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INERTIAL CONFINEMENT FUSION REACTOR DESIGN STUDIES RECOMMENDED GUIDELINES

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PREFACE

This report, prepared at the request of the Department of Energy Office of Fusion Energy, is intended to provide a summary of guidelines for monitoring technical progress in the inertial confinement fusion power plant design studies recently commissioned by DOE. The information presented here has been prepared by two working groups. One working group, chaired by Robert Krakowski (LANL), has prepared guidelines for comparison of inertial fusion and magnetic fusion reactor designs (Sec. III). The second working group, chaired by Roger Bangerter (LBL/LLNL), has developed unclassified guidelines for the target gain information to be used in the studies. In this report, target information is presented for direct-drive KrF (Sec. IV) and indirect-drive ions (Sec. V). Guidelines for indirect-drive KrF targets and direct-drive ion targets are still being developed by the Target Working Group and will be provided as Addenda to this report as soon as they are available.

Ronald C. Davidson
Chairman
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I. GOALS OF ICF REACTOR DESIGN STUDIES

Since inertial confinement fusion (ICF) was first considered as an energy source in the early seventies, there have been more than forty ICF reactor studies.[1] These studies included a variety of drivers and generally gave predicted cost of electricity (COE) comparable to those of magnetic fusion energy (MFE). The quality, level of detail, and goals of these studies varied widely. Some studies produced relatively complete point designs of power plants,[2] others concentrated primarily on reactor cavity design,[3] and still others were broad parametric searches for attractive operating points.[4] All of these studies are now less current, and most, if not all, are less detailed than the ongoing MFE ARIES study.[5] Therefore, to bring ICF power plant designs more nearly onto a par with MFE reactor design new studies are needed.

The Office of Fusion Energy is preparing to fund two new ICF power plant design studies. These studies should have four goals:

- Advancement of the state-of-the-art in ICF power plant design.
- Comparison of ICF and MFE plant designs.
- Development of a sound basis for future programmatic decisions.
- An assessment of ICF for power production including technical feasibility, economics, safety, and environmental considerations.

In regard to the first goal, it is important to emphasize that the funding for the contracts will exceed the funding of most previous ICF studies. Therefore, the contractors should be expected to address quantitatively a number of issues that have

previously been addressed less quantitatively. The second goal must also be emphasized. A comparison between ICF and MFE can only be meaningful if the studies of the two approaches are done at a comparable level, using similar general rates, assumptions, and guidelines (Sec. III).

It is expected that some aspects of the new designs will be based upon extrapolations of physics and technology beyond the present state-of-the-art. In order to assist DOE to evaluate the magnitude and probability of success of these extrapolations in physics and technology, the contractors should provide, for each major reactor system, an assessment of the development program that is needed to advance the physics and technology from its present status to the status that is required for the performance of that system as specified in the design. This assessment should include a quantification of the magnitude of the extrapolations involved relative to prior advances, the identification of major feasibility issues, and an evaluation of the role of the ICF Defense Program in resolving these issues.

II. MAJOR REACTOR SYSTEMS AND GUIDELINES

The major reactor systems include a target factory, a driver, a reaction chamber, and the balance of plant (BOP). The properties of, and requirements on, all systems except BOP are strongly influenced or determined by target physics and design. Most target designs are classified. The charter to do classified target physics and design resides at Los Alamos National Laboratory, Lawrence Livermore National Laboratory, Sandia National Laboratories, and KMS Fusion. Therefore, as part of the

studies, the Office of Fusion Energy and the Inertial Fusion Division have established a Target Working Group to develop target information. The Target Working Group consists of individuals from the Department's ICF laboratories.*

A. Target Gain

The target information is compiled in unclassified sections of this report (Secs. IV and V) to be used in the studies. The target gain is given as a function of the relevant beam parameters such as total beam energy, focal point radius, wavelength or ion range, alignment tolerance, number of beams, etc. Three cases are provided: a base case using information from current target designs, a more speculative case with higher gain, and a conservative case. Contractors should evaluate the consequences of all cases, but primary emphasis should be given to the base case. The fraction of target output energy in neutrons, x-rays and debris is given in Ref. 6.

It is important for credibility to have all aspects of the studies documented. Therefore, the Target Working Group will produce classified reports documenting the calculations, experiments, and assumptions used to obtain target gain and output of neutrons, x-rays, and debris.

Given target gain and output, the contractors will have enough information to design and evaluate drivers, reaction chambers, and BOP. Thus, to study and design most of the major

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systems, the contractors will have no need of classified information.

B. Target Factory

Targets are currently handcrafted for a few shots per day. For economical power production, the cost of targets must drop several orders of magnitude and the production rate must be increased to about 10^5-10^6 targets per day. Therefore, mass-production techniques must be introduced. These extrapolations in cost and production rate are sufficiently large that, despite some excellent previous studies, large uncertainties remain. It is important to reduce the uncertainties since target production costs appear to contribute significantly to total COE. Therefore, the studies must continue to address this issue.

The most recent and complete DOE-supported study of target costs was performed for the Heavy-Ion Fusion Systems Assessment.[7] Since the completion of this study, there has been some evolution in target design and also substantial progress in handcrafted target fabrication techniques. Furthermore, some of the newer target fabrication techniques appear suitable for mass production. Therefore, new studies are needed. The studies must include conceptual techniques for fabricating the targets and must be performed by a group that includes at least some individuals with industrial experience and demonstrated expertise in the mass production of small, high precision components. These individuals must be familiar with advanced manufacturing R&D. Target inventory and shelf life, and tritium inventory, handling, and control must be addressed. Target factory development needs must be detailed.

The Target Working Group has provided unclassified gain curves (Fig. 4.1). The contractors can use these gain curves for their studies. The Target Working Group will use the methods developed by the contractors to estimate the cost of classified targets. It appears likely that words similar to the following could be included in the reports: "Using the methods described above, we estimate the cost of classified targets to be x times the cost of unclassified targets."

C. Drivers

The contractors have chosen to use KrF lasers and heavy-ion accelerators as drivers. The DOE laboratories have already developed design concepts for these drivers. The contractors should consider the information from the laboratories on each driver. To obtain a balanced view, the contractors should also solicit and evaluate criticism of the various driver candidates. The contractors could adopt or modify existing driver designs or develop their own designs. It is important that the final report, for each driver, address quantitatively technical feasibility, cost, efficiency, lifetime, reliability, beam precision, focusing, pulse shaping, and target performance. Development issues and key required development tests should be specified.

D. Reaction Chamber

There is a spectrum of ICF chamber designs ranging from bare-wall concepts that use distance to achieve wall survivability against neutrons, radiation, charged particles, and target debris to concepts that place a neutronically thick layer (usually

liquid or granules) between the target and the first structural wall. Contractors may choose either extreme or something between. As with regard to drivers, the contractors may choose to adopt or modify existing designs or to innovate. The following topics are representative of those that should be addressed quantitatively: illumination geometry, optics protection, mechanical and thermal stress, fatigue, radiation damage, lifetime, tritium breeding, tritium handling, cooling, activation, radioactive inventories, safety, materials, cost, maintenance, decommissioning, and waste disposal, etc. There should also be some discussion of material requirements, resources and availability. Development steps for reactor chambers should be described.

Standard safety evaluations for prompt and delayed dose in severe accidents must be performed. Specifically, it is recommended that the distance to the site boundary be calculated for each of the concepts evaluated such that the whole body dose from all sources does not exceed 25 Rem using the ICRP Report No. 26 weighting factors.

To calculate the maximum dose to an off-side individual for comparison with the above criteria, the following approach should be used:

- The source term for the calculation should be determined using a deterministic analysis to obtain the "maximum credible accident," i.e., the credible accident with the potential for the largest off-site dose. Guidance for performing the deterministic analysis should be obtained from Reference 8.

- Dispersion factors (X/Q) should be determined from USNRC Regulatory Guide 1.145 for stable, light wind conditions (Stability Class F, 1 meter/sec wind-speed).
- Dose conversion factors should be obtained from References 9 and 10. The dose conversion factor given in Reference 10 for tritiated water should be multiplied by 1.5 to account for skin absorption, as per ICRP guidance.

E. Balance of Plant

This category includes all structures and systems not specifically identified above. The design and analysis of this part of the plant should be done at the same level as, and be consistent with, the ARIES study[5] (See Sec. III).

F. Optimization and Interfaces

There are a number of topics that must include joint consideration of the plant parts considered above. The most fundamental of these is overall plant optimization. In this regard, the contractors could use optimization codes such as ICCOMO[11] and SAFIRE[12] to obtain optimal COE and its sensitivity to parametric variations of yield, rep rate, driver characteristics, etc. It is recommended that 1000 MWe be chosen as the net output for the base case, but it should also be determined how the COE depends on net output in a range at least as large as 500-2000 MWe.

Other design topics that must be quantitatively addressed are: target injection and tracking and beam steering systems, optics protection (neutrons, x-rays, debris), optics damage thresholds, the connections among tracking and steering accuracy, target survivability, focal radius, optical mounts, and vibration and distortion of optics. Possible sources of vibration and

distortion include the mechanical effects of the microexplosions on the target chamber and surrounding structure as well as vibration and distortion caused by the passage of the beam, neutron energy deposition, radiation induced swelling, etc. The connection between residual chamber pressure and beam propagation must be addressed. In particular, beam propagation in the chamber appears to be an important issue for ions. Questions of propagation efficiency, beam overlap, instabilities, charge and current neutralization, and the geometry of any needed return current channels must be addressed. Finally, the isolation and maintenance of the major subsystems such as driver, target factory, chamber, and balance of plant must also be addressed.

Target injection, tracking, and survivability may be difficult issues. Because of the differences between direct and indirect drive, it is possible that careful studies using only unclassified information might conclude that ICF is not feasible; however, the perceived difficulties may not apply to classified targets. The opposite situation might also occur. It is therefore recommended that the Target Working Group in concurrence with DOE be given the responsibility to ensure that the conclusion of the studies is consistent with classified information.

III. COMMON BASES FOR COMPARISON OF ICF AND MFE REACTOR DESIGNS

An important result of the ICF reactor study will be a quantitative comparison with contemporary counterpart studies in MFE (e.g., ARIES[5]). It is crucial, therefore, that ground rules and guidelines be clearly established and defined at the onset of the ICF reactor study. Qualitatively, a set of minimal conditions

must be met before meaningful comparisons can be made. Most of these minimal conditions can be met by good planning and goal-setting at the onset of the ICF study, as well as by using existing resources within the ICF and MFE communities, rather than consuming a significant part of the study effort per se. These conditions include:

- Same COMPARABLE level of net-electric power (at least for MFE/ICF comparison cases); parametric cost-sensitivity studies around this reference power level would be desirable. 1000MWe
- Similar level of detail in describing physics, engineering, and (plant) operational assumptions. If this does not prove feasible because of less-developed reactor study base for ICF, as a minimum, a clear definition of the physics basis, engineering constraints, accuracy and credibility of technology projections, and plant operational assumptions should be made.
- Same COMPARABLE level of conceptual engineering design detail for each of the key reactor subsystems within the conceptual design, when possible.
- Same COMPARABLE level of coupling between fusion-power-core (FPC) design (done in greater detail) and balance-of-plant (BOP) design (done in less detail).
- Same COMP. costing procedure methodology (e.g., NECDB) and same unit-cost database (both in magnitude and scaling).[13] Feed-back between the two studies with regard to the unit-cost base is likely to benefit both studies.
- Same * (range of) global plant characterstics [e.g., nth-of-a-kind, net-electric power, BOP recirculating power requirements

* COMPARABLE

(assumptions), plant availability, decommissioning, construction lead time, safety and environmental cost credits, etc.].

- Same* general philosophy vis-a-vis costing, role of parametric systems and tradeoff studies, direction and depth of point conceptual design (i.e., establish and monitor optimum design points using parametric system analysis and cost tradeoff studies).
- Same* level of resolution of safety and environmental issues (including resource estimates, waste disposal requirements, level of inherent/passive safety, etc.); use of a common methodology (e.g., ESECOM[14]) would be desirable.
- Same* ground rules for time and cost estimates of needed R&D to achieve a given point design, as well as assessing the credibility of achieving that end-result within the projected time and cost targets.

Described below are the design procedures, methodologies, and philosophies being used by the ongoing ARIES tokamak reactor study. This material is presented here to provide a base with which to compare similar procedures, methodologies and philosophies to be adopted by the ICF reactor study. The degree to which these can be matched will determine the effectiveness of any eventual ICF/MFE comparisons. It is expected that the feedback between the two studies will be bi-directional.

Figure 3.1 describes schematically a process that has evolved over the years for MFE and is now being applied to the ARIES project. The cost of electricity (COE, mill/kWeh), and to a lesser extent the total cost (TC,M$) and unit direct cost (UDC,$/We), are used as "object functions" in a design-based

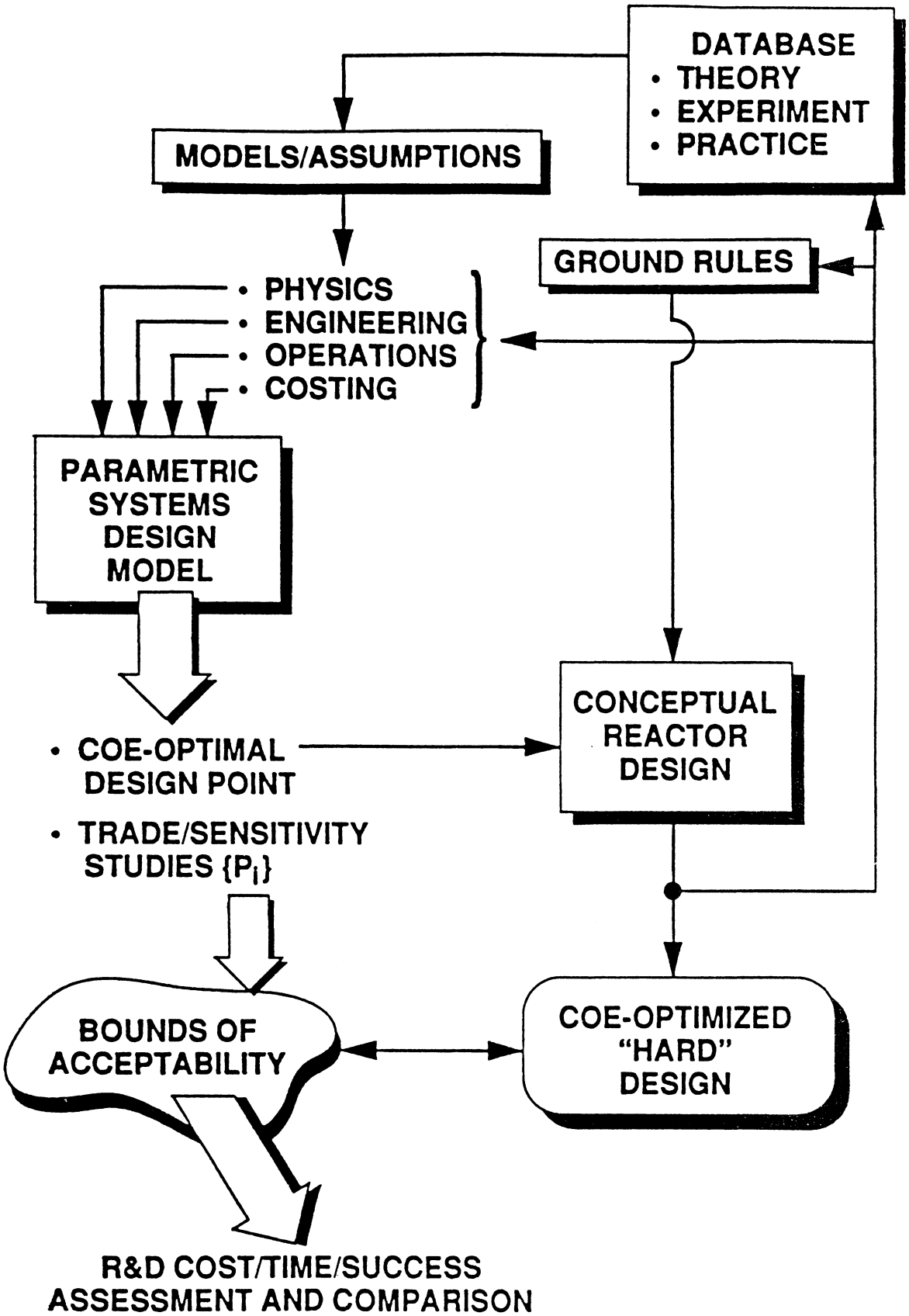
DATABASE
• THEORY
• EXPERIMENT
• PRACTICE
MODELS/ASSUMPTIONS
GROUND RULES
• PHYSICS
• ENGINEERING
• OPERATIONS
• COSTING
PARAMETRIC SYSTEMS DESIGN MODEL
• COE-OPTIMAL DESIGN POINT
• TRADE/SENSITIVITY STUDIES {P_i}
CONCEPTUAL REACTOR DESIGN
BOUNDS OF ACCEPTABILITY
COE-OPTIMIZED "HARD" DESIGN
R&D COST/TIME/SUCCESS ASSESSMENT AND COMPARISON

Figure 3.1

physics/engineering/costing parametrics systems model. This comprehensive model produces a COE-optimal (minimum or otherwise constrained by the design) "strawman" design that in turn provides guidance to the conceptual reactor design activity. As shown in the figure, information from the design process is fed back to the cost-based systems design model. The main role of the systems design model is to perform a range of "credibility checks" using trade-off and sensitivity studies throughout the conceptual design process and the technical assessment that follows. This sensitivity of cost to key physics and engineering assumptions, rather than bottom-line COE, are the important outputs from this design and analysis activity. The final designs are accessed in terms of the range and flexibility of an operating space in which that final (best) design resides, asexpressed in terms of the required R&D cost, time, and success probability (credibility). In short, the bottom-line result should provide a quantified measure of credibility in achieving the optimized end-product projected by the study; it is the engineering and physics needs and means by which an attractive COE is achieved, rather than the value of the COE per se, that is important in assessing the needed R&D. Since most "successful" designs will project a "competitive" COE, and since this COE is subject to the physics and engineering uncertainties underlying all parts of the COE estimate, comparisons and/or ranking concepts on the basis of COE alone is unwise. Instead, the credibility of achieving the physics and engineering needed to report a competitive COE should form the basis for comparing concepts.

Given an "in-principle" acceptance of the above-described design process, or an equivalent methodology, a set of concrete points of comparison should be established, agreed, and implemented in the ICF reactor studies contract. Summarized below is a preliminary (working) list of such ground rules, guidelines, procedures, and normative parameters.

- 10th-of-a-kind commercial plant, but estimate 1st-of-a-kind cost factor.
- P_E = 1000-MWe(net) net-electric output, but examine cost, physics, and engineering sensitivity of lower and higher plant capacity.
- DT fuel cycle.
- Use NECDB[13] methodology and assumptions (typical values given below are for ARIES project,[15,16] in 1988 dollars).

- plant life, yr	30
- plant lead time, yr	6
- contingency factor	0.15 (standard construction) 0.25 (nuclear construction)
- neutron radiation life, L(MW yr/m^2)	20 (nominal, material-dependent)
- spare parts multipliers	1.0 (i.e., no spares for all systems)
- effective cost of money, nominal/constant-dollar (1/yr)*	0.0957/0.0435
- inflation rate (1/yr)	~~0.06~~ 0.05
- effective tax rate	0.3664
- tax depreciation life, yr(plant/replaceables)	15/5

*nominal = then current; constant-dollar = inflation-adjusted cost.

- fixed charge rate, FCR(nominal/constant-dollar)	0.1638/0.0966
- interest during construction, IDC(nominal/constant-dollars)	0.2630/0.1652
- escalation during construction, EDC(nominal/constant-dollar)	0.2335/0.0
- COE components	
- capital	computed
- operating and maintenance[13] (M$/yr, P_E in MWe)	$69.2(P_E/1200)^{0.5}$
- first-walk/blanket replacement	computed
- decommissioning allowance (mill/kWeh)	0-1 (dependent on level of safety assurance)
- deuterium fuel (mill/kWeh)	~0.05
- indirect costs	
- construction equipment and services	12.8% or 15.1% direct cost for LSA rating of 3 or 4
- home office engineering and services	5.2% direct cost
- field office engineering and services	6.4% or 8.7% direct cost for LSA rating of 3 or 4
- owner's cost	15% direct cost, plus the above three

- Use standard unit costs (and scalings) for comparable materials, assembles, and systems that include materials, installation, RDACs, and contingency costs, with all items expressed on an appropriate and common basis.
  - high heat-flux areas, $\$/m^2$
  - first vacuum walls, $\$/m^2$

- structural, breeder, multiplier materials, $/kg
- main heat transport, $/Wt
- reactor building, $/m^3
- steam generator, $/Wt
- intermediate heat exchanger, $/Wt
- turbine plant equipment, $/We(gross)
- electric plant equipment, $/We(gross)
- etc.

- Use a common cost accounting system, appropriately adjusted to include accounts specific to ICF or MFE. The attached table gives the cost accounting breakdown used by the ARIES project.
- Use a common cost summary sheet, a sample of which from ARIES is given on the attached table.
- Express key parameters and figures of merit on a common basis [e.g., blanket energy multiplication relative to DT neutron energy; mass power density, kWe/tonne; neutron wall loading, MW/m^2; direct versus base versus total plant cost; "wall-plug" versus direct heating efficiency; engineering versus plasma Q-values; etc.). Other or related points of technical comparison that should emphasized are:
  - Powers: net-electric, gross-electric, thermal, and recirculating power.
  - Fuel Performance: burnup fraction, tritium inventory, breeding.
  - Driver Parameters: energy, power, forces, efficiency.
  - Blanket Performance: neutron and heat fluxes, radiation life, availability, reliability, repairability, safety.

- Safety and Environment: threshold dose release fractions (TDRFs) to give a critical (200 rem) or chronic (25 rem) dose at the site boundary, total radioactive inventories (MCI, BHP), contact doses, waste disposal indices (tonne/MWe, m^3, etc.).

In summary, examples of both guidelines and means of comparison have been suggested for consideration by the ICF reactor-study groups. These guidelines are based on approaches generally followed by past MFE reactor studies, and most recently by the ongoing ARIES studies. Furthermore, it is expected that the assumptions used in the ongoing ARIES tokamak reactor study will not be met with full agreement by the ICF reactor study groups, and adjustments will have to be made. While the exact methodology given herein may not be advisable, desirable, or possible to follow for the ICF study, some methodology, nevertheless, should be proposed, approved and followed. Further insight on how to compare these highly conceptual ideas undoubtedly will be generated by dialogues with the ICF reactor-studies contractors. Careful front-end planning in this area is essential to a meaningful technical comparison of the study results with similar projections for MFE.

IV. TARGET REQUIREMENTS FOR DIRECT-DRIVE KrF

This section provides a brief summary of current high-gain direct-drive KrF capsule designs and illumination uniformity requirements. These designs represent relatively mature designs in that they have undergone a number of iterations with respect to issues associated with hydrodynamic stability, effects of

long-wavelength drive nonuniformities, and laser energy coupling. In these designs we have attempted to use our current "best" understanding of the physics associated with these issues. As more experimental and theoretical work is carried out, some aspects of the current design will change. However, we believe that these changes will not significantly affect the information provided in this summary.

A. Direct-Drive High-Gain Performance

The gain curve(s) (thermonuclear energy out/incident laser energy in) for directly driven KrF capsules are shown in Fig. 4.1. The gain curve is shown as a band to represent our current "level of risk" understanding associated with hydrodynamic stability issues. The upper (optimistic) curve represents designs which have been optimized to implode on a nearly Fermi degenerate isentrope. Using our current understanding of issues related to Rayleigh-Taylor hydrodynamic instability and its effect on capsule performance, these designs would have more restrictive requirements on capsule and drive uniformity than the designs represented by the lower (conservative) gain curve shown in Fig. 4.1. The capsule designs represented by the lower curve have been optimized to reduce the effects of Rayleigh-Taylor unstable growth on capsule performance.

Our present studies of the Rayleigh-Taylor growth rates for directly driven capsules show that the growth rates $\gamma(t)$ can be given (approximately) by the form:

$$\gamma(t) = \sqrt{\frac{A(t)kg(t)}{1 + kL(t)}} - \delta k V_a(t)$$

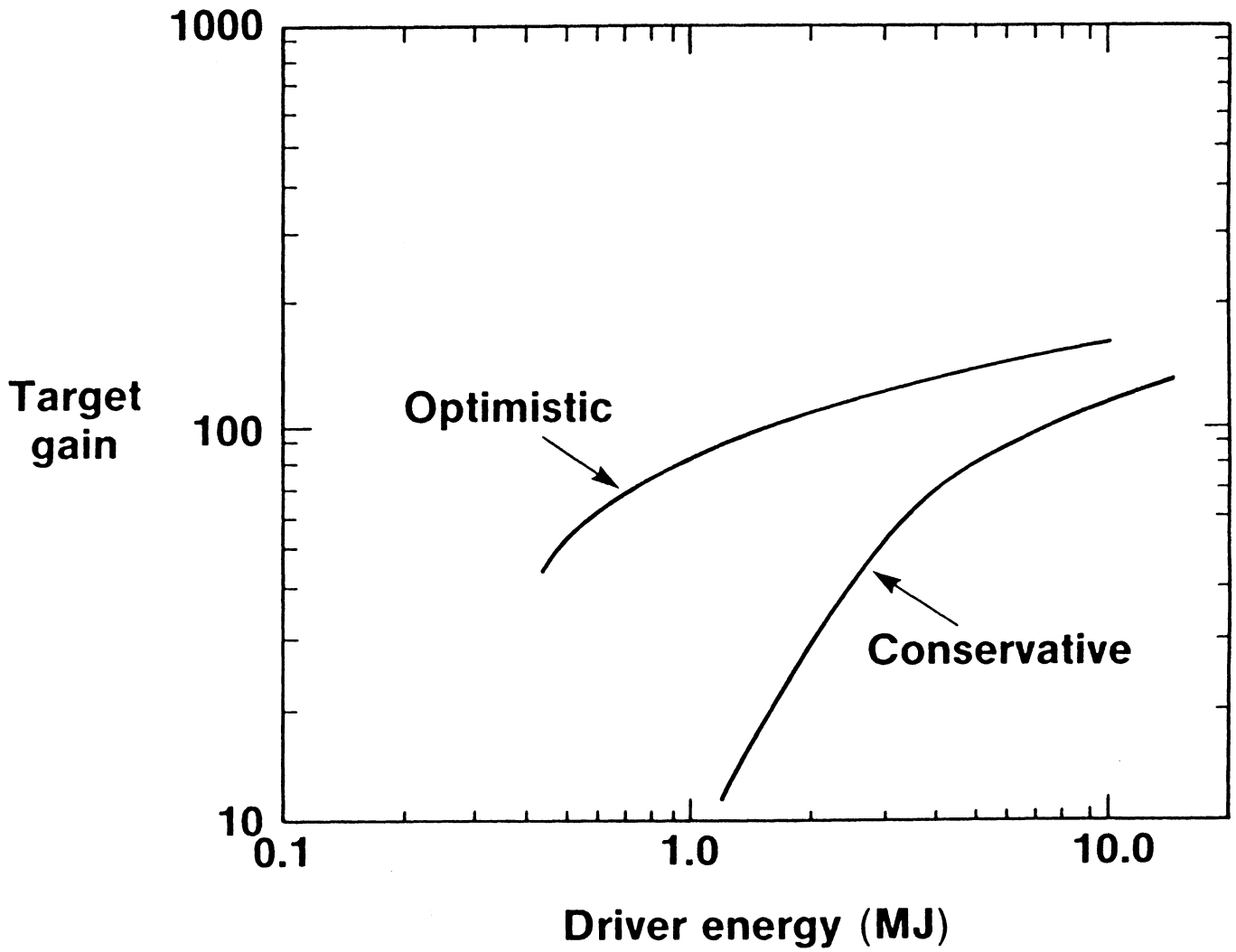

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Figure 4.1

where A(t) is the Atwood number, g(t) is the acceleration, k is the unstable wave number, L(t) is the front surface density scale length, $V_a(t)$ is the ablation velocity, and δ is a constant which ranges between 2-3 depending on the definition of A, L, and V_a. There are two stabilizing terms in this expression (L and V_a). The lower curve on the gain curve(s) represent designs for which the stabilizing effects of L and V_a have been optimized while maintaining relatively high gain performance.

The values of L and V_a can be increased over those found in the capsule designs representing the upper curve by changing the isentrope of the implosion. This could be done by seeding the ablator with high-atomic-number impurities or by using pulse shaping. Currently we have restricted our considerations to pulse-shape modifications so that the capsule designs could be more easily scaled with respect to incident laser energy. For the purpose of this study, the base case capsule gain should be taken to be the arithmetic mean of the optimistic and conservative curves in Fig. 4.1.

An estimate of the required outside surface finish can be obtained using the present understanding of Rayleigh-Taylor unstable growth rates and an initial model spectrum representative of machined surfaces (as $\ell^{-5/4}$).

B. Illumination Uniformity Requirements

The irradiation pattern on the capsule can be represented as the product of two factors: (1) a single-beam factor that depends on the focusing geometry, the f-number of the lens, the capsule conditions, and the individual beam profiles, and (2) a geometric factor that is determined by the number and orientation of the individual beams about the capsule, and the energy or

power imbalance between the beams. (The balance of time-integrated individual beam energies does not preclude the occurrences of instantaneous differences in intensity between beams at different times in the pulse.)

B.1 Number of Beams and Focal Spot Radius

Figure 4.2 shows the predicted rms irradiation nonuniformity on the capsule for 24-, 32-, 60-, and 96-beam irradiation configurations. The individual beam radial-beam profiles in all cases is assumed to be $\sin^2 x/x^2$ characteristic of the intensity envelope produced by distributed phase plates. All of the beam configurations provide adequate uniformity at a focal ratio (beam radius at the 5% intensity point divided by the capsule radius) of ~1 (tangential focus). However, as the capsule implodes, this ratio increases due to the inward motion of the critical surface. By the time the laser pulse has finally turned off, the focal ratio typically doubles. From Fig. 4.2 it is clear that a minimum of 32 beams is required to obtain a high level of uniformity over the duration of the laser pulse. However, when issues associated with other contributions to illumination nonuniformity are included it is found that a 32-beam system requires much more control over power balance and beam mispointing than a system with more beams. Therefore, in terms of stating a requirement on the number of beams and their focal spot radii, a minimum of 60 beams is required and the initial focal spot radius should equal the radius of the capsule. As to the beam placement, assuming that the 60 beams are symmetrically disposed about the capsule is a good first approximation. If a detailed location of the optimal placement of the 60 beams is required, this information can be provided.

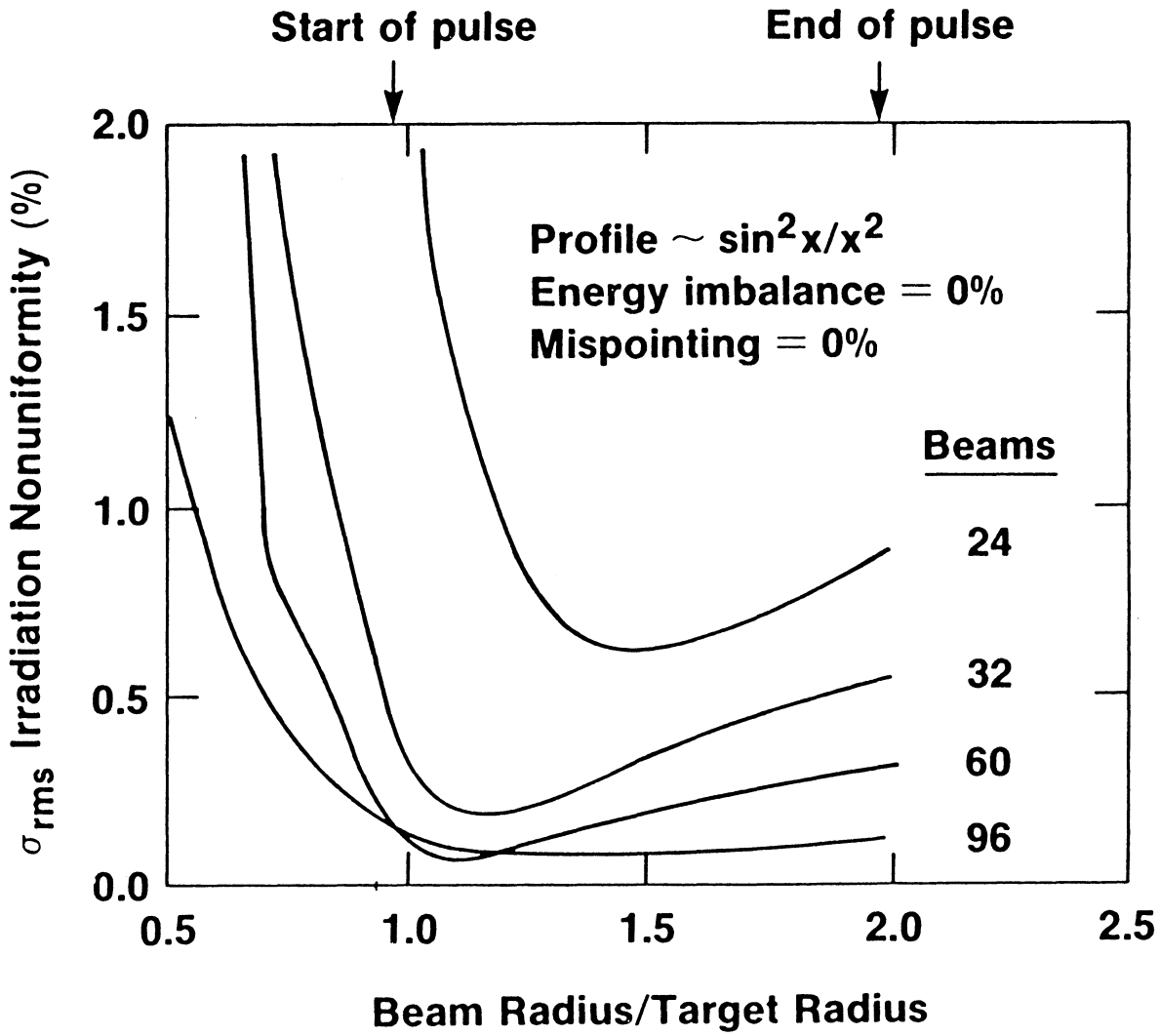

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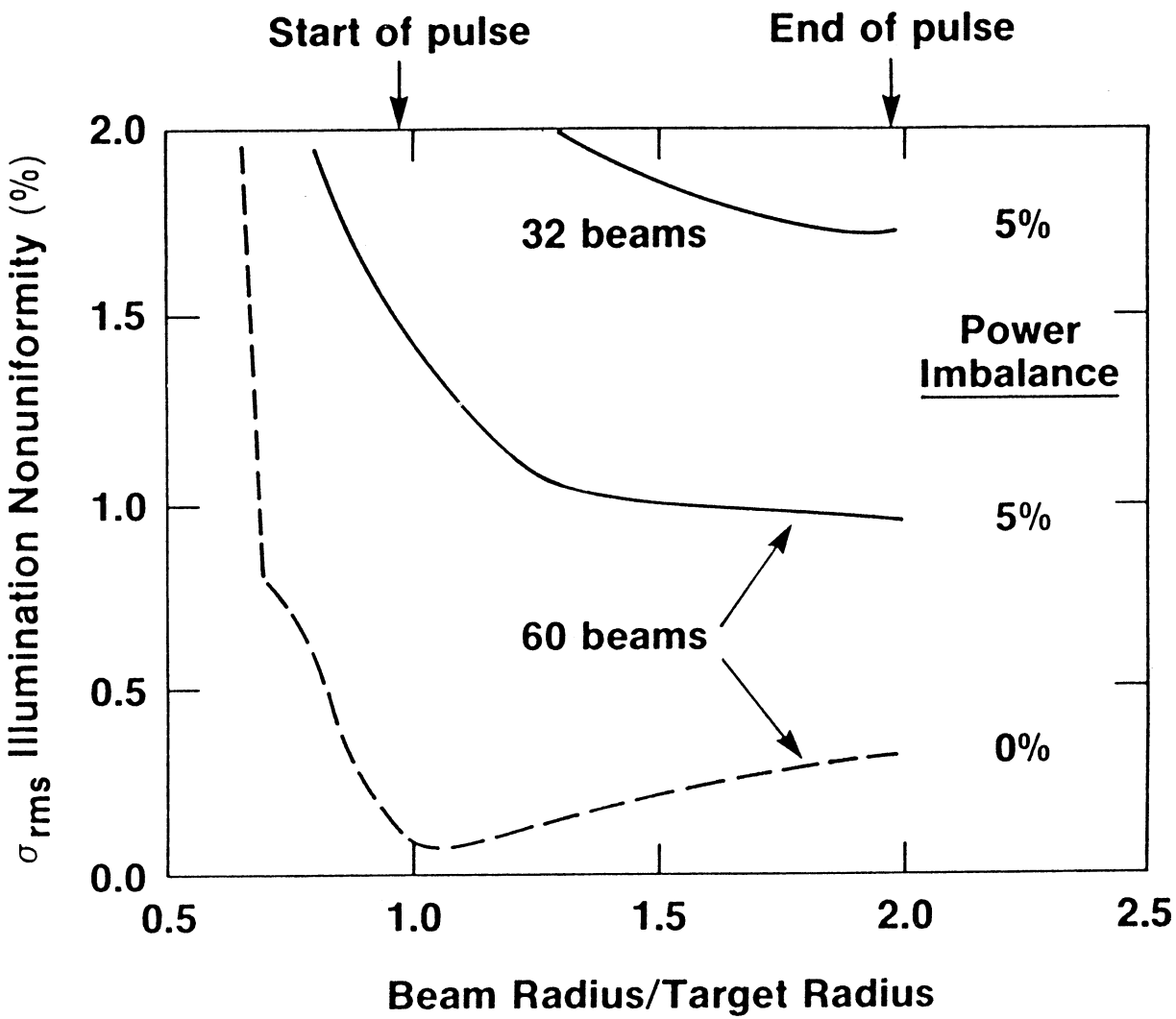
Figure 4.2

B.2 Power Balance and Beam Alignment

The effects of beam (power) imbalance and beam alignment on capsule performance results in temporally varying illumination nonuniformities with spectral magnitudes that vary with time. Analysis has shown that these illumination nonuniformities produce mainly low-order modes ($\ell < 6$). Two-dimensional simulations of designs representing the upper gain curve have shown that the $\ell \leq 6$ modes must have amplitudes less that 1-2% (rms). Using this requirement, an estimate of the power imbalance and beam alignment (mispointing) can be obtained. Figure 4.3 shows that a 60-beam system requires power balance which must be better than ~5% rms for 1% rms illumination nonuniformity for $1 \leq \ell \leq 6$. The amount of beam mispointing that can be tolerated is shown in Fig. 4.4. The rms nonuniformity is plotted as a function of the maximum beam mispointing, measured in terms of the target radius. The mispointing is chosen to be random in magnitude (up to the maximum indicated), and random in direction; the error bar indicates the spread in values that is obtained for different sets of pointing errors at a given maximum. For a 60-beam system, a random mispointing of 0.1 of the capsule radius will result in ~1.2% rms illumination nonuniformity. The calculations in Fig. 4.4 assume perfect power balance. The combined results of power imbalance and beam mispointing add in quadrature.

B.3 Capsule Positioning

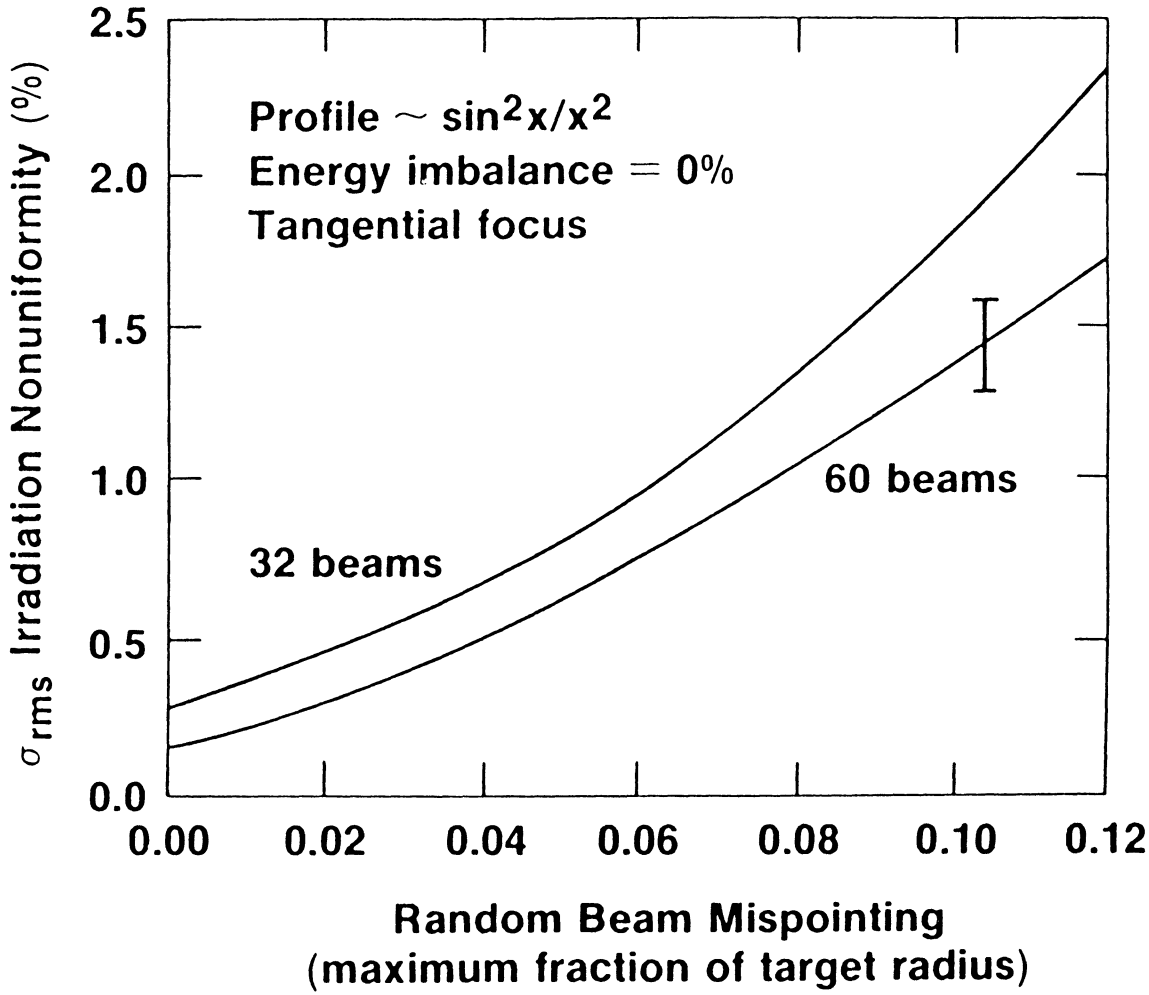
Uniformity calculations indicate that the capsule mispositioning with respect to the center of the chamber must be less than 0.1 of the capsule radius in order to maintain the nonuniformity below 1% rms. These calculations did not take into



(Assumes: profile ~ $\sin^2 x/x^2$; perfect beam balance)

TC2520

Figure 4.3



TC2521

Figure 4.4

account the time dependent effects on the capsule drive of the energy which misses the capsule due to its miscentering. This would depend on the particular capsule design and the pulse shape under consideration.

B.4 Individual Beam Uniformity

The required level of individual beam uniformity is still an area of active research. It is difficult to give a precise answer as to the requirements because capsule performance is affected by both the magnitude of the nonuniformity as well as the modal content of the resulting beam overlap pattern. Some form of beam smoothing technique will be required, and smoothing (or averaging) times will have to be as short as possible (tens of picoseconds). Therefore, since this study is limited to a KrF laser system, some form of ISI beam smoothing will have to be employed. As an estimate of the level of illumination uniformity required, initial calculations indicate that the asymptotic level of illumination nonuniformity will have to be < 1% rms and that the averaging times must be less than 10-20 ps.

V. TARGET REQUIREMENTS FOR INDIRECT-DRIVE IONS

A. Target Performance

Figure 5.1 gives target gain as a function of driver energy, ion range, and focal spot size for targets driven by two diametrically opposed beams or beam clusters. The peak power requirements for these targets are given in Fig. 5.2.

The curves in Figs. 5.1 and 5.2 should be considered the "base case." Concepts exist that should give gains about a factor of two higher. Thus the gain can be multiplied by a

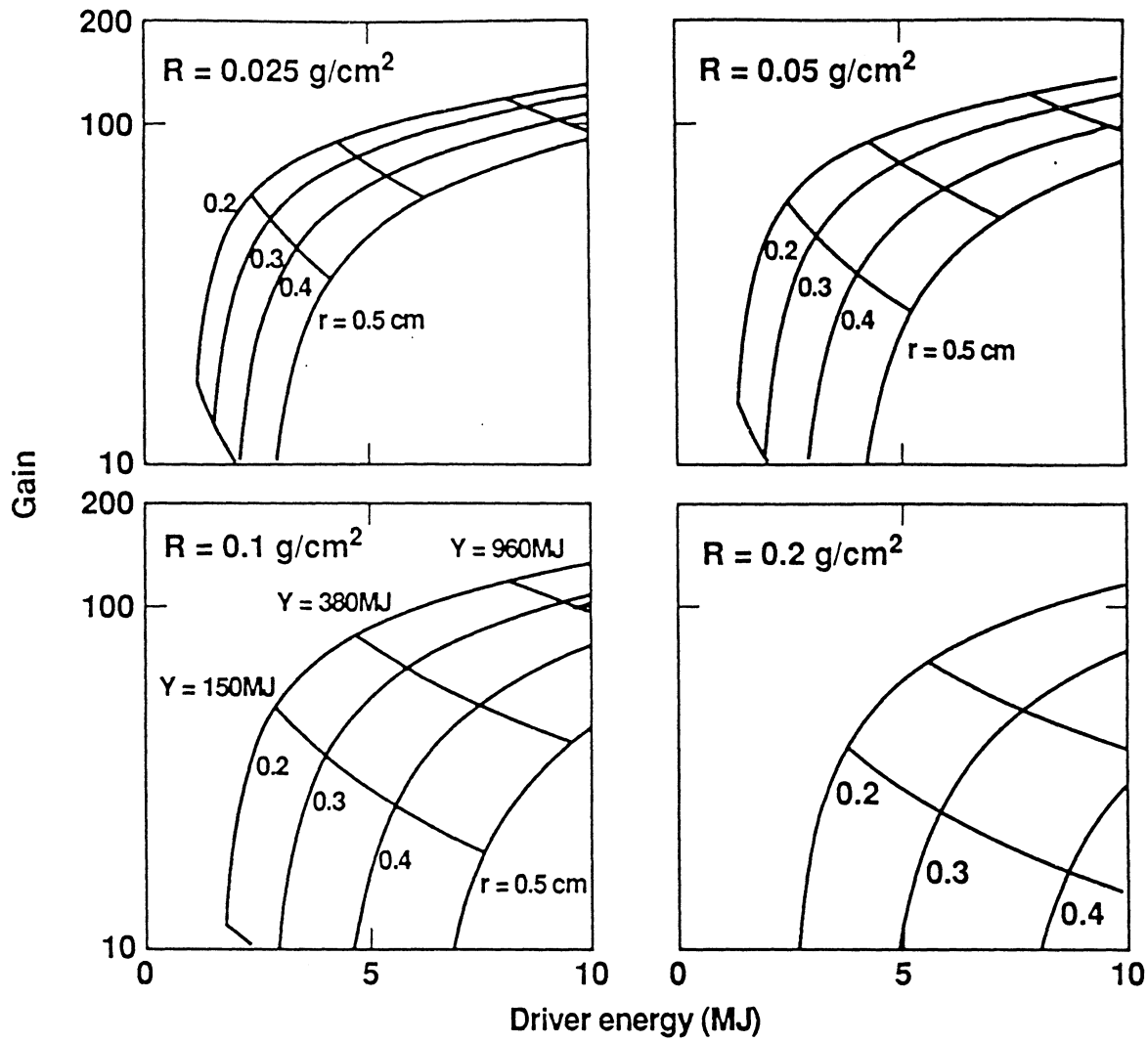

R = 0.025 g/cm2
R = 0.05 g/cm2
R = 0.1 g/cm2
R = 0.2 g/cm2
Y = 960MJ
Y = 380MJ
Y = 150MJ
0.2
0.3
0.4
r = 0.5 cm
Gain
200
100
10
0
5
10
Driver energy (MJ)

Figure 5.1

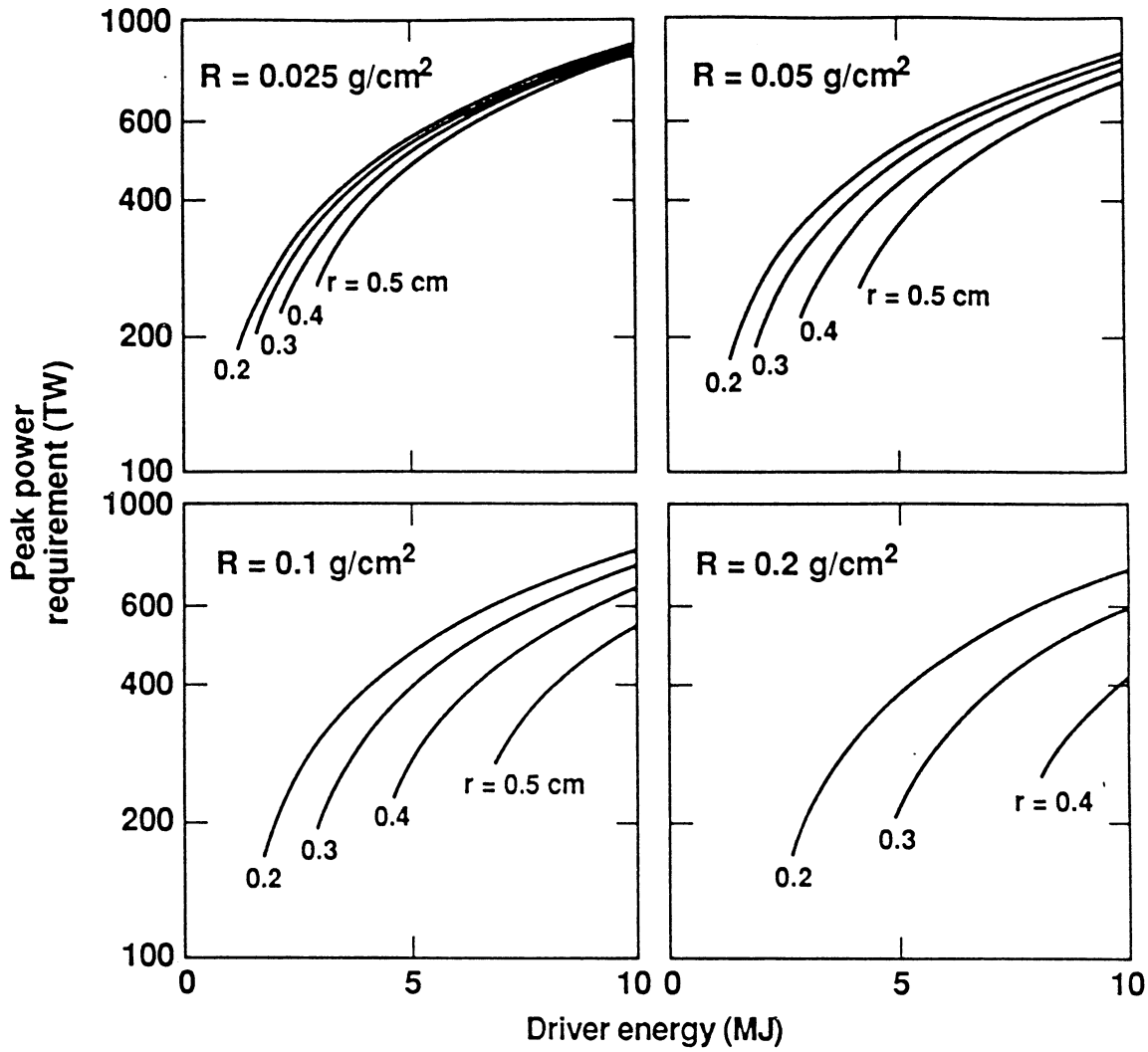

1000
600
400
200
100
R = 0.025 g/cm2
r = 0.5 cm
0.4
0.3
0.2
R = 0.05 g/cm2
r = 0.5 cm
0.4
0.3
0.2
R = 0.1 g/cm2
r = 0.5 cm
0.4
0.3
0.2
R = 0.2 g/cm2
r = 0.4
0.3
0.2
Peak power requirement (TW)
0
5
10
Driver energy (MJ)

Figure 5.2

factor of two to give a more speculative case; the power curves remain unchanged. For a lower limit, the gain should be multiplied by 0.7; the power curves again remain unchanged.

Ion range as a function of ion mass and kinetic energy is given in Fig. 5.3.

B. Pulse-Shape Precision, Power Balance and Beam Alignment

As noted in Sec. V.A, there is considerable flexibility in pulse shape; however, once a pulse shape is chosen, the power at any time during the pulse must be within 3% of its nominal value. This requirement must be met for both beam clusters.

The centroid of each beam or beam cluster must be aligned within 20% of the focal spot radius. If beam clusters are used and if the beam errors are statistically independent, each beam can clearly have looser tolerances than the tolerance on the entire cluster.

Misalignment and imperfections in the beams and lenses may lead to some fuziness in the beam radius. If the conditions on power balance and centroid alignment are satisfied, the effect of beam fuzziness can be estimated by using only that fraction of the beam energy that falls in the focal spot radius when using Figs. 5.1 and 5.2. Thus, within limits, there is a trade-off between target gain and beam alignment.

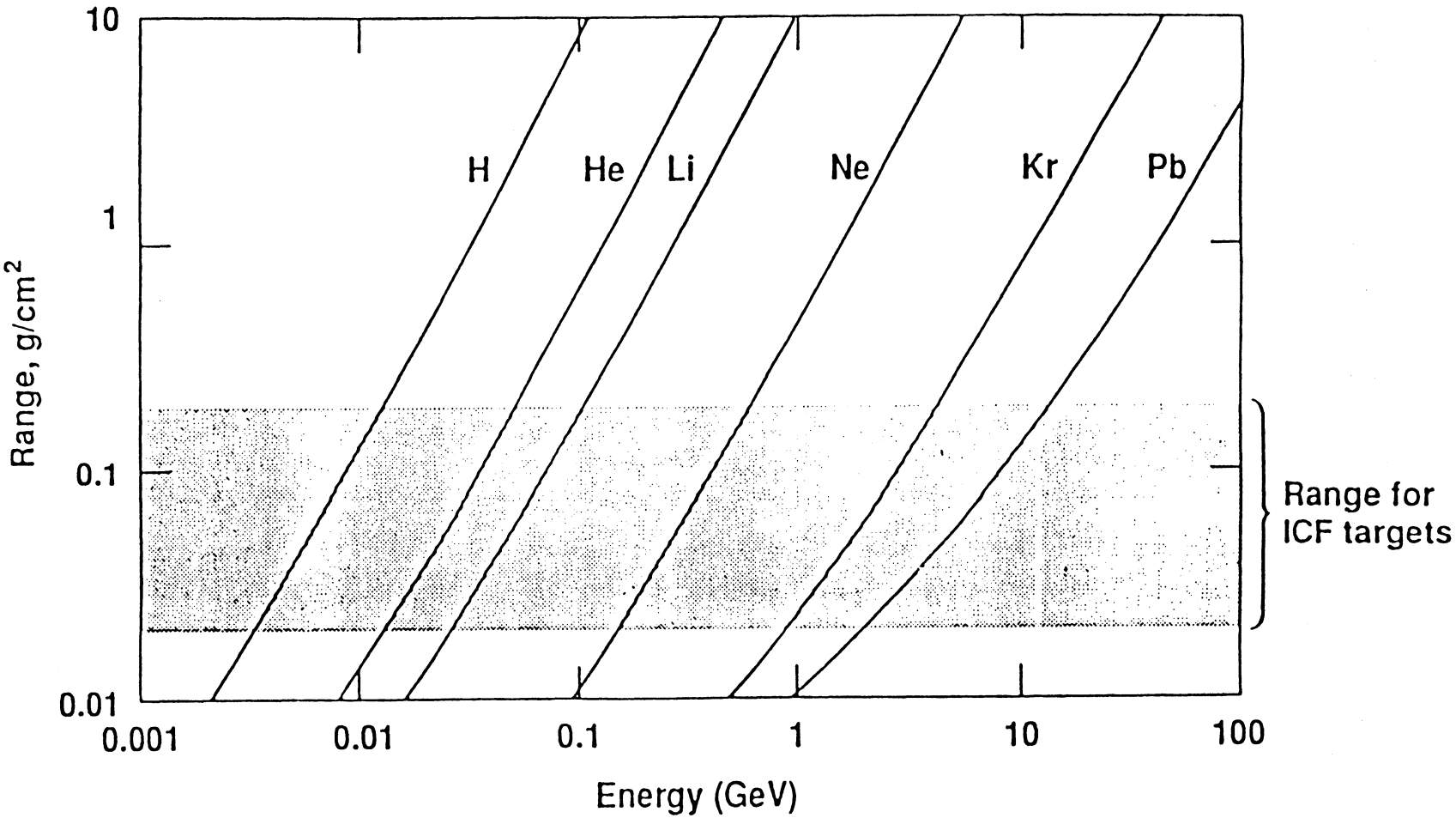

10
1
0.1
0.01
Range, g/cm²
0.001
0.01
0.1
1
10
100
Energy (GeV)
H
He
Li
Ne
Kr
Pb
Range for
ICF targets

Figure 5.3

FIGURE CAPTIONS

Figure 3.1 Study logic used by ARIES project.

Figure 4.1 Target gain versus incident KrF laser energy for directly driven single-shell capsule designs. The lower gain curve represents capsules which have been optimized with respect to reducing the effects of hydrodynamic unstable growth on capsule performance. The upper curve represents designs which would be considered optimistic with respect to capsule surface finish and illumination uniformity requirements.

Figure 4.2 Irradiation nonuniformity (σ rms) as a function of focus ratio for 24-, 32-, 60-, and 96-beam geometries, assuming a smooth $\sin^2 x/x^2$ radial beam profile.

Figure 4.3 Irradiation nonuniformity (σ rms) as a function of focus ratio for 32 and 60 beams, assuming a 5% rms power imbalance and smooth $\sin^2 x/x^2$ radial beam profiles. The dashed line is the reference σ rms for 0% rms power imbalance for the 60-beam system.

Figure 4.4 Effect of beam pointing error on irradiation nonuniformity for 32- and 60-beam system. A smooth $\sin^2 x/x^2$ radial beam profile is assumed.

Figure 5.1 Target gain as a function of driver energy, focal spot radius and ion range.

Figure 5.2 Peak beam power requirement as a function of driver energy, focal spot radius and ion range.

Figure 5.3 Ion range as a function of ion kinetic energy for a variety of ions.

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REVISED TARGET INFORMATION FOR ICF REACTOR STUDIES

This document is a supplement to Sections IV and V of Inertial Confinement Fusion Reactor Studies Recommended Guidelines, September 1990. In some cases the material given here replaces material given in the Guidelines and in some cases it provides additional information.

I. Summary of Target Gain and Driver Requirements for Short Wavelength Laser Driven Indirect Drive Targets

Target gain, using indirectly driven capsules for inertial fusion energy production, will be a function of a large number of variables, including laser geometry, focusability, pointing accuracy, wavelength and possibly beam smoothness and bandwidth, as well as target performance determined by such effects as hydrodynamic instabilities and plasma physics effects in hohlraums. Most of these effects are coupled and a system optimization must be carried out to determine the best set of operating conditions. Since most of the target physics is classified, many of the choices which go into any particular set of gain curves must remain classified. Figure 1 shows two gain curves which we believe span the range of target gains likely to be achievable using standard capsule and hohlraum designs. The lower curve is based on detailed target design studies carried out for the Department of energy Defense Programs LMF (Laboratory Microfusion Facility). This gain curve is consistent with an extrapolation to the megajoule scale of all current data. This curve represents our best estimate of the gain which would be achieved in a first of a kind experimental high gain facility. The higher gain of the upper curve results from an increased coupling efficiency which we believe can be achieved after optimization of both the laser-plasma interaction effects and the target geometry. Advanced target designs could have gains of about a factor of two higher than the upper curve. These designs have increased physics uncertainties and have been less thoroughly analyzed than our baseline designs; however, for these studies the enhanced performance curve should be used as the base case. The LMF baseline

curve is the conservative case. The enhanced performance curve should be multiplied by 2 to give the more optimistic case called for in the Guidelines; however, the optimistic case should not be used for laser energies less than 2.5 MJ. Figure 2 shows the peak power requirements for the two gain curves in Figure 1. The power curve for enhanced hohlraum performance may be used for the optimistic case. About 70% of the total energy is delivered during the peak power part of the pulse. The rest is delivered in a pulse shape which is 4-5 times the duration of the peak power pulse.

In order for the laser energy to be efficiently utilized, it is necessary that the laser beam be capable of achieving a spot size which is near diffraction limited. It is also important that the pointing errors be limited to a few microradians. A convenient way of stating these requirements is to specify a focal spot within which the laser energy can be delivered. Both gain curves in Figure 1 assume that all of the useful energy of each beam can be delivered into a 1.5 mm diameter spot. This spot size includes both the size of the focal spot and any pointing errors. At best, all energy outside this spot will not be useful in driving an implosion. In a worst case scenario, this energy could adversely affect an implosion if it exceeds a few percent of the total energy. In addition, both curves assume a laser geometry similar to that being planned for Nova Upgrade. The Nova Upgrade laser plan calls for 288 independently pointed beams. This large number of beams is distributed in three or four rings of beams on each side of the target at angles distributed between about 30 and 60 degrees from the target axis. The large number of beams allows great flexibility for achieving irradiation uniformity at the capsule. It also relaxes the instantaneous power and energy balance requirements and allows an RMS variation of 10% or more. It should ultimately be possible to reduce the number of beams to a total ranging between 20 and 50. With a smaller number of beams, the power balance must be better than about 5% and the gain may be lower. For these studies we recommend a minimum of 50 beams.

II. Direct Drive Laser Targets

The gain curves for directly driven targets have been modified. Figures 3 and 4 give the curves that should now be used. The curves in Figure 3 assume that the laser focal spot radius is constant in time. Because detailed target designs are not yet available for this study, assume the well known hydrodynamic scaling laws to get focal spot radius, i.e. assume the radius scales as $E_L^{1/3}$ where E_L is laser energy. Use a radius of 2.8 mm at 4 MJ to get the coefficient. Similarly assume that peak power scales as $E_L^{2/3}$. Use a peak power of 500 TW at 4 MJ to get the coefficient. For all other details the original Guidelines remain valid. The curves in Figure 4 assume that the focal spot radius is "zoomed" so that the focal spot radius remains equal to the critical surface throughout the implosion. If the contractors wish to consider zooming, additional details will be provided. In Figures 3 and 4 the lower curve is the conservative case, the upper curve is the optimistic case and the base case is the arithmetic mean.

Researchers at the Naval Research Laboratory (NRL) have proposed a potential direct-drive gain curve (Fig. 5), obtained from scaling published indirect-drive gain results, which would require zooming and the use of capsules containing high Z dopants in the ablator to reduce the number of e-foldings the capsule would experience during the acceleration phase. In addition, in order to achieve high hydrodynamic efficiency and reduce the required laser intensity, NRL designs are assuming larger initial aspect ratio capsules when compared to the Laboratory for Laser Energetics (LLE) designs (Figures 3 and 4). NRL estimates indicate that if the average number of e-foldings experienced by the capsule during the acceleration phase could be reduced to <5, the capsules would survive the acceleration phase without rupturing the over dense imploding shell. As of this date there are no NRL point designs to show that the reductions in growth and the high gain shown in Figure 5 can be achieved simultaneously.

Energetically a simple Meyer-ter-Vehn type of model shows that it is possible to achieve gain levels similar to that shown in Figure 5. In

general, the difference between the LLE gain curves and the NRL proposed gain curve is in the level of optimism associated with the physics of Rayleigh-Taylor unstable hydrodynamics and deleterious plasma physics effects. Based on our present theoretical understanding, the LLE gain curves represent a more conservative view associated with capsule performance than the proposed NRL gain curve with respect to hydrodynamic stability issues.

Considering the present lack of experimental data to verify the theoretical understanding associated with direct-drive Rayleigh-Taylor unstable hydrodynamics and plasma physics issues relevant to high gain capsules, it is difficult to assign a level of risk associated with each laboratory's gain curves. It is certainly the goal of each laboratory's effort to obtain as high a gain as possible at a given incident laser energy while maintaining some finite probability that the implosion would work. Theoretical and experimental research will continue to be applied to resolving the issues associated with the uncertainty in capsule performance due to unstable hydrodynamics and potential plasma physics issues over the coming years.

Due to the present lack of any point designs associated with the proposed NRL gain curve, it is proposed that the contractors use the LLE provided gain curves in their initial analysis. If the LLE gains result in economically feasible power plant designs achieving higher gains, as implied by the NRL proposed curve, based on new capsule design work will only make the problem easier. If the gains from the LLE results prove to be too low, it is then proposed that the contractors use the results from the NRL proposed gain curve to do their analysis. If the NRL gain curve is used, appropriate caveats associated with the fact that no point designs currently exist, which numerically show that such gains can be achieved while maintaining good hydrodynamic stability, should be included.

III. Heavy Ion Target Gain

The curves in the original guidelines remain unchanged; however, the optimistic case (2 times the base case) should not be used at driver energies below the "knee" in the base-case curves. The knee occurs at a target yield of about 200 MJ in the curves of Figure 5.1 in the Guidelines. Therefore, the curves in Figure 5.1 may be multiplied by 2 only if the yield exceeds 200 MJ (400 MJ after multiplication).

Directly driven gain curves are becoming available. The calculations give gains in excess of 100 at about 1 MJ; however, directly driven ion targets have illumination requirements similar to directly driven laser targets. If the contractors wish to use direct drive for ions, we may be able to have detailed information in about a year.

The Target Working Group has considered the case of single-sided illumination for ions. Current calculations indicate that the gain is comparable to the gain for two-sided illumination. Therefore, the contractors may use the curves in the guidelines for single-sided illumination; however, single-sided illumination is still sufficiently speculative that the contractors should continue to carry a two-sided option, even if they wish to evaluate the single-sided option.

IV. Target Costing and Output

No new target designs are currently available for these studies. Therefore, for target cost estimates, the contractors should use the target shown in The University of Rochester Laboratory for Laser Energetics, Annual Report, 1 October 1984-30 September 1985, DOE/DP/4020-05, January 1986, p. 126. CH_2 is not a particularly good structural material. The contractors should use CH instead.

For target output information, HIFSA used R.O. Bangerter, J. W-K., Mark, and G. Magelssen, "Simple Target Models for Ion Beam Fusion Systems Analysis," UCID-20578, Lawrence Livermore National

Laboratory (1985). The contractors should also refer to Charles D. Orth, "Improved Understanding of First-Wall Vaporization-Condensation in Inertial Confinement Fusion Reactors," UCRL-93899, Rev. 1, Lawrence Livermore National Laboratory (1986) and to the Sirius reports. If these three unclassified sources do not contain enough information, the contractors may have to calculate their own spectra.

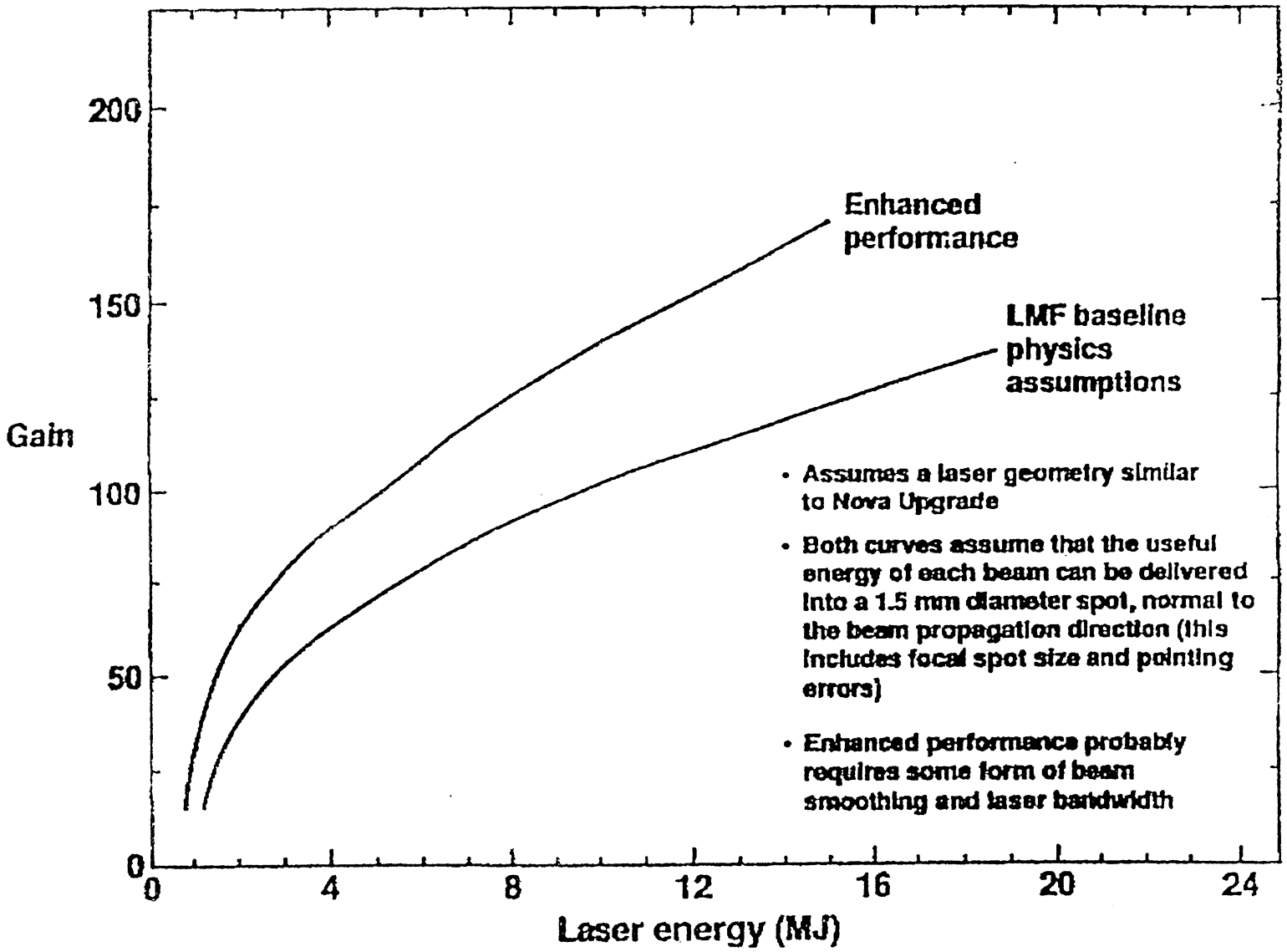

Figure 1. Gain as a function of laser energy for indirectly driven targets.

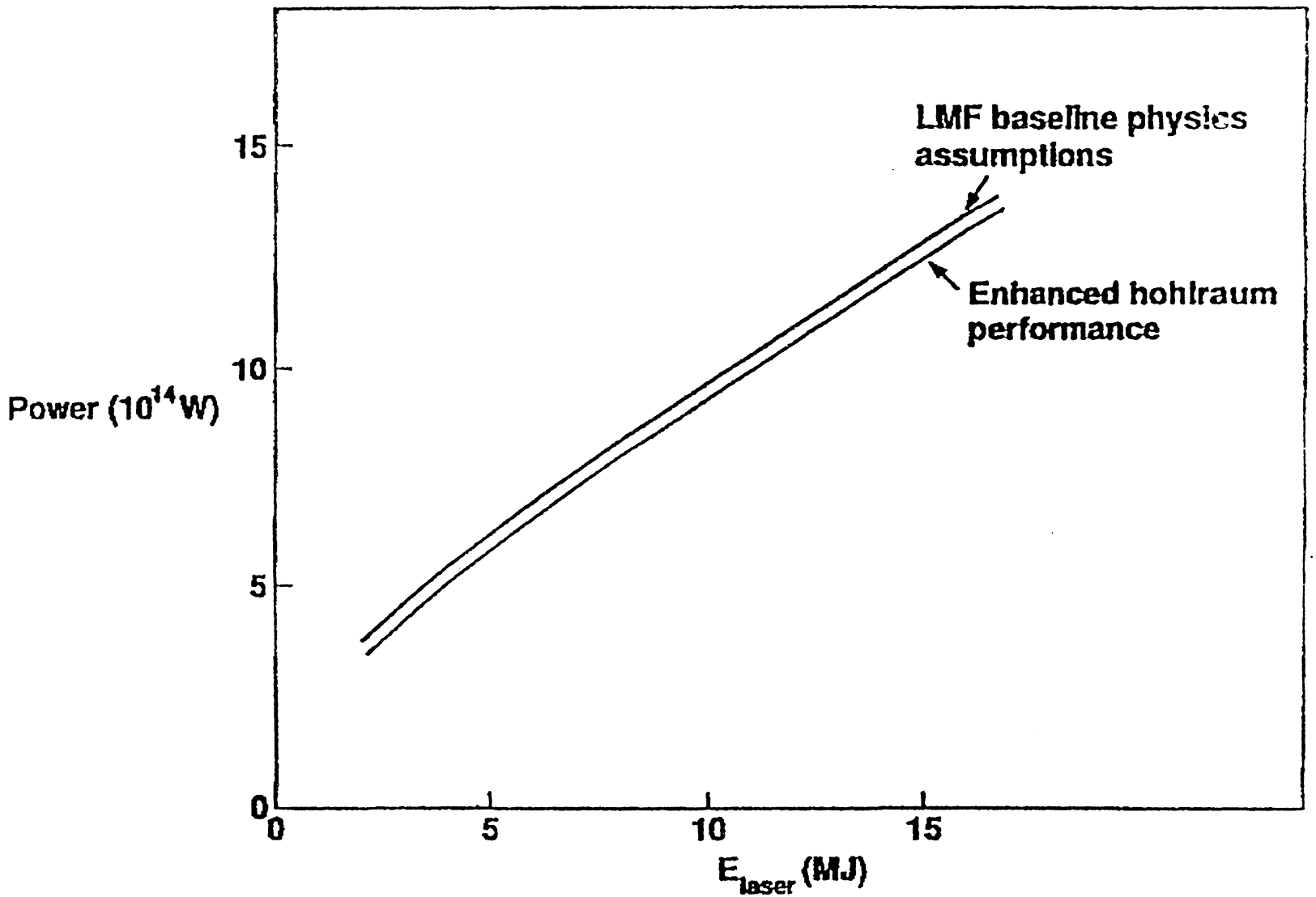

Figure 2. Power as a function of laser energy for indirectly driven targets.

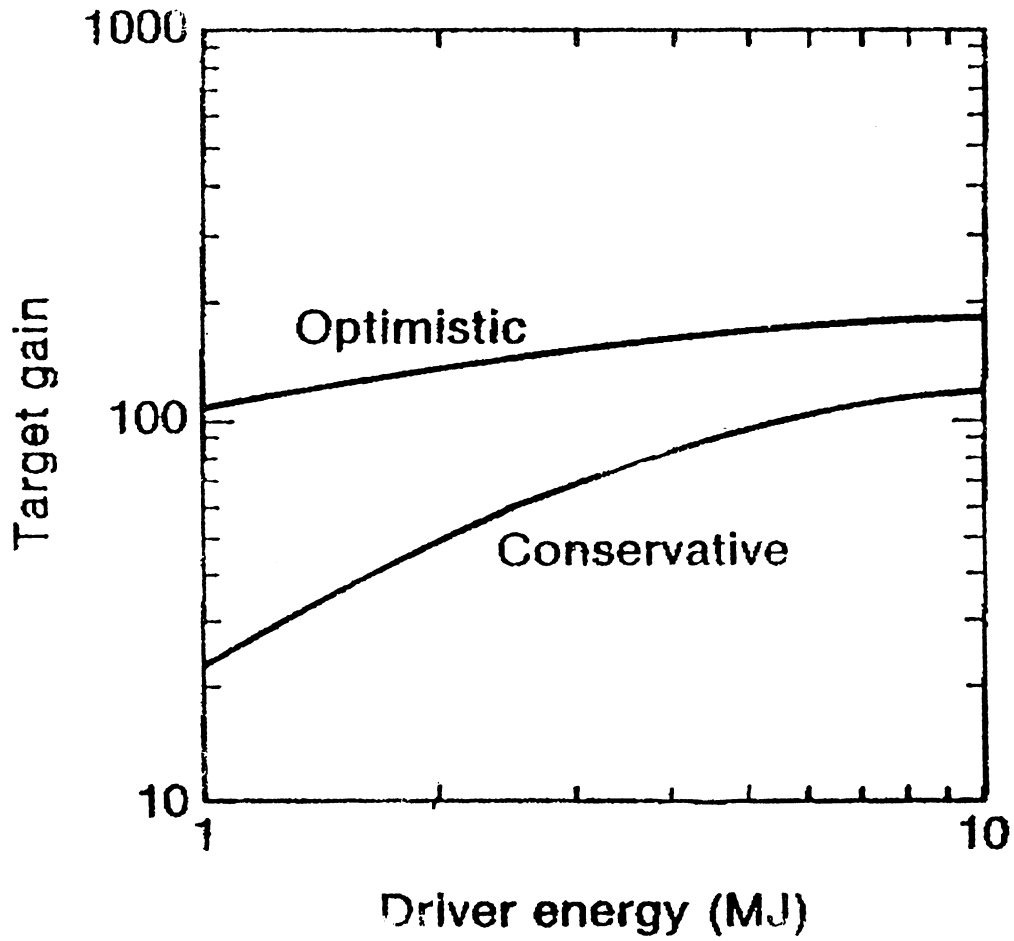

Figure 3. Gain as a function of energy for directly driven laser targets.

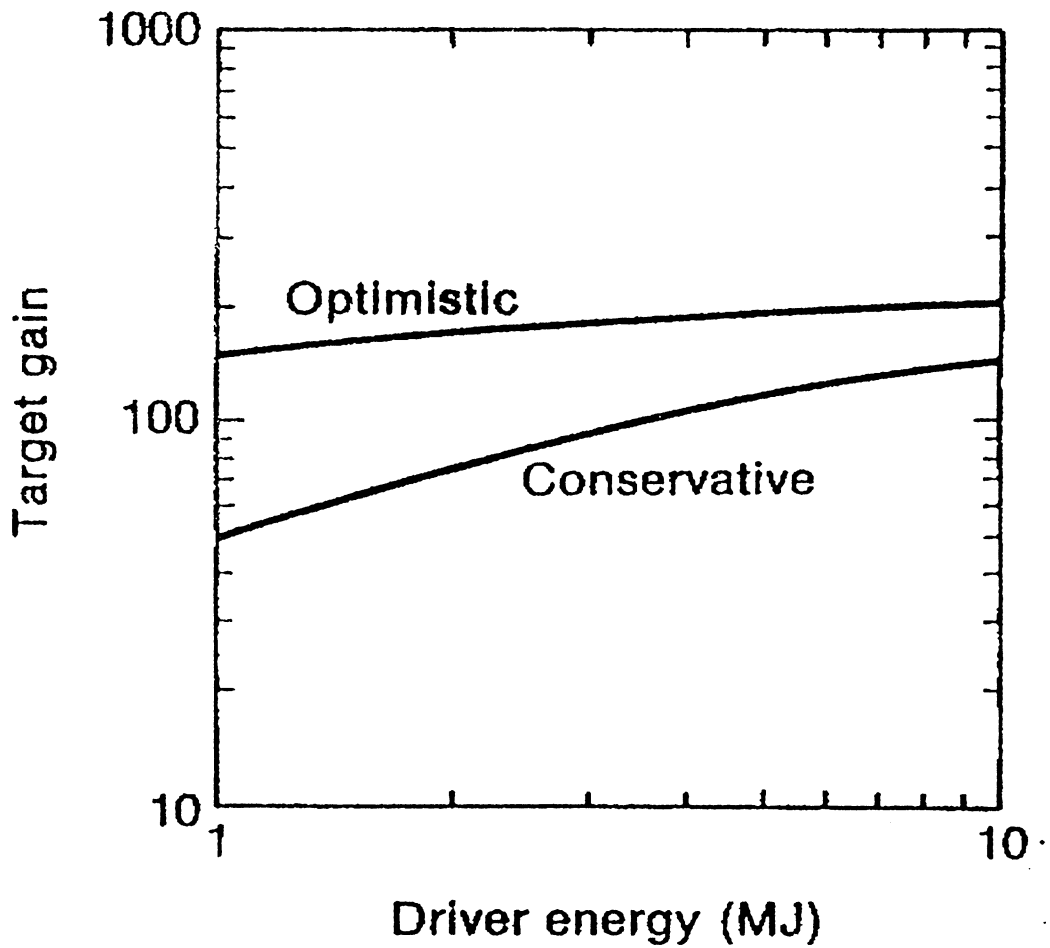

Figure 4. Gain as a function of energy for directly driven laser targets. These curves assume zooming.

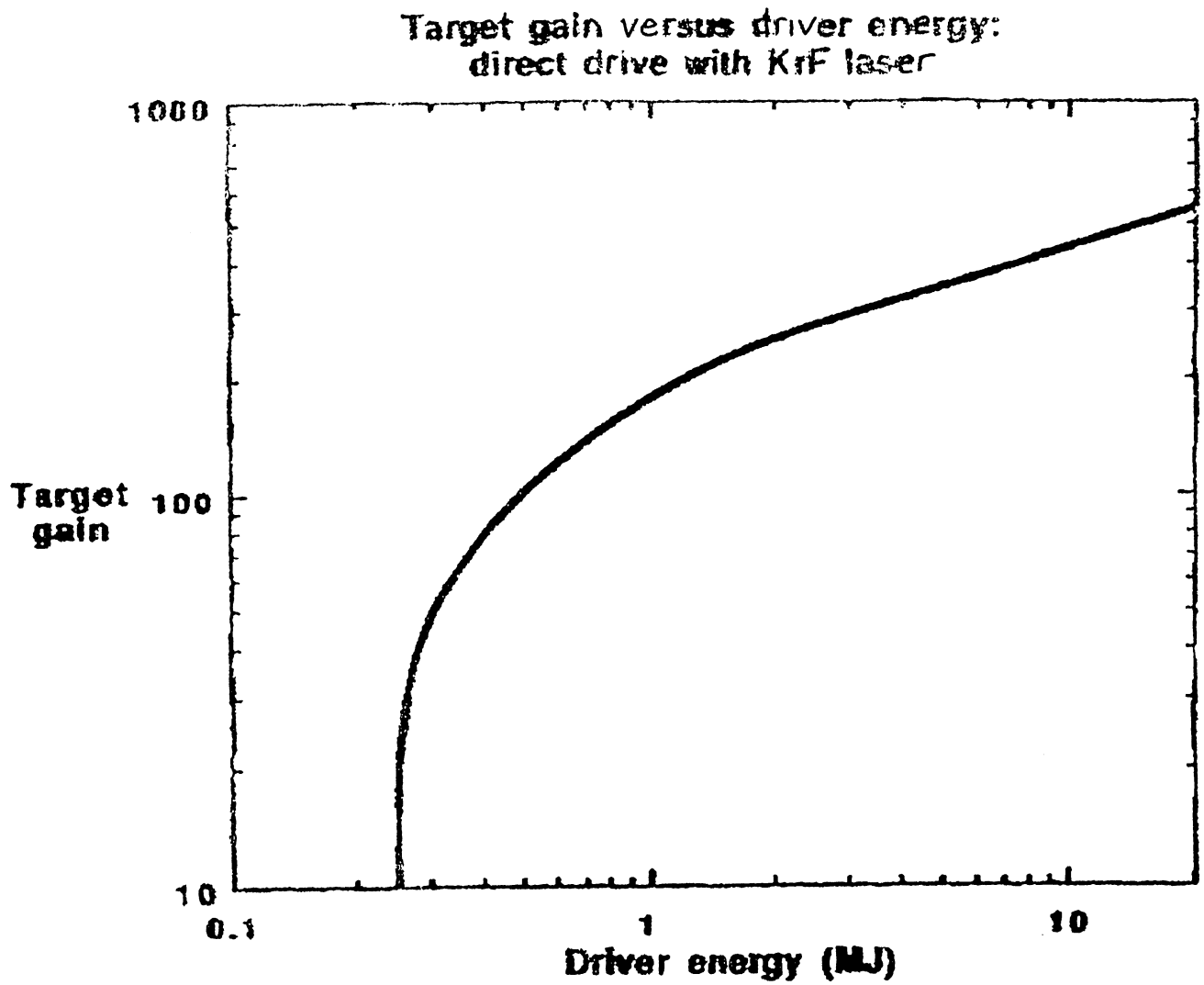

Figure 5 NRL gain curve for directly driven laser targets.