibility, and preheat conditions.

4. Include symmetry issues, which involves illumination geometry, energy balance among beams, alignment precision, beam smoothness, and shot-to-shot reproducibility.

5. Demonstrate beam quality to assure that the beam is free of contamination and hot spots which could cause unacceptable preheat.

6. Develop target designs that are consistent with all known experimental and theoretical knowledge of target performance.

7. Demonstrate that targets satisfying the above conditions can be fabricated.

Target Fabrication Issues

The major target fabrication issues are cryogenic fuel technology, foam technology, and improved techniques for characterization of capsules, fuel, and foams. The required characterization and the effects of various defects (e.g., surface debris, fill tubes, holes, seams, and inhomogeneities) need to be investigated by the designers of LMC targets.

The cost to equip the LMF's target fabrication facility is estimated at approximately 24 million dollars for a shot rate of two targets per day. A minimum of 40 to 45 fabrication support personnel will require a structure of 23,000 to 30,000 ft^2. An additional 90 to 95 R&D personnel, with space needs of 25,000 to 35,000 ft^2, will be required. These estimates do not include administrative personnel.

Target fabrication costs are also dependent on the amount of work which is done on-site. It is recommended that as much work as possible be done on-site to enhance the technical interactions between groups, reduce the response times, and minimize the duplication of capital equipment.

Experiment Area Requirements

The high yields of an LMF will produce severe prompt as well as delayed experimental conditions and environments which must be carefully considered in designing the Experiment Area (EA). The EA must establish the proper pre-shot target conditions, provide the interface between the driver and the target, diagnose target performance, quantify experimental results, and protect the instruments and data, personnel, and the public from the effects of energy release of 1000 MJ of thermonuclear yield. The major effects that must be considered are the prompt emission of x rays, neutrons, gamma rays, charged particles, and debris. These interact with the surrounding material to produce material ablation, shock waves, shrapnel, spall, pressure pulses, thermal stress, and electromagnetic pulses (EMP). Delayed effects such as hot vapors, liquid metal, induced radioactivity, unburned fuel, toxic material, corrosion, and condensation will impact the experiment and the ability to do future work. Phase II design studies must address these issues.

Experimental Rate

Many tests can be done at low yields, where conditions will not be so harsh as to preclude the use of more delicate diagnostics. Early LMF experiments will be of this nature. It is estimated that, to develop high-gain targets and perform significant weapon physics and nuclear effects experiments, about 2000 tests will be needed at yields of less than 10 MJ; about 3000 at yields of 10 to 100 MJ; and more than about 1000 tests at 100 to 1000 MJ. Once high gain is achieved, one 1000-MJ test per week should be achievable, with one every 3 days desirable. About 500 experiments per year at all yields are required.

Environmental, Safety, and Siting

Environmental and siting activities consume a large share of a project's resources during its early phases. Postponing consideration of these factors can lead to gross cost estimating errors, major redesigns, or even project cancellation. Environmental hurdles can be insurmountable for a project wedded to one site. Early attention to environmental and safety issues allows for more innovative solutions, greater inherent safety, and more flexible project management. Neglect of them leads to costly add-on fixes that are inherently less satisfactory than proper original designs. The project must conform to the requirements of the National Environmental Policy Act (NEPA). The first step in the preparation of NEPA documentation is the preparation of an Action Description Memorandum (ADM). This is the highest level of NEPA documentation that may be prepared without specific DOE authorization. Because of the importance of the NEPA documentation to the timely execution of the project, ADM-level documentation should begin as early in the conceptual design process as possible.

There are strong arguments for locating the LMF convenient to the existing ICF laboratories. Convenience, R&D synergism, and better focus and control of R&D efforts are positive factors. The recruiting and retention of the facility staff are also eased by siting the facility near existing DOE organizations. These factors must be weighed against waste transport and disposal, land use, accidental releases to the environment, and decommissioning costs. Only thorough evaluation of safety and NEPA issues can support an objective evaluation of these potentially conflicting factors. In a like manner, there is much to be gained by siting where the facility would fall within the scope of an existing Environmental Impact Statement. Such an alternative must be weighed against other siting considerations, including anticipation of LMF operational and external political factors during the lifetime of the facility. Although such factors are at present secondary to the selection of the driver technology, wrong choices may delay the project or degrade its usefulness.

Project Management and Staffing Requirements

The LMC development program must accomplish four things. First, it must identify the requirements; these have been set forth in this document. Second, it must have a viable technical approach, that is, a driver and target experiment area concept with all conceivable show-stopping issues identified and addressed.

Third, it must have a credible cost estimate, including realistic, acceptable indirect costs. Finally, it must have a strategy with cost-risk-schedule options available which are responsive to external political and economic realities, recognizing that those realities change more rapidly and are less predictable than the technical issues. All of these issues must be included in future LMC planning.

A realistic yet moderately aggressive management approach to LMF implementation is recommended. All critical technical approaches will be demonstrated at full LMC level of performance; time and resources permitting, full-scale prototyping will be required to minimize scale-up risk. Extensive industrial involvement in the LMF project is anticipated.

Personnel requirements are estimated to vary from 150 to 550 full-time equivalent (FTE) personnel during the life cycle of the LMF. A large fraction of the work force can be contractor supplied. LMF operating costs are expected to run between 10 and 20 percent of the Total Estimated Cost (TEC) of the facility, per annum. To minimize these costs, LMF operating criteria must be incorporated early into the facility design. Capital improvement costs will involve at least one performance upgrade, with an estimated cost of 4 to 8 percent of the TEC, and an annual capital equipment budget of 5 to 15 percent of the operating budget, with the larger amount needed in the earlier years.

The primary stages of development, depicted in Figure 8 (Chapter VIII), are (1) the period leading up to LMF construction authorization, (2) LMF construction and shakedown, and (3) LMF operation. In parallel with the first two stages is a risk reduction program, designed to address issues of target performance. The first stage is one of building technical competence by demonstrating capabilities and deepening understanding of pertinent physical phenomena. The second stage will focus on the detail design issues of construction of the facility, the objectives of the facility shakedown, and the execution of the initial experimental series. The third stage is the LMF experimental program, which will commence during LMF shakedown. A necessary early part of this stage is a target development program, which is critical to all applications of ICF.

Costs and Costing Methodologies

To serve the objectives of this study, a standard costing methodology is defined in this document for all of the LMF candidate concepts. The Phase I portion of the cost estimating task specifies all of the driver-independent costs, defines all of the items to be included, and defines indirect cost factors that must be included in Phase II concept studies. The driver-independent costs are estimated to be approximately 300 million dollars (1987 dollars).

Conclusion

During Phase I of the LMC study, aimed at identifying the issues involved in developing an LMC, driver-independent issues and requirements of the LMC have been defined. Using point designs for the candidate LMF concepts, Phase II of the study will identify the driver-dependent issues based on the established requirements. The results of this study will serve to support the DOE Inertial Fusion Division in planning and implementing the ICF program, and will provide guidance to the ICF laboratories in establishing their research and development programs.

Several significant milestones were achieved during this Phase I study. All of the ICF laboratories cooperated in this requirements study, and the requirements were defined from examination of the applications rather than from the perceived feasibility of the technology. A consensus was achieved on an absorbed capsule energy having reasonable confidence of achieving high yield (and hence high gain) within a few years of experimentation on the LMF.

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David Bixler (DOE) was the chairman of the LMC steering committee. Phase I committee members and associates were Roger Bangerter and William Hogan of Lawrence Livermore National Laboratory (LLNL); David Cartwright, Donald Dudziak, Douglas Wilson, and David Harris of Los Alamos National Laboratory (LANL); Donald Cook and Steven Goldstein of Sandia National Laboratories, Albuquerque (SNLA); Timothy Henderson and Jon Larsen of KMS Fusion, Inc.; Charles Verdon of the University of Rochester's Laboratory for Laser Energetics (LLE); Andrew Schmitt of the Naval Research Laboratory (NRL); Denis Keefe and Edward Lee of Lawrence Berkeley Laboratory (LBL); and Leonard Goldman of LLE, currently of Bechtel National Corporation. The steering committee was the motivating factor behind the total effort. The individuals named had key roles in executing the study. Also supporting the steering committee was Orville Barr of InterScience, Inc., chiefly responsible for integrating the individual technical contributions into a cohesive document.

Steering committee members recruited a number of people, either individually or as teams, and tasked them to contribute different portions of the report. The Target Requirements task team, chaired by Roger Bangerter, was made up of William Mead of LANL, George Allshouse of SNLA, John Gardner of NRL, Charles Verdon, and Leonard Goldman; and received assistance from Douglas Wilson and Andrew Schmitt. The Experimental Environment task team, chaired by William Hogan, was made up of Donald Dudziak and Philip Goldstone of LANL; Robert Kauffman and Michael Tobin of LLNL; Jon Larsen; Mark Hedemann and Rick Olson of SNLA; and Leonard Goldman. They received assistance from David Harris and John McLeod of LANL; Charles Orth, John Pitts, and Laurance Suter of LLNL; and Robert Peterson of the University of Wisconsin. The Management and Staffing task team consisted of Donald Cook and Steven Goldstein of SNLA; receiving assistance from Paul Drake and Demos Kyrazis of LLNL, and from Gerald Barr, James Furaus, Jerome Hands, Dawn McMillen, Charles Shirley, and Rick Olson of SNLA.

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XI APPENDICES

APPENDIX A WEAPON PHYSICS WITH ICF SOURCES

1. Introduction

The LMC's objective is to achieve a laboratory fusion capability with thermonuclear yields of 200 to 1000 MJ (1/4 ton). This requires achieving high gain (about 100) from an inertial fusion target driven by a laboratory driver of about 10 MJ or more.

Once high yield is reliably achieved, this facility would be in demand to perform experiments to develop and exploit the many applications of laboratory fusion.[1] This appendix discusses the applications related to the development of nuclear weapons. Applications to the study of vulnerability, lethality, and nuclear effects (VLE) are discussed in Appendix B.

A high-yield ICF facility will complement underground nuclear tests--not replace them. High-yield ICF experiments would not be scaled-down nuclear weapon tests, because the important physical parameters do not all scale in the same way. Furthermore, some important weapon phenomena require larger spatial or temporal scales. However, spectra, fluxes, and fluences over sizeable areas can match those of many nuclear sources. With these capabilities, the scope and significance of the weapon physics and vulnerability experiments that can be done in the laboratory will increase significantly. Compared to underground testing, laboratory facilities provide greater diagnostic access and more rapid turnaround for design iteration, permitting experimental parametric studies.

Even if construction were approved in the near future, such a facility would not be available for several years. The specific weapon issues that will be important at that time cannot be forecast now. However, the usefulness of such a facility can be demonstrated by employing examples from current weapon and VLE issues; when the facility is built there will surely be similar new issues.

2. Characterizing High-Gain Targets and Their Outputs

The initial ICF high-gain capsules tested will provide useful output for many weapon physics and VLE applications. However, some of these applications may require output characteristics different from the unmodified output. By altering the design of the targets, the output characteristics can be varied significantly. For example, the fraction of yield going into prompt, hard x rays can be increased.

Pulse length is an important parameter which experimentalists would like to control; ICF target burn times are very short. Several techniques have been proposed for lengthening the pulse. In the Compton balloon concept, the target is surrounded by material with a good Compton scattering cross section, stretching and delaying the hard x-ray pulse. The gamma-ray output can also be varied by a large factor.

3. Weapon Physics Experiments

While high-gain ICF capsules will have insufficient energy to drive some experiments of interest, many ICF experiments could be done on some aspects of complex weapon design physics. A series of capability maps can be defined to characterize the utility of ICF experiments. In general, a capability map is defined using the equation of state (EOS) or opacity of a variety of materials as a function of their atomic number, material density, or specific energy. Two other important parameters are the volume in which the desired conditions exist and the time duration. The

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1. 1985 Laser Program Annual Report, Lawrence Livermore National Laboratory, Livermore, Calif., UCRL-50021-85 (1986), pp. 8-52 to 8-58.

volume must be large enough that the proper relative scale lengths for various processes can be established, and that the available diagnostics have sufficient resolution to see the effect being studied. The duration of the experiment must be chosen so that the proper relative importance of diverse phenomena with various growth rates is established, and the diagnostics must have good enough temporal resolution to resolve the desired effects.

Although ICF experiments cannot cover the entire region of interest for EOS experiments, yields of 100 to 1000 MJ cover most of the region of greatest uncertainty. Yields of 10 MJ are not very useful for these experiments.

A high-gain ICF facility can do experiments in a unique laboratory regime of high density and temperature physics.

Portions of the physics of nonequilibrium fusion can be studied. High-yield ICF experiments, operating in the appropriate parameter range, would significantly broaden the relevant atomic physics data base.

Advanced weapon concepts include, among others, the x-ray laser. The output from an ICF source can be tailored to allow study of certain physics aspects of these and other nuclear directed-energy weapons (NDEW's).

Although x-ray laser experiments have already been accomplished on Nova, high-yield ICF experiments can include additional realistic atomic-physics experiments. Different ionization states can be achieved in various experiments as a function of atomic number. ICF experiments would contribute to fundamental understanding of x-ray lasers. Yields of 100 to 1000 MJ are necessary for the best simulation of the relevant atomic physics.

4. Conclusions

If available today, an ICF facility with 100 to 1000 MJ of thermonuclear yield could produce data of great importance to the weapon designers. Such ICF experiments could not address all of the problems of importance to the weapons program. However, they could make important contributions to the fundamental understanding of many physics processes.

A high-yield ICF laboratory facility could also help retain weapon design personnel, maintain their expertise, and contribute to the scientific knowledge base relevant to nuclear weapons if testing becomes more limited. Thus, the ICF facility will help the U.S. maintain a credible thermonuclear weapon capability.

A high-gain facility could be available by the mid- to late-1990's if a national commitment is made to build it. While some of the current physics uncertainties may be resolved by that time, new and equally important issues will arise. A facility as unique and flexible as the LMF could unquestionably make important contributions to our national defense whenever it is built. If it were built in the 1990's, it could address current NDEW issues as well as being an important asset during any future testing limitations.

APPENDIX B WEAPON EFFECTS SIMULATION WITH ICF SOURCES

1. Introduction

This information comes from an investigation into the potential applications of a high-yield ICF capability to the simulation of nuclear weapon radiation effects. The term high yield means that target output energies are in the range of 200 to 1000 MJ. Such a laboratory microfusion capability (LMC) will probably require the attainment of high thermonuclear target gain. High gain means of order 100 times more energy is released from the fusion target than drive energy is absorbed. The achievement of such a capability could have significant impact on areas needing bursts of copious amounts of intense radiation. One such application is simulation of nuclear weapon radiation environments for hardness and survivability testing of nuclear weapon systems.

Two methods are used for effects testing: underground testing (UGT) at the Nevada Test Site using nuclear explosive devices, and laboratory aboveground experiments (AGEX) using simulators. Of the three nuclear weapon radiation output components (neutrons, gamma rays and x rays), x-ray simulation provides the most difficult AGEX challenge.

The conclusion is that a high-yield laboratory microfusion capability can complement existing and planned simulation facilities, providing a laboratory source meeting DOE x-ray testing needs with excellent fidelity, and which could meet most of the DOD testing needs, also with excellent fidelity.

2. Nuclear Weapon Effects Simulation

U.S. nuclear weapons are designed to withstand hostile environments from current and projected threats and countermeasures. Hardness requirements are obtained by considering the different threats in different engagement regions. At high altitudes above the sensible atmosphere (exoatmospheric), there is little attenuation of the x rays so they can present the most stressing threat to these systems. Inside the atmosphere (endoatmospheric), x rays are quickly absorbed, and the most stressing nuclear radiation threat can come from penetrating gamma rays and neutrons. Blast and bomb debris from very close nuclear bursts, and bomb-driven electromagnetic pulses (EMP) are also issues in lethality and survivability, but they are not discussed here because these effects are adequately studied using other laboratory facilities.

Radiation effects testing is performed in incremental steps. Electronic parts and devices (e.g., microcomputer chips) are individually tested and hardened first. Then they are incorporated into circuits and the circuit boards with the devices are hardened. These parts are then put into subsystems and components which are tested further for hardness. Finally the subsystems and components are combined into the full system assembly (e.g., the arming, fuzing, and firing--AF&F--system) and the system is subjected to a final UGT proof test. Extensive use is made of both laboratory AGEX's and UGT's during this process. AGEX work includes assessment testing as various circuit configurations are examined during the weapon hardware development phases. Once a final subsystem is decided upon, AGEX's are conducted to assure that the subsystems are ready for the final UGT.

There are several reasons why improved AGEX testing capabilities are needed for future weapon systems development:

1) Present military strategy dictates very smart, flexible systems.

2) Systems are becoming more complex, incorporating state-of-the-art technology.

3) More systems are using active electronics which must perform reliably during threat encounters.

4) Missions and threats are becoming more complex and stressing.

5) Potential increased UGT limitations may require greater reliance on simulators.

All of the above require more laboratory AGEX's to enhance the effectiveness of UGT's. The newer electronics technologies have smaller feature sizes, are more complex, and can be more sensitive to radiation threats. Even if it is possible to continue at the present level of UGT activity, the necessity of improved AGEX sources will be driven by the need for better understanding of technical radiation effects issues. AGEX sources are capable of repeated testing at a much higher data rate than UGT's, and are very useful in preparation for UGT's. Finally, if problems are discovered in an UGT, AGEX's are needed to understand and correct the problems prior to the next UGT.

Testing issues for the three characteristic nuclear radiations (neutrons, gamma rays and x rays) are as follows. The physics of neutron damage in electronics is well understood and excellent simulation fidelity is obtained with current sources. Neutron irradiation is used both to harden electronic devices to ionizing radiation and to test the hardness level against the neutron requirements for the device. Gamma rays can penetrate more deeply than x rays into the weapon system, producing electron-hole pairs in electronic devices.

Performance can be degraded by the amount of gamma-ray energy absorbed (dose) in the material and how fast (dose rate) the energy is absorbed. Laboratory sources are acceptable for gamma-ray effects testing, and new sources are being built to correct deficiencies.

The most difficult simulation fidelity task occurs in the area of x-ray effects testing. There are many different threat aspects requiring vulnerability and survivability testing to assure adequate hardness. Different weapons and different engagement altitudes produce different threats, and the most stressing threat can also change depending on which part of the system is being considered. Also, a threat spectrum becomes harder as the x rays penetrate inside the reentry body (RB); the outer portions of the RB attenuate the softer x rays. The resulting simulation requirements depend on the energy and intensity of the x rays and the area required to expose the test object.

Today, laboratory x-ray testing is performed on pulsed power accelerators with electron-beam diode loads. Beams of high energy electrons strike an anode material, producing an intense source of x rays. These x rays, called bremsstrahlung radiation, irradiate the test object. AGEX x-ray testing is currently limited by two factors: the test area is restricted to small sizes, and the x-ray energy spectrum does not properly simulate some of the two broad categories of effects, those in materials and those in electronics.

Over the years, the most credible means of testing the vulnerability of weapon components to x rays has been to expose them to the radiation from an underground test. Laboratory radiation sources and calculations are used for pre-UGT screening, taking advantage of the fact that they are relatively inexpensive, so that experiments and calculations can be repeated as needed while varying the test parameters. However, laboratory radiation sources have not been entirely trusted because their x-ray spectra have not, in the past, matched those of the postulated threat.

3. Potential Applications of ICF to Nuclear Weapon Radiation Effects Testing

When ICF capsules are driven to high yield in the laboratory, the resulting radiation output will be useful as an x-ray source for weapon effects testing. High yield in the laboratory implies high gain, unless a much more economical driver technology is developed than is currently available. It will be shown here that a microfusion yield of 200 MJ has very high payoff for application to weapon effects testing.

ICF capsule output spectra can be tailored to meet the fidelity requirements of a desired test. Configurations have been investigated for two threat spectra, the lightly shielded spectrum outside the RB's x-ray shield, and the shielded shine-through spectrum produced inside the x-ray shield by threats.

4. Summary of the Potential Application of ICF to Weapon Effects Testing

The output from ICF capsule designs can be modified to provide excellent simulation fidelity of x-ray threats over larger areas than conventional pulsed power simulators. The ICF sources could be designed to achieve better fidelity with respect to x-ray energy spectra and time history than conventional laboratory simulators.

In summary, ICF simulation of nuclear x-ray effects has the capability of meeting the DOE nuclear hardening and survivability testing needs with excellent fidelity. Such a capability also has the potential of meeting most of the DOD x-ray effects testing needs with excellent fidelity. Weapon effects simulation experiments on the LMF will provide a valuable complement to the capabilities of existing simulation sources. All laboratory AGEX sources would still have difficulty testing the largest objects, such as satellites and large missiles, because of their size.

APPENDIX C HIGH-GAIN TARGET DEVELOPMENT ON THE LMF

1. Introduction

In order to make capsules work, and then optimize them, four things need to be controlled and understood:

Symmetry needs to be well controlled. Time-dependent symmetry, as well as the time-independent symmetry may be important. This appears to be feasible.

Drive pulse shape and the resulting shock structure inside a capsule should be precisely understood. This, too, appears to be feasible.

Ignition physics and the state of the compressed fuel must be known. Knowledge of how the fuel size, shape, areal density (ρr), hotspot configuration, etc., of real capsules compares with simulations will be invaluable in helping coax designs into burning.

Mix and shell breakup are important. However, the physics of mix and shell breakup and, more importantly, what to do to minimize them, is not completely understood. The goal of LMF mix and shell breakup experiments is better understanding of the physics of these instabilities and, where possible, direct assessment of them in specific high-gain capsule designs.

To be confident that high-gain capsules will work on an LMF, a suite of flexible, high-data-rate hohlraum and capsule diagnostics is needed. Many of the Nova diagnostics are excellent prototypes.

2. Typical Targets

Cryogenic capsule designs have been proposed to provide 200 to 1000 MJ yield, depending on the convergence achievable.

In general, there are two generic types of drive being considered for LMC experiments: indirect and direct drive. This discussion mainly addresses indirect-drive target development.

3. Symmetry

According to our current understanding of pure radiation driven implosions, there are several common needs for controlling symmetry.

Precise energy deposition is required for all targets in order to achieve the required capsule irradiation symmetry. This usually means beam pointing to an accuracy of 100 to 200 microns. Pointing requirements can vary for alternative drivers or numbers of driver beams. Nevertheless, symmetry requirements make precision pointing and energy deposition diagnostics essential for any system.

Symmetry considerations also make control and measurement of the beam energies essential. The incident energy may not be known to adequate accuracy. Experience indicates that calorimetry of high-energy beams is not simple; the resultant uncertainty often reduces the value of experiments. The LMF must be able to measure energy delivered to the target with a precision meeting the target designers' requirements.

The final common need is for a symmetry diagnostic at the capsule location.

4. Strategy for Controlling Symmetry

The strategy for controlling capsule irradiation symmetry for an indirectly driven target can be divided into two phases. First, hohlraum characterization experiments are required to understand the details of the capsule's environment. Second, experiments are required to observe directly the drive symmetry at the capsule location.

The second phase, while necessary, is not sufficient to assure that a given hohlraum-driver combination will provide adequate capsule drive symmetry over the full range of high-performance target designs. The reason is that direct symmetry experiments necessarily require compromises which alter parameters at the few percent level. Corrections can be made for these perturbing compromises if the hohlraum physics is understood. Consistent results from both experimental phases described above give the designers both the confidence and the knowledge needed to make intelligent corrections.

An example of this two-phase strategy, from experience with the Nova ICF facility, is as follows. In the spring of 1986 a hohlraum characterization series was performed which indicated that key assumptions about the hohlraum were correct and that the radiation environment was being predictively modeled correctly. Qualitative and quantitative analysis of these data then allowed Livermore target designers to make statements about beam transport, beam pointing accuracy, etc.

The time-integrated pinhole camera was one of several Nova diagnostics which indicated the correctness of the most fundamental hohlraum assumptions. Other verification came from 1.5-keV time-integrated 8X x-ray microscope pictures. Further corroboration came from a spatially imaging soft x-ray streak camera. On the LMF, this data can be improved with a gated camera, like the GXI.

In addition to verifying the designers' fundamental assumptions, this hohlraum characterization experimental series also provided measurements which indicated that the details of the capsule's environment can be predictively modeled. The diagnostics included witness plates and witness slabs viewed by Nova's streaked optical pyrometer (SOP). Other quantitative checks came from analysis of the 8X x-ray microscope, dante x-ray diode (XRD), and SDSS-thru-a-slot data.

These hohlraum characterization experiments were the first phase in efforts to control capsule drive symmetry with Nova. They showed that the details of the capsule's environment are understood in these hohlraums. In the second, on-going phase, flux symmetry at the capsule location is being measured. One diagnostic approach uses a diagnostic capsule containing D-D and a trace of argon. A snapshot of the argon x-ray emission with the versatile GXI shows the shape of the fuel at stagnation.

Capsules have been imploded with deliberate drive asymmetries. Computer hydrodynamic simulations are then used to confirm the estimated asymmetry. Then targets were designed with corrections to achieve symmetrical drive and the resultant GXI image of the fuel at stagnation is symmetrical to within the instrument resolution.

On an LMF, proof tests like these, when coupled with hohlraum characterization experiments, will give great confidence that the symmetry in multi-megajoule hohlraums is understood.

5. Pulse shaped symmetry

To date, all Nova symmetry experiments have been performed with 1-ns flat-top pulses. When pulse shaping is applied, the approach to understanding and controlling the symmetry will be improved further. These improvements are discussed here since LMF diagnostics will undoubtedly reflect them.

These measurements will allow calculation of the time-resolved flux asymmetry. Measurement of the flux at the capsule location early during the shaped pulse, as well as integrated over the entire pulse duration, will provide data for checking the accuracy of model estimates. Several experimental approaches are being considered for these experiments. Although this discussion of symmetry is specifically applicable to laser drivers, similar experiments can be performed with ion-beam drivers, often using Nova-like diagnostics.

6. Temporally Shaped Drive

In order to achieve a high-gain spherical implosion, a relatively precisely controlled drive must be applied to the capsule. The degree of precision required depends on the target design; absorbed energy is a crucial parameter.

Pulse shaping diagnostics on the LMC will almost certainly evolve from the approaches currently being developed. These plans involve several different basic experiments and then bridge the remaining gaps with calculations.

If these experiments succeed, then the shock structure will be understood and controlled on Nova. Because of differences between Nova and high-gain LMF implosions, this cannot be said with the same confidence for the LMF.

7. Ignition Physics and State of the Fuel

Knowledge of the state of the fuel as it is igniting, and comparison with simulations, will be invaluable in achieving propagating burn conditions. Some critical parameters relating to high-gain burn conditions are yield, yield rate, main fuel ρr, hot spot parameters (size, density, and temperature), shell ρr, and shell ρr versus time. Note that "no-burn" experiments are as critical as propagating-burn experiments. Arguments can be made that no-burn experiments will be more instructive for sorting out the physics of poor performance than burn experiments. The arguments are based on the following observations:

1) significant diagnostic compromises will be made when shooting a capsule that has a chance of causing destruction of the diagnostics;

2) even poor thermonuclear performance will cause significant hydrodynamic perturbations to a system which, even without burn, may be behaving very differently than modeled; and

3) state-of-the-art target design includes rule-of-thumb opinions based on no-burn simulations which can be critically evaluated and extended only in no-burn experiments which complement the burn experiments.

8. Mix and Shell Breakup

Mix and shell breakup are generally considered harmful and best avoided. However, the physics of mix and shell breakup, and more importantly, what can be done to minimize them, are not completely understood.

The goal of mix and shell breakup experiments on the LMF is a better understanding of the physics of these instabilities and, where possible, direct assessment of them in specific high-gain capsule designs.

Shell breakup experiments for LMF targets will be extensions of techniques being used at LLNL and NRL. These experiments measure the growth of perturbations on planar samples with the use of x-ray backlighting. The principal diagnostics for these are imaging x-ray streak and framing cameras. They require a driver beam to provide the x-ray backlighting.

For mix experiments, it is less clear how to proceed on an LMF, since there is no body of experimental techniques that have been proven to work. However, by the time the LMF is available, many techniques will have been developed. The following is a description of recent and planned Nova experiments.

Three very flexible diagnostics, the streaked crystal spectrograph (SCS), the gated crystal spectrograph (GAX), and the gated x-ray imager (GXI) are fundamental to plans for Nova mix experiments. SCS stagnation spectra, obtained from a radiation driven capsule with some argon tracer, are extremely useful for diagnosing Nova capsule implosions. Quantitative analysis of the argon lines and the continuum from these data has led Livermore researchers to postulate a mixing hypothesis to be tested in future experiments.

Whether or not this hypothesis survives further Nova experiments, there are several points to be made that are germane to the LMF. First, mix experiments will mainly provide necessary, but insufficient data for hypothesis testing. An experiment which unambiguously measures capsule mixing probably cannot be done, because of the heavily convolved nature of the system. Secondly, time-resolved spectroscopy will be a conspicuous part of any experimental series exploring shell-fuel mixing on the LMF.

In addition to spectroscopic approaches to mix studies on the LMF, radiochemistry (radchem) experiments and time-resolved experiments involving n-gamma spectroscopy, should also be considered. These represent a new approach over current efforts, requiring far more yield than can be achieved in current ICF facilities.

9. Achieving High Gain

After the capsule's environment is satisfactorily understood, perhaps in a few tens of full-system, full-diagnostic shots (historically, such shots are only a small portion of the total number of system shots required), then the LMF would be ready to attempt making a capsule burn. Rough estimates of the number of shots required can be determined by considering two extreme scenarios.

Scenario 1 --If the first cryogenic target shot works as anticipated, and only one class of fueled targets is available during the first year, then an experimental sequence of variable target gain would be performed with burn variations of this target, where the gain is varied principally by changing the convergence. Variations in gain due to pulse shape changes would also be of great interest to target designers. About ten shots of 100 to 1000 MJ yield would be required, making this one of the most extensively studied capsules to date. A few no-burn investigations into fuel ρr, size, ion temperature, etc., at a couple of convergence ratios and pulse shapes would provide invaluable information for designing the next generation of capsules. That would require about ten more no-burn shots.

Scenario 2 --If cryogenic targets don't work as anticipated on the first shot, and only one class of fueled targets is available during the first year, essentially the same experimental series as in Scenario 1 would be required. The pulse shape and the convergence would be varied to understand the burn performance. Such studies, requiring about 10 shots at up to 100 MJ yield, if properly diagnosed, would be extremely enlightening, even if the capsule doesn't work as expected.

These scenarios can be expanded by the number of target designs that can be fabricated. Being able to fabricate one fundamentally new design per year seems reasonable, but possibly may be optimistic.

Human endurance dictates about 10 shots for each possibility instead of about 100. Precision cryogenic target implosions are difficult experiments. Every aspect of these shots will be a research effort in its own right: the driver performance, precise to a few percent; the target diagnostics; the capsule design; the capsule fabrication and its fielding and diagnostic hardware. Bringing them together in the early days of the LMF will be a programmatic tour-de-force which can be done, but it will require intensive effort.

APPENDIX D TUTORIAL

When a confined gas is adequately heated its molecules become agitated to the point where some of their electrons are no longer bound within them. The gas becomes a plasma: a collection of positively charged ions and negatively charged electrons. Because of its energized state, the plasma glows, so that it can be seen in such natural phenomena as lightning, or the static-electric arc generated when one touches some object after walking across a carpeted floor. When sufficiently heated, the ions become bare nuclei completely stripped of their electrons. Further heating of a confined plasma increases the random motion of the nuclei and electrons, and these charged particles bump into each other with greater force until, if adequately heated, some light nuclei overcome their mutual electrical repulsion and fuse together to form heavier nuclei. This is thermonuclear fusion, and for reactions of interest the process is exothermic, releasing net energy in the form of energetic particles and radiation. A plasma of deuterium and tritium (hydrogen isotopes) must be heated to about 10 kiloelectron-volts (about 100 million degrees Celsius) to produce useful fusion. Other fusion plasmas require even higher temperatures.

The extreme temperature for a thermonuclear reaction requires that the plasma be isolated from any other material. In order to accomplish this and still keep the plasma confined long enough to achieve thermonuclear fusion, two confinement schemes have been pursued in the laboratory: magnetic confinement and inertial confinement. In magnetic confinement, the plasma is confined with a magnetic field, using the principle that charged particles move slowly across magnetic field lines. The plasma must be very low-density (rarefied to the point of being a hard vacuum, for most purposes), because plasmas of higher densities escape too easily through the surrounding field of any presently available magnets. Because of its very low density, the plasma must be confined for several seconds in order to achieve release of useful amounts of energy from the fusion process. In inertial confinement fusion (ICF) the plasma is rapidly compressed and confined by its own inertia, so that the fusion process must take place in about a billionth of a second (a nanosecond). Here, the plasma density must be extremely high (many times the density of lead), in order for adequate fusion to take place in such an extremely short time. Because of the vast differences in the two confinement schemes, their accompanying technical problems are vastly different.

In ICF a small capsule filled with a thermonuclear fuel (usually deuterium and tritium, D-T) is rapidly compressed by exposing it on all sides to intense radiation. The interaction of this radiation with the outer surface (ablator) of the capsule causes the ablator material to quickly vaporize and blow off. The rocket action of the rapidly expanding vaporized material compresses the confined fuel until the necessary conditions of density and temperature are reached for efficient thermonuclear burning. A small fraction of the fuel at the center of the capsule is heated to the temperature required for thermonuclear ignition. This core of burning fuel heats the remaining compressed fuel until it burns for the duration of the confinement time. This can be achieved by two techniques: direct or indirect drive. Both techniques employ high-energy laser or ion beams, called driver beams. In indirect drive, which is the mainline technique under development, the driver beams do not directly illuminate the fuel capsule. The second technique, which is an alternate technique, has the driver beams impinging directly on the capsule.

To achieve thermonuclear ignition, the ICF fuel must be compressed to extreme densities as well as be heated to extreme temperatures. Prematurely heating the fuel greatly increases the work which must be done to compress it to the required density. There are many conceptual variations of compression and ignition. One of the most efficient processes for reaching ignition requires the fuel be compressed with a minimum of heat addition from either external sources or shock waves. This is done when the fuel is compressed by the imploding fuel pusher with only relatively weak shock heating. Other deleterious external sources of fuel preheating include energetic electrons (called suprathermal or fast electrons) and (for ion-beam drive) beam contaminants. These particles can readily penetrate to the fuel, prematurely heating it. Upon interaction with the capsule, laser beams of wavelength greater than about 0.5 micrometers produce excessive amounts of fast electrons, thus eliminating the longer wavelength lasers as likely candidates for ICF drivers. In fact, the shorter wavelength irradiation has two very important properties: it produces much lower amounts of fast electrons, and its energy couples to the target more efficiently.

Just as fuel preheating is detrimental to compression and ignition, efficient burning of the compressed fuel requires that sources of cooling not be introduced. One such source is mixing into the fuel by breakup of the capsule during the implosion. Achieving implosions with little or no mix requires a high degree of symmetry of the drive energy impinging upon the capsule. The drive intensity must be uniform over the surface of the capsule to within 1 or 2 percent. Driver uniformity requirements are believed to be more stringent for direct drive, but the overall efficiency of direct drive is believed to be significantly better. There are plasma and fluid-dynamic instabilities that must be reckoned with in both drive techniques. While driver-capsule coupling and fluid-dynamic instabilities are of greater concern with direct drive, certain driver-hohlraum interaction phenomena unique to indirect drive also present serious problems. In recent years, the ICF program has made substantial progress in understanding and dealing with the problems associated with both drive techniques.

To produce thermonuclear ignition in a laboratory setting, using laser beams or ion beams to ignite the capsule, will require that the capsule be enclosed in a specially designed test chamber. When a large fraction of the fuel in the capsule burns, a micro-explosion occurs, producing several hundred megajoules (MJ) of energy. Many important effects result from this energy release. Immediately, x rays, neutrons, gamma rays, charged particles, and capsule debris expand into the chamber environment. These prompt emissions interact with any surrounding material to produce electromagnetic pulses, shrapnel, ablation, shockwaves, spall, pressure pulses, and thermal stress. Delayed effects such as those associated with hot vapors, liquid metals, induced radioactivity, unburned fuel, toxic materials, corrosion, and condensations will occur. In moderate to high vacuum target chambers (less than 0.1 torr) the inner surface of the chamber walls will be ablated by the x-ray energy absorption. This ablation will cause shockwaves, and the ablated material will generate a pressure pulse. In chambers with 1 to 10 torr of gas the chamber wall ablation may not occur since the emitted x rays will be absorbed in the gas. However, a blast wave will be produced.

The emitted neutrons also cause a variety of effects. Because they are very penetrating, they will pass through unshielded regions of the target chamber (possibly including the first wall) and will be moderated and captured in the shielding or in material beyond the chamber. This requires shielding for personnel and careful design to avoid strongly activating material which will preclude the presence of personnel in the vicinity, consequently causing undue delay between experiments. Also, because of the intense neutron pulse, some material in the chamber may experience degradation of its material properties, such as tensile strength. Neutrons pose a serious problem with any exposed optics, such as the final optics of a laser driver.

This environment will provide an excellent opportunity to study the consequences of thermonuclear explosions under controlled laboratory conditions, to examine the detailed physical properties of matter under extreme densities and temperatures, and to develop a better understanding of the conditions of a thermonuclear burn using correlation between experiments, computer codes, and theory.

XII LMC PHASE I GLOSSARY of TERMS AND ACRONYMS

Ablator: The outer surface of a target capsule which absorbs the energy driving the implosion. The ablated material accelerates rapidly outward. This outward momentum creates a reaction force which drives a radially inward implosion of the remaining target capsule material, thereby compressing the fuel contained within the capsule.

ADM: Action Description Memorandum

AEC: US Atomic Energy Commission, predecessor of ERDA and DOE.

AF&F: Arming, fusing, and firing.

AGEX: Laboratory experimental facilities for simulation of nuclear weapon effects.

AGT: See AGEX.

ALARA: As low as reasonably achievable, a requirement to reduce radiation exposures below legal maxima whenever technically and economically feasible.

Areal density (ρr): The path integral of the density through a material. For example, water at STP has a density of 1 gram per cubic centimeter. A body of water 1 meter thick thus has an areal density of 1000 grams per cm^2. In ICF capsules the integral path is a radius, and since the greek letter ρ is used for density, the areal density is called the ρr product.

ASME: American Society of Mechanical Engineers

Atmosphere formation: The formation of an initial plasma at a surface absorbing radiation. This plasma atmosphere enhances the absorption of the ensuing energy.

Aurora: A KrF gas laser (0.25 micrometer wavelength) being constructed and tested at LANL.

Availability: The measure of the ability of the LMF to perform as intended, i.e., the ability to sustain a desired shot rate. See reliability.

Backlighting: Illuminating a subject from behind, to obtain a silhouette. This technique is applied in ICF to obtain target images or implosion rates by placing the target between an x-ray source and an x-ray imaging or streak camera.

Burn: The process in which thermonuclear fuel is consumed in a thermonuclear (fusion) process, producing an energy release.

calorie (cal): Engineering and physical unit of energy, equal to the energy needed to raise the temperature of 1 gram of water 1 Celsius degree. Not to be confused with the Calorie, a unit of nutritional energy, which is 1000 calories.

Capsule: The fuel-containing assembly of an ICF target. Energy irradiating the capsule is partially absorbed, driving a complex series of hydrodynamic processes, including the implosion of the capsule to small diameter and high density, and the heating of the center of the compressed fuel. Also called a pellet.

Capsule gain: In reference to the LMC study, this is the ratio of the fusion yield of a capsule to the drive energy absorbed in its ablator. This term has also been used to mean the ratio of the fusion yield of a capsule to the driver energy incident upon the target structure containing the capsule.

CEQ: Council on Environmental Quality.

CFR: Code of Federal Regulations.

Chroma: A 2-beam, 0.53-micrometer, frequency-converted Nd:glass laser with an output of several hundred joules, operated by KMSF for supporting experiments and target characterization.

Class (of clean room): The average number of particles of dimensions exceeding some minimum (typically 1/2 micrometer) per cubic foot of air. Clean room classes are defined from a few (10) up to 100,000, with a lower class number indicating a cleaner environment.

Compression: The process of volume reduction, occurring during an implosion, which increases the capsule fuel density.

Convergence ratio: The ratio of the linear dimensions of the target capsule (its radius) before and after an implosion. A convergence ratio of 10 implies that the volume of the capsule is reduced by a factor of about 1000.

CPO: Central project office, the core design team and administrative staff managing a project.

Core project team: The senior CPO administrative staff, functional representatives (FR's), and other key individuals that, as a group, retain full control of and accountability for the project.

Curie (Ci): Unit of radioactivity of an object; proportional to the total number of nuclear disintegrations per second.

Dante: A family of time-resolved x-ray instruments on Nova.

DBA: Design Basis Accident. Also accidents of specific nature, such as earthquake (DBE), tornado (DBT), and fire (DBF).

D-D: Fusion fuel involving two deuterium atoms.

Deuterium (D): The second isotope of hydrogen with a nuclear charge of +1 and an atomic mass of 2. It is used as a fuel in nuclear fusion reactions and as a substitute for ordinary hydrogen in some crystals utilized for frequency conversion (wavelength shifting) of laser light. Also used in the form of heavy water (D_2O) to moderate some nuclear reactors.

DEW: Directed energy weapons

Diode accelerator: A particle accelerator in which ions are accelerated across a single electric field in a diode (two-element) structure. Used in ICF light-ion drivers.

Direct drive: The process in which an ICF driver's output beams directly impinge upon the ICF fuel capsule and drive the implosion.

DNA: Defense Nuclear Agency, an element of the DOD.

DOD: US Department of Defense (usually DoD).

DOE: US Department of Energy, successor organization to ERDA.

DOL: US Department of Labor.

DONSI: Determination of No Significant Impact.

DOT: US Department of Transportation.

DP: Defense Programs, of the DOE.

Drive: The energy incident upon the fuel capsule, driving the implosion.

Driver: The machine which provides the energy to an ICF target in the form of intense, high-power beams of laser light or particles.

D-T: Fusion fuel involving deuterium and tritium in approximately equal amounts.

EA: Environmental Assessment. Also: Experiment area, that part of the LMF where applications experiments are conducted, including the target chamber(s), target and its support systems, target diagnostics, and applications experiments.

EBFA: Electron Beam Fusion Accelerator, built at SNLA for electron-beam ICF experiments. Subsequently converted to light ions, renamed PBFA I.

EE: Environmental Evaluation. See EA.

ED&I: Engineering, design, and inspection.

8X: Nova's eight-power x-ray microscopes.

EIS: Environmental Impact Statement.

Electron-volt (eV): A unit of energy corresponding to the kinetic energy of an electron that has been accelerated across an electric field of 1 volt. Also used as a unit of temperature, corresponding equivalent temperature of such electrons.

EMP: Electromagnetic pulse.

EO: Executive Order.

EOS: Equation of state.

EPA: US Environmental Protection Agency. The Administrator of the EPA must approve all EIS's and has significant responsibilities and authorities in regulating the releases of air and water pollutants and in the regulation of radioactive and hazardous wastes.

ER: DOE Office of Energy Research

ERDA: US Energy Research and Development Administration, successor organization to the AEC and predecessor to the DOE.

ES&H: Environmental, safety, and health.

Excimer: A molecule existing only in an excited state, and which cannot exist in thermal equilibrium with its environment.

ED&I: Engineering, design, and inspection.

Extended project team: The core project team plus the work package managers (WPM's).

Fluence: The time-integrated flux, thus the total energy or particles per unit area.

Flux: The energy or number of particles per unit time and per unit area passing through a mathematical surface in space. See fluence and irradiance.

FONSI: Finding of No Significant Impact.

Foot: The lower intensity precursor in pulse-shaped drive, used to begin the implosion.

FRD: Flat-response detectors, broad spectral response x-ray detectors.

FWHM: Full width at half maximum, the width of a distribution function measured between the two points of 50% of maximum value.

Gamma ray: Very energetic electromagnetic energy originating from nuclear processes, typically much more energetic than hard x rays.

GAX: Gated crystal spectrograph.

GXI: Gated x-ray imaging camera.

FR: Federal Register. Also: Functional representatives, members of the core project team responsible for the technical planning and execution of the project.

Halite/Centurion (H/C): A program of underground nuclear tests involving the ICF program.

HE: High explosive

Heavy ion: An ion of high mass, e.g., an electrically charged atom of an element from the middle to high end of the periodic table. In ICF, heavy ions are accelerated with linear (typically induction) accelerators.

Hertz (Hz): The number of repetitive events or cycles per second.

High gain: Ratios approaching 100 for total fusion yield to driver energy.

High yield: Total fusion yield approaching 1000 MJ. This does not necessarily require high gain, if large driver energy is economically available.

Hydrodynamic instability: Fluid instabilities in capsules caused by the acceleration of the interface between two materials of different densities.

Hybrid Drive: Target concepts that utilize both direct and indirect drive.

HVAC: The heating, ventilation, and air conditioning systems of a building.

IEMP: See SGEMP.

Inertial confinement fusion (ICF): A concept of using beams of energy (laser light, x rays, or ions) to compress fusion fuel (D-T) to high density and to heat at least some of the compressed fuel to high enough temperatures that fusion reactions begin to occur, releasing energy. The compressed fuel cannot escape the fusion reaction region because the reactions take place on a time scale so short that the fuel's inertia limits its outward motion.

Ignition: The fuel conditions in which the energy from fusion reactions at the central core of an implosion is partially trapped in the dense outer portion of compressed fuel, causing further fusion reactions and self heating.

Indirect (radiation) drive: The process in which the driver output (laser light or ion) beams are converted to other energy by a converter to drive the capsule implosion. See direct drive.

Interaction physics: Physical phenomena involved in the interactions between the driver beams, hohlraum (if any), target capsule, and the plasmas that are generated. These complex interactions must be understood for ICF targets to achieve high gain or high yield.

Ion: An electrically charged particle, usually an atom with one or more of its electrons removed.

IR: The infrared portion of the electromagnetic (light) spectrum, characterized by wavelengths longer than, and photon energies less than, those characteristic of visible light. CO_2 lasers operate in the far (thermal) IR spectrum, about 10.6 micrometers, and ICF solid-state Nd:glass lasers operate in the near IR spectrum, about 1.05 to 1.06 micrometers.

Irradiance: The flux irradiating a real physical surface.

ISI: Induced spatial incoherence, a process of randomizing laser beam wave fronts temporally and spatially to produce uniform (or tailored) illuminations.

Joule (J): Unit of energy, equivalent to the product of 1 watt of power times 1 second of time. One joule is approximately 1/4 calorie (1/4000 Calorie).

KDP: Potassium dihydrogen phosphate, nonlinear optical crystals used to convert the output wavelength of Nd:glass lasers from their fundamental in the infrared (1 micrometer) to 1/2, 1/3, or 1/4 that wavelength, in the visible (green), near ultraviolet, or far ultraviolet, respectively. Other materials are also useful for this application.

KD*P: Potassium dideuterium phosphate crystals. Also called d-KDP.

Kiloelectron-volt (keV): One thousand eV. A unit of energy, often used to express the energy of electrons or ions in plasmas, the energy of x rays, or the temperature of plasmas.

Kilojoule (kJ): One thousand joules.

Kiloton (kT): Unit of energy equivalence between HE and nuclear explosives.

KMSF: KMS Fusion, Inc., Ann Arbor, Michigan

KrF: Krypton fluoride, an excimer molecule which produces laser radiation in the ultraviolet portion of the optical spectrum, near 1/4 micron wavelength. KrF lasers are usually electrically excited, often with large area electron beams.

LANL: Los Alamos National Laboratory, Los Alamos, New Mexico

LASL: now LANL

LBL: Lawrence Berkeley Laboratory, Berkeley, California

Life Cycle Cost (LCC): The total integrated cost of a project during its projected lifetime, including construction, capital equipment, and operations & maintenance, in current dollars.

Light Ion: An ion of low mass, typically an electrically charged atom or the bare atomic nucleus of an element near the light end of the periodic table. In ICF, light ions are typically accelerated across a small gap in a high-voltage short-pulse diode accelerator.

Linac: A linear particle accelerator, with potential ICF driver use accelerating beams of heavy ions.

LLE: Laboratory for Laser Energetics, University of Rochester, New York.

LLNL: Lawrence Livermore National Laboratory, Livermore, California

LMC: Laboratory Microfusion Capability, a projected capability to create and utilize the yield from high-gain fusion targets.

LMF: Laboratory Microfusion Facility, the laboratory facility to provide the LMC.

LOS: Line of sight.

LTE: Local thermodynamic equilibrium. In ICF this primarily implies equality of the radiation and particle temperatures.

MBE-4: The Multiple Beam Experiment, a heavy ion accelerator exploring the acceleration of 4 beams simultaneously. Built by the LBL with funding from the DOE Office of Energy Research.

Megajoule (MJ): One million joules. The LMC goal of 1000 MJ is approximately equivalent in energy release to 500 pounds of TNT (1/4 ton).

MeV: Million electron-volts.

Micrometer: A unit of length, one millionth of a meter. Visible light is characterized by wavelengths between about 0.4 and 0.7 micrometer. Sometimes called micron.

Mix: Mixing of contaminants into the fuel of an imploding capsule, which can inhibit or prevent ignition.

Nanometer (nm): One-thousandth of a micrometer, one-millionth of a millimeter.

Nanosecond (ns): 10^{-9} seconds. Light travels one foot in one ns at 186,000 miles per second. Typical ICF target hydrodynamic (hence driver pulse) times are 0.1 to 10 ns. Target events can occur in small fractions of a ns.

NAS: National Academy of Sciences, Washington, D.C.

Neodymium:glass (Nd:glass): A laser material consisting of a few percent of active ions of neodymium doped into a glass. The glass typically contains many other ions to improve the absorption of exciting light, and transfer the energy to the neodymium, which stores the energy until it is released in the laser pulse. Neodymium is also doped into many crystals in small lasers, with YAG and YLF crystals often being used. Nd:glass lasers are usually optically excited, often with xenon-quartz flash lamps electrically excited by high voltage capacitors.

NDEW: Nuclear directed energy weapons; DEW's driven by nuclear explosives.

NEPA: The National Environmental Policy Act which established the national environmental policy.

NLUF: National Laser Users Facility, operated by UR/LLE for independently funded contractors.

NOI: Notice of Intent.

Non-LTE: A condition of not being in LTE.

Nova: A ten-beam, 100-TW Nd:glass laser fusion physics experimental facility at LLNL. Completed in 1985.

NPDES: National Pollutant Discharge Elimination Systems permit.

NRC: US Nuclear Regulatory Commission.

NRL: US Naval Research Laboratory, Washington, D.C.

NTS: Nevada Test Site.

Omega: A 24-beam Nd:glass laser facility at LLE.

One-dimensional (1-D): Calculations that assume perfect spherical symmetry. The 1-D yield of a capsule is the yield predicted by such a simplified calculation.

Opacity: The lack of transparency of a material to the flow of radiation; opacity is wavelength dependent.

PBFA: Particle Beam Fusion Accelerator, in two models: PBFA I and PBFA II. Built by SNLA, PBFA I was originally constructed as EBFA I, and since has been converted to weapon simulation experiments (Saturn). PBFA II is a light-ion (principally protons or lithium ions) accelerator for ICF experiments.

Pellet: See capsule.

Pharos: A series of Nd:glass lasers at NRL, used to study laser-plasma interaction physics. The current laser is Pharos III.

Photon: The minimum packet (quanta) of electromagnetic energy, usually treated as a particle of light.

Picosecond (ps): 10^{-12} seconds. A time interval of 1/1000 ns. Target and driver diagnostics often require time resolutions of the order of 10 ps in order to follow a rapid evolution of events. Light travels 0.3 mm per ps in vacuum; the frequency of visible (500 nm) light corresponds is approximately 600 cycles per ps.

Plutonium (Pu): A heavy element manufactured in DOE production reactors and used in nuclear weapons.

Preheat: The deposition of energy in the fuel of an ICF capsule before it is compressed by the implosion. Preheat raises the temperature, and hence the pressure, of the confined fuel, thus decreasing the compression ratio that can be achieved with a given energy. The reduced compression reduces the final fuel areal density, which reduces the trapping of energy in the outer fuel during the burn, reducing the gain, increasing the required drive energy, or even precluding ignition or burn.

Propagating burn: A burn in which the energy released from an early (in time) portion of the burn heats addition fusion fuel to sufficient temperature to contribute to the burn. See ignition.

PSAR: Preliminary Safety Analysis Report.

PSD: Prevention of Significant Deterioration.

Pulse-Shaped Drive: A careful tailoring of the temporal profile of the drive pulse to a capsule, which implies similar control of the driver output pulse. This usually means a long, low-energy precursor (called the foot) to begin the implosion without excessive heating, followed by the main drive pulse at full energy.

QA: Quality assurance, the complete program which assures that project hardware and software quality is adequately specified, documented, inspected, and preserved. QA includes all aspects of project quality, including documentation, drawings, procurement, inventory control, and auditing.

QC: Quality control, the inspection of hardware and software to assure that it meets project quality standards.

Radiation drive: See indirect drive.

Rayleigh-Taylor instability: A common, fundamental hydrodynamic fluid instability which may be detrimental to ICF capsule yield.

RB: Reentry body.

RCRA: Resource Conservation and Recovery Act

RDT&E: Research, development, testing, and evaluation.

Reliability: The fraction of shots which fall within specified performance bounds. Although usually applied to drivers in ICF research, in the LMF it will also apply to target performance for weapon effects simulation experiments. There may be many reliability numbers: one for low-energy shots, one for high-value shots, one for simulation experiments, etc. There may also be reliability numbers for individual target diagnostics. Overall reliability influences maintenance strategy and planning, but outsiders should focus on the reliability achieved on high-value shots. In a well run facility the overall reliability will be high, and the reliability on high-value shots will be extremely high. Achieving high reliability may degrade the shot rate (the availability) since they are measures of fundamentally different characteristics.

rho r product (ρr): The areal density of an ICF target, expressed in grams per cm^2, found by integration of the material density along a radial path through the material.

SAR: Safety Analysis Report.

SDSS-thru-a-slot: A spatially imaging soft x-ray streak camera which views through a slot aperture. Not related to an earlier instrument called the SDSS.

SGEMP: System-generated EMP. EMP pulses originating within a system due to absorption of x rays. Also called internal EMP or box IEMP.

Shot Rate: The frequency of shots of a given type. There are several ways to classify shot rates. One is the rate at which driver testing and set-up shots are fired, one is the rate of firing simple target shots for diagnostic set-up and calibration, one is the rate at which high-yield high-value targets are fired, one is the rate at which shots that are 100% successful are fired, etc. Another classification is the rate limited by the driver turn-around time, versus the rate limited by the target chamber turn-around time, versus the rate limited by data analysis time, versus the rate limited by funding availability, etc. There are trade-offs between shot rate and reliability which allow optimization of the data return per dollar expended, and which will vary with the nature and cost of individual experiments.

SHPO: State Historic Preservation Officer.

SNL: Sandia National Laboratories, Albuquerque, New Mexico, (SNLA) and Livermore, California (SNLL).

SNM: Special (or strategic) nuclear material used in nuclear weapons, including plutonium, tritium, and highly enriched uranium.

Solid-state (laser): A laser based on a solid lasing medium, like Nd:glass or crystalline materials, as opposed to a gas laser (like KrF) or a liquid laser (like dye/solvent combinations).

SOP: Standard Operating Procedure.

Streaked optical pyrometer.

STP: Standard temperature and pressure, 0° C and 1000 millibars.

Target: The entire structure placed where the ICF driver beams are pointed in the experimental chamber. The target may consist of a simple flat disk of material, or may be a complex structure with many parts.

Target Physics: The physical phenomena involved in the irradiation, implosion, ignition, and burn of ICF capsules.

Terawatt (TW): 10^{12} watts. A unit of power corresponding to one kilojoule of energy per nanosecond. LMC targets will require irradiation powers of the order of 1000 TW in order to implode properly. Since 1000 TW means 1 MJ per nanosecond, then implosion times of about 10 nanoseconds require approximately 10 MJ of energy.

TM: Thermo-mechanical.

TN: Thermonuclear.

Total estimated cost (TEC): The estimated total construction cost of the project, including conventional structures and systems, specialized systems, supporting prototype development and testing, overhead, project management, indirect costs, ED&I, and final integration and testing.

Transuranic (TRU): Elements of higher Z than uranium (92), including plutonium. None occur naturally in significant quantities.

TREE: Transient radiation effects in electronics.

Tritium (T): The third isotope of hydrogen, with an atomic number of 1 and an atomic mass of 3. T is radioactive, with a half-life of about 12.7 years, and thus must be manufactured. T is used with D as a fusion fuel (D-T).

TSCA: Toxic Substances Control Act.

UGT: Underground testing of nuclear weapons or weapon effects.

Uranium (U): A heavy element used to fuel commercial power reactors, in nuclear weapons, for radiation shielding, for dense counter-weights, and for high-penetration projectiles.

UR: University of Rochester, New York

USC: United States Code.

UV: The ultraviolet portion of the electromagnetic (light) spectrum, characterized by wavelengths longer than, and photon energies greater than, those characteristic of visible light. The UV portion of the spectrum lies between visible light and x rays. Lasers used for driving ICF targets typically operate in the UV. KrF lasers operate there directly, at about 1/4 micrometer, while Nd:glass lasers operate in the IR and are frequency converted to the UV, either to 1/3 or 1/4 micrometer (or to the visible, 1/2 micrometer).

UW: University of Wisconsin at Madison.

VLE: Vulnerability, lethality, and effects.

Watt (W): The international unit of power, that is the rate at which work is done. One watt corresponds to the flow of one joule of energy per second. The power density emitted by or impinging upon a surface is expressed in watts per square centimeter, while the watts per cm^3 is the density of power release (or absorption) throughout the volume of a process or equipment.

WBS: Work Breakdown Structure.

WPM: Work package managers, the members of the extended project team who supervise the design, construction, and testing of the project's structures, hardware, and software.

WRD&T: (Nuclear) Weapons RD&T of DOE Defense Programs.

X ray: That portion of the electromagnetic (light) spectrum falling between the ultraviolet and gamma rays. X rays originate from atomic processes and are often characterized as soft (lower energy, near the UV, perhaps up to a few keV) or hard (tens of keV to several MeV).

XRD: X-ray diode detector.

XRL: X-ray laser.

YAG: Yttrium aluminum garnet.

YLF: Yttrium lithium fluoride

Z: The atomic number of an element. The Z of an element is exactly the number of positive charges (protons) in the atomic nucleus.

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