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TITLE: OVERVIEW OF U.S. HEAVY-ION FUSION COMMERCIAL ELECTRIC POWER SYSTEMS ASSESSMENT PROJECT

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OVERVIEW OF U.S. HEAVY-ION FUSION COMMERCIAL ELECTRIC POWER SYSTEMS ASSESSMENT PROJECT

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ABSTRACT

The U.S. heavy-ion fusion (HIF) research program is oriented toward development of multiple-beam induction linacs. Over the last two years an assessment has been performed of the potential of HIF as a competitive commercial electric power source. This assessment involved several technology performance and cost issues (e.g., final beam transport system, target manufacturing, beam stability in reactor cavity environments, and reactor cavity clearing), as well as overall power plant systems integration and tradeoff studies. Results from parametric analyses using a systems code developed in the project show cost of electricity (COE) values comparable with COEs from other magnetic fusion and inertial confinement fusion (ICF) plant studies; viz, 50-60 mills/kWh (1985 dollars) for 1-GWe plants. Also, significant COE insensitivity to major accelerator, target, and reactor parameters was demonstrated.

1. THE HIFSA PROJECT

The Heavy-Ion Fusion Systems Assessment (HIFSA) is a study of the prospects for successful commercial heavy-ion fusion electric power generation using induction linear accelerator (linac) drivers. Led by Los Alamos National Laboratory (LANL), the project team also included Lawrence Livermore National Laboratory (LLNL), Lawrence Berkeley Laboratory (LBL), Stanford Linear Accelerator Center (SLAC), the University of Wisconsin (UW), and McDonnell Douglas Astronautics Co. (MDAC). Funding for the project has been provided by the US Department of Energy (USDOE) and the Electric Power Research Institute (EPRI). The HIFSA project is guided by an advisory board drawn from several of the organizations listed above.

Many of the existing ICF reactor and balance-of-plant (BOP) concepts developed for laser fusion apparently require only minor modifications for HIF. There are also a few reactor concepts developed specifically for HIF. Much effort has been devoted to development of these concepts over the past decade. These considerations led to concentration of limited HIFSA project resources on:

o innovations and cost/performance modeling for HIF target, accelerator, and final beam transport concepts; and

O an HIF commercial power plant systems code to identify key cost/performance issues, explore significant tradeoffs, quantify parameter sensitivities, and search for global optima.

The principal figure of merit used in the HIFSA studies to characterize commercial HIF power plants is unit cost of electricity. The total capital cost, which largely determines COE in capital-intensive HIF power plants and thus is a measure of the difficulty of financing the construction of an HIF plant, is an important secondary HIFSA figure of merit.

The HIFSA project is only about two years old and is a small part of the US HIF program, which is largely devoted at present to accelerator R&D. However, much of the work on targets, reactors, and other systems in both US and and non-US laser and light-ion fusion programs is directly applicable to HIF. Although the HIFSA project is small compared to other fusion programs, the results of the HIFSA studies are expected to play a vital role in providing guidance for HIF program planning through identification of promising commercial plant subsystem concepts and operating parameter space.

Perhaps the best prior overall design studies of commercial HIF are the HIBALL studies [1,2]. During the HIBALL studies, a technically credible commercial HIF power plant scenario with competitive projected COE was developed. The results of the HIBALL study, while not entirely satisfactory because of the plant scale (4000 MWe) required for competitive COE, are widely viewed as having established the technical feasibility of commercial HIF, provided high-gain targets and affordable target mass production methods are also demonstrated. In particular, the HIBALL radio-frequency (rf) driver appears to require little new fundamental technology. Of course, considerable development will be required to qualify reliable, affordable commercial systems. Also, some details of accelerator design, beam merging, final focus, etc., may be different than presently envisoned.

Once technical feasibility is established and economic promise is indicated, support for the R&D required to realize the potential of HIF must be provided. HIF is faced with the same cruel dilemma confronting all of fusion in the US today -- several factors have diminished, at least for the present, the interest of government, the public, and public utilities in long-range new energy technologies. These include: (1) intense competition for federal R&D funding; (2) perceptions of fusion as too difficult, too far in the future, too big, and too expensive; (3) the cost of the next generation of R&D facilities; (4) the problems of fission; and (5) temporary easing of the energy "crisis."

Past and present US HIF Program R&D funding levels have been adequate for investigating beam transport and accelerator physics and design issues theoretically, with some small supporting experiments. The present level of funding is not adequate for extending the experiments for examination of the parameter space for commercial applications of HIF or for engineering and constructing large prototype accelerator components.

For ICF the short-term answer to the funding dilemma is the development of less-costly concepts for the next generation of R&D facilities. For the longer term, the attractiveness of ICF with respect to cost, reliability, and safety must be even more firmly established. To enhance the attractiveness of HIF relative to other approaches to ICF:

- O accelerator capital cost, which is still the largest contributor to COE for an HIF power plant, must be reduced;
- O commercial plant scale for competitive COE must be reduced below the 4000-MWe level of the HIBALL studies; and
- O the projected efficiency and reliability advantages of heavy-accelerators over other drivers should be verified.

2. HIFSA ACCELERATOR STUDIES

2.1. Heavy-Ion Induction Linac Technology

The proposed technology for commercial-applications heavy-ion induction linacs is an extension of well-established electron induction linac technology developed at LBL, SLAC, and elsewhere. High repetition rates, high current transport, and operational reliability have been demonstrated for electron induction linacs. HIF induction linac design is complicated by non-relativistic particle velocities that change significantly throughout the acceleration of the ions. The accelerator comprises a high-brightness ion source, a high-current injector, a low-energy accelerating section, a main induction accelerating section, and a final pulse compression section. The main accelerating section is the most costly, with the cost of the other sections about one-fourth of the total. In the proposed concept, multiple beamlets are accelerated by common induction cores, allowing a larger total current to be transported within a single accelerating structure.

The ion source may be either a conventional, albeit large-pulse, multiple-beamlet source with electrostatic focusing or an advanced metal vapor source of the type developed and tested at LBL during the period of the HIFSA study. These new metal-vapor sources can provide intense beams of multiply charged ions, with high selectivity in some cases. The injector and low-energy section of the accelerator match the ion source to the main induction accelerator section through the use of pulsed drift tubes.

The main accelerator section includes a series of induction cores that operate at a fixed voltage step per module and are driven by pulsers whose pulse duration decreases as ion velocity increases. In simple terms, the ion beam acts as one side of a transformer with a single turn and the induction cores as many turns on the other side. The pulse length varies from a few microseconds to about 100 ns and the design of the induction cores and pulsers must vary from one end to the other of the main accelerator section. The inductor core material may be ferritic steel, iron, or metallic glass (metglas), with the optimum selection based on considerations of module performance and cost. Rapidly decreasing metglas costs have made cost-effective the use of this material for induction linacs. The shape of the voltage pulse applied at each acceleration step is approximately trapezoidal with a slight voltage "tilt" that applies a longitudinal compressive force to the ion pulse.

At the high-energy end of the main accelerator section, a final "kick" must be given to the back end of the ion pulses so that they will be compressed during final transport to the target. The ion pulse energies exiting the main acclerator section are typically 5 to 15 GeV, with pulse lengths of 60 to 100 ns decreasing to approximately 10 ns at the target. The compression section consists of induction modules that provide the appropriate voltage pulse profile to compress the ion pulse.

More details of the induction linac technology studied during the HIFSA project are published elsewhere [3]. Estimated costs and performance over wide ranges are also given.

2.2. Accelerator R&D Issues

For purposes of the HIFSA study, principal accelerator design parameter values were allowed to vary over ranges believed reasonable and achievable. The systems integration code described below was used to create a database that was then searched for optima. These parameters (and ranges) included pulse energy (1 to 10 MJ), ion species (130 to 210 amu), number of beamlets in the accelerator (4 to 16), and output emittance (15 to 30 microrad-m). Other accelerator design parameters were fixed at values regarded as near optimum or reasonable. For example, undepressed tune (the phase angle between a single ion passing through an inductor and the accelerating electromagnetic wave) was set at 60° and depressed tune (phase angle for a large ion pulse as determined by collective space-charge effects) at 8°. In effect, the greater the tune depression with stable transport, the greater the current that is being stably accelerated. In the past, theoretical analyses indicated that a depressed tune angle of 24° was the minimum that could be expected with stable transport. Experiments conducted at LBL during the period of the HIFSA project demonstrated stable transport at a depressed tune of 3°. Improvements to the theoretical analysis gave agreement between theory and experiment. The suggestion has been made that beginning with larger undepressed tune angles, perhaps 85°, could permit even higher tune-angle depressions and acceleration of even greater charge in a single beam line. This topic has been identified as an R&D need that should be assigned modest priority.

Examination of cost/benefit for different ion charge states, particularly the intermediate +2 state and higher charge states up to at least +4, with medium priority is indicated because, as is discussed in the section on integrated-plant studies, a change from +1 to +3 significantly reduces accelerator capital cost and COE. The principal reason is that +3-charge ions can be accelerated to the same energy in roughly one third the length of main accelerator required with +1-charge ions if the voltage increment per accelerator module is the same.

The practicality of acceleration of higher charge states, previously thought to involve severe limitations on the current that could be stably transported, has been demonstrated in recent experiments. However, the vacuum requirements in reaction chambers for focusing and transport may be more stringent and an examination of this question with medium priority is indicated.

Adequate higher-charge-state ion sources are also necessary if higher-charge-state commercial HIF induction linac drivers are to be practical. Requirements include a large fraction of ions generated with the desired charge and low emittance. Therefore, if higher-charge-state HIF is to be pursued, then development of suitable sources must be accorded high priority.

Although HIF could be made to work without beam neutralization, the cost/performance benefits of neutralization for focusing and final transport are very large. Neutralization becomes even more important if higher ion charge states are used. For the HIFSA studies, neutralization sufficient to obtain the anticipated benefits at negligible additional cost was assumed. Because of the importance of this issue, R&D to develop and demonstrate cost-effective charge neutralization is assigned highest priority.

Estimated COE for commercial HIF power plants does not seem to be very sensitive to ion mass over the broad range 130 to 210 amu for fixed ion charge state. It would be interesting to extend the range of ion masses studied to lower values to establish the practical limits. More important, ions with charge +1 and of mass much lower than the lower end of the range examined in the HIFSA study may meet target requirements nearly as well as 210-amu ions with +3 charge. The difference can be compensated for by small improvements in accelerator beam emittance. For low ion masses, beam neutralization is crucial for cost-effective final beam transport and focusing. If cost benefits similar to those estimated for going from +1 charge to +3 charge with 210-amu ions can also be achieved by going to +1-charge, 70-amu ions, problems that might arise in developing higher-charge-state ion sources could be avoided. High priority for experiments and analysis of this alternative is recommended.

The optimum number of beamlets varies with position in the accelerator as ion energy changes. Development of low-cost methods for splitting and combining beamlets with small beam energy losses could permit modest reductions in accelerator cost. The HIFSA project team concluded that development of better understanding of beam transport and bending through simulation and experiment is required with medium priority. The team members are also of the opinion that substantial additional cost reductions and performance imporvements for inductor cores, pulsers, and insulators are possible and recommend further R&D in these areas with high priority.

In multipulsing, two or more ion pulses are accelerated through the linac close together in time, with the interval determined by the time required to reset the induction cores. The pulses are simultaneously delivered to the target along beam-transport lines of different lengths. The potential modest benefit is accelerator cost savings due to halving of the current that the linac is required to accelerate plus potential improvements in efficiency as a result of higher duty factors. Offsetting these benefits in part are increased cost for additional beam transport line length and some loss in efficiency resulting from the requirement for fast reset of the induction cores. With two-sided or more symmetric target illumination, the additional beam transport line length required for double-pulsing is not very great.

In multipassing, the same ion pulse is passed through the main accelerator more than once to achieve the final ion energy. The savings in accelerator cost due to reduction in length seem potentially larger than those resulting from reduction in current for multipulsing. Higher duty factors can help efficiency. Efficiency loss resulting from the requirement for fast reset of the induction cores and the cost of extra beam-transport-line length will offset some of the potential gain. In addition, pulsing circuits for each inductor must be designed to accelerate ions at different energies in successive passes. Higher cost and/or reduced efficiency may be associated with these increased requirements. On the other hand, length scaling of accelerator is expected to more favorable than current scaling. A thorough assessment of this design option requires resources greater than those available for the HIFSA project.

3. HIFSA REACTOR/BALANCE OF PLANT (BOP) STUDIES

Only adaptation of a few existing laser fusion concepts with which HIFSA team members have substantial experience was considered. For lack of effective advocates on the HIFSA team, other promising concepts [1,2,4-6] developed for laser fusion and/or specifically for HIF were not included in the HIFSA studies. A combination of concepts providing a wide range of reactor repetition rates, capable of accomodating a wide range of target yield, and compatible with both conventional steam cycles and advanced power generation was desired to permit thorough exploration of the attractive characteristics of heavy-ion induction linac drivers -- high pulse repetition rates at little additional cost and high efficiency.

HIFSA reactor/BOP studies focused on:

- identification and quantification of additional design requirements for HIF, areas where HIF requirements are less constraining, and required interfaces between HIF reactors and drivers, fuel cycle, and BOP;

- identification and quantitative exploration of significant tradeoffs between reactor and driver, fuel cycle, and BOP design requirements and desirable features; and

- formulation of cost/performance models suitable for incorporation in the commercial HIF power plant systems code.

All reactor plant and BOP tructures, interfaces, and equipment were treated.

Four classes of ICF reactor plant/BOP concepts were selected for the HIFSA studies: (1) a granular-wall concept (a variant of the LLNL CASCADE concept [7]); (2) a liquid-metal-jet concept (a variant of the LLNL HYLIFE concept [8]); (3) a wetted-wall concept (a variant of the LANL wetted-wall concept [9]); and (4) a magnetically protected dry-wall concept (a variant of the LANL magnetically protected concept [10]).

The first of these includes first-wall protection by a thick bed of solid particles in a rotating vessel for structure protection from all target emissions, a high-temperature, high-efficiency (55%) Brayton cycle, minimal containment, a pulse repetition rate up to 10 Hz, and two-sided target illumination. The second concept uses a thick array of liquid-metal jets to protect reactor structure from all target emissions, a conventional steam cycle, and conventional containment and is limited to about 2 Hz and few-sided illumination. The third reactor-plant/BOP concept employs thin liquid-metal films injected tangentially at high speed onto inexpensive, easily replaced curved reactor cavity walls to protect from target x rays and debris ions and allow separation of reaction chamber and blanket functions, a conventional steam cycle, and conventional containment. It provides up to 10-Hz repetition rates and few-sided through semi-symmetric illumination. The last concept involves a very large dry-wall reaction chamber with diversion of target-debris ions away from exposed surface through direct-conversion systems for higher efficiency and removal, a conventional steam cycle for blanket energy conversion, and conventional containment to provide repetition rates up to 20 Hz, allow symmetric target illumination, and low neutron damage rates.

The HIFSA reactor-plant/BOP studies were not intended to be a final contest between concepts. The concepts studied involve different degrees of optimism. The differing degrees of optimism were retained to permit exploration of the potential benefits and/or penalties. To a large extent, differences in state of development of the concepts were ignored.

4. HIFSA FINAL BEAM TRANSPORT ANALYSIS AND MODELING

4.1. Introduction

The technological requirements for transport of heavy-ion beams from final focusing magnets to targets in HIF reactor cavities have been analyzed as part of the HIFSA project. Excessive disruption of focused beams will limit driver energy delivered appropriately to targets and hence target performance. Conversely, for specified target performance, constraints may be placed on allowable values for other HIF system parameters, such as (1) beam emittance, momentum tilt, pulse energy, and peak power; (2) ion energy, mass, and charge; (3) cavity radius and gas density; (4) number of beams and beam port radius; and (5) target spot radius. An important factor that drives beam disruption is the growth of instabilities resulting from interactions of the beam with gas in the cavity. Meaningful cost/performance analysis requires a thorough understanding of the tradeoffs involved.

4.2. Beam Disruption By Streaming Instabilities

Heavy-ion beams traversing HIF reactor cavities stream through gas that remains after the cavity is cleared in preparation for injection of the next target. The residual gas may comprise target debris, fusion neutron transmutation products, and materials evaporated and sputtered by target emissions. Some of the residual gas becomes ionized through collisions with the beam ions. The ion-beam/cavity-gas system is dynamically unstable and charge clumps start to grow. Growing electric fields drive the ion beam to expand radially.

The principal objective of the analysis briefly described below was estimation of ion beam, reactor, and target parameter value ranges for which heavy-ion beams would not be unacceptably disrupted by interaction with residual cavity gas. The first step in the analysis was development of an improved model for beam evolution in time as heavy ions traverse a reactor cavity. The heavy-ion charge state distribution, the ion density in the background gas around the ion pulse, and the density and velocity distributions of the electrons liberated by the interactions of the heavy-ions with the background gas are treated. This model includes the application of Maxwell's equations, kinetic equations for charge transfer, and a continuum fluid-dynamical model for the electron motions. The radial electric fields driving instability growth are computed. A dispersion relation is solved for growth rates of the streaming instabilities as functions of mode number, time, and position. Finally, the perturbation of the beam ion distribution at the target is calculated to obtain the fraction of the beam energy deposited on the target as a function of the parameters listed above.

4.3. Summary of Computed Results

Fig. 1 shows the final transport length (distance from final focusing quadrapole to target) for which 99% of an 0.5-MJ pulse of 10-GeV ions injected through a quadrapole of 10-cm bore will be deposited on a 2.0-mm-radius target as a function of cavity gas (lithium vapor) number density. Efficient beam transport is also assured for any smaller transport distance.

These results suggest that streaming instabilities are much less disruptive to transport of heavy-ion beams through HIF reactors than previous studies had indicated. The instabilities simply do not grow fast enough to disrupt the beams as they traverse the cavity. Constraints on reactor, accelerator, and target design can be relaxed in several directions. The density of gas remaining in reaction chambers after cavity clearing could be increased substantially, resulting in higher pulse repetition rates. Some reactor concepts that otherwise could not be efficiently used for HIF (e.g., those with high-vapor-pressure materials in the reaction chamber) would become more attractive. Transport at lower ion energy, higher ion charge, and/or higher beam emittance is also an option that could significant reduce accelerator cost. In particular, a combination of (1) backgound gas densities as large as $10^{15}/cm^3$ (corresponding to equilibrium of pure lithium at 550 °C), (2) ion charge as great as +4, and (3) ion energy as low as 4 GeV may be feasible.

Details of the beam transport model and additional computed results have been published elsewhere [12-13]. Experimental verification of the predictions of the new beam transport model in the near future is important.

5. HIFSA TARGET COST/PERFORMANCE MODELING

With the exception of targets with spin-polarized fuel, no fundamentally new, credible target concept seems to have been described in nearly a decade. Therefore, only calculations to extend the credible target design parameter space to give accelerator designers as much freedom as possible was done for HIFSA. Concepts that were considered in greatest depth involve single-shell and double-shell fuel capsules with symmetric, two-sided, and single-sided illumination. High-density ablators and tampers, magnetic insulation, and spin-polarized fuel were studied less intensively.

The approach adopted for the HIFSA studies was to fit with simple polynomial expressions existing best-estimate gain curves computed using detailed target-physics codes (gain/ driver-pulse-energy relationship with a function of spot size and ion range as a parameter), such as those in Fig. 2 [14]. Best estimate gain curves were adjusted parametrically to reflect different degrees of optimism concerning target physics. Best estimate variations about the reference gain curves were performed using the scaling relationships of the Meyer-ter-Vehn model [15] and an alternative formulation developed during the HIFSA target studies for some of the target concepts [16]. In some instances, arbitrary assumptions were made concerning potential future advances in materials properties.

An improved HIF commercial-applications target cost model [17] has been developed through consultation with an **ad hoc** panel of experts as part of the HIFSA project. The model treats significant differences in costs for a wide variety of distinctly different target concepts. Target costs are scaled with important ICF plant parameters such as driver pulse energy and repetition rate and total fusion plant capacity. The generic formulation can be conveniently interfaced with cost models for other fusion plant systems. Although the emphasis in HIFSA is on HIF deuterium-tritium targets, the same general principles and many specifics are directly applicable for laser and light-ion fusion and other fuels.

In general, assumed superior target performance with no changes in target cost will lead to lower estimates of COE. For different target designs with the same degree of physics optimism, some of the improved performance of the more complex targets usually will be offset by increased cost of manufacture. Comparisons of COE for various target designs are presented in the section on integrated-plant systems studies. More details of target performance are published elsewhere [18].

6. INTEGRATED-PLANT SYSTEMS STUDIES

6.1. Introduction

To permit efficient exploration of the large design parameter space, MDAC developed a commercial power plant systems code for design tradeoff, parameter sensitivity, and cost optimization studies [19-20]. This personal-computer code requires inputs in the form of (1) computed results from a more detailed induction linac design/performance code (LIACEP [3]) developed at LBL and fit with simple scaling relations by MDAC and (2) target performance, fuel-cycle, and reactor design and cost scaling relationships provided by LANL and LLNL.

6.2. Summary of Representative Cost/Performance Results

Except where otherwise noted, all of the HIF power-plant COE estimates presented are for 1000-MWe, one-reactor plants in which single-shell targets are illuminated from two sides with 16 beams of +3-charge-state, 130-amu ions with (ion range)X(spot radius)$^{3/2}$ = 0.03 g/cm$^{1/2}$.

Substantial reductions in optimum COE can be obtained by switching from acceleration of +1-charge ions to acceleration of

+3-charge ions. The magnitude of the COE benefits are indicated in Fig. 3. Also shown in Fig. 3 is the breakdown into contributions to total COE of major plant subsystems. The difference in COE for the two charge states is almost entirely due to the difference in driver cost. For such capital-intensive plants, COE is largely determined by capital charges.

The scaling of COE with pulse repetition rate is illustrated in Fig. 4 for the four reactor-plant/BOP concepts included in HIFSA studies. In general, the COE minima are both broad and shallow. The minimum COE for none of them is prohibitively large.

The inherent low-pulse-repetition-rate/large-target-yield character of the liquid-metal-jet reactor concept restricts severely the operational parameter space accessible to it. This, plus the large size of the reaction cavity, the complexity of the reactor structure, and the safety-related and electric-power-generation-related design conservatism of the reactor plant and BOP result in relatively high COE for this concept. The magnetically protected dry-wall concept has near-optimum COE over a very wide pulse-repetition-rate range. However, the very large reaction cavity required even with small target yields, plus similar safety-related and power-generation-related conservatism, result in a similar minimum COE. The wetted-wall and granular-wall reactor concepts also have relatively large near-optimum pulse-repetition-rate operating ranges.

The wetted-wall concept assumes similar design conservatism. Nonetheless, COE's significantly lower than those for the first two reactor concepts are achieved through much smaller reaction cavities and simpler construction. The results for the granular-wall reactor concept illustrate the magnitude of the savings in COE that can be obtained if expensive containment structures and intermediate loops can be eliminated and higher power generation efficiencies can be achieved. Success in establishing credibility for the advantageous modifications to conventional ICF reactor plant and BOP designs embodied in the granular-wall reactor plant concept clearly can be important for economically attractive HIF power production. The other HIF reactor-plant/BOP concepts appear to be compatible with some of the improvements assumed for the granular-wall reactor.

Optimum COE's for the four reactor plant concepts for single-shell, double-shell, symmetric-illumination, and advanced targets are given in Fig. 5. The differences for the five target concepts are perhaps somewhat less than might have been predicted **a priori**, but as expected the two optimistic target concepts (the range multiplier and the advanced) give the lowest COE's. The reason for this relative independence of target concept is that for fixed values of (ion range)X(spot radius)$^{3/2}$, the gain curves are relatively steep with similar slopes and start at nearly the same driver pulse energy, so that the pulse energy at which high gain is attained is nearly the same.

The optimum COE values for different ion masses and (ion range)X(spot radius)$^{3/2}$ values in Fig. 6 indicate that the dependences of optimum values of COE on these two parameters are relatively weak. The results of the systems study showed disappointingly small difference in COE for single-pulse linacs compared to double-pulse linacs. Costs for additional beam transport lines and the relatively flat scaling of linac cost with beam current are the principal causes for this result. Up to 1500 MWe, the maximum plant size for which the cost data base is considered to be accurate, one reactor is optimum. At very large plant capacity, more than one reactor will be optimum.

Scaling of COE with plant net electric power is illustrated in Fig. 7 for the wetted-wall reactor-plant/BOP concept and +3 ions. Using scaling relationships consistent with those used in the HIFSA studies, the +1-ion HIBALL-II plant was scaled down to 1000 MWe from the original 4000-MWe point design and corresponding COE values are also plotted in Fig. 7. The strong economy of scale displayed depends on the assumptions that construction time does not increase with plant size and that other factors do not erode the projected economies of scale.

6.3. Near-Optimum Parameter Ranges

One of the most encouraging results of the HIFSA studies is that unexpectedly broad design parameter ranges for which COE is near the minimum were found. Ranges of values for some key design parameters for which calculated COE was within 5% of the mimimum COE are listed in Table I for the case of one-reactor, 1000-MWe plants with targets illuminated by +3, 130-amu ions. It is important to recognize that arbitrary combinations of parameter values within the listed ranges are not always feasible. However, if one parameter value is set arbitrarily, then some value within the listed ranges for each of the other parameters is consistent with the specified value. This result suggests that if for some unforeseen reason some part of design parameter space turns out to be inaccessible or unattractive, then other feasible or attractive designs can be found.

7. SUMMARY OF HIFSA PROJECT ACCOMPLISHMENTS, RECOMMENDATIONS, AND PROJECTIONS

Key technical issues in the design and cost/performance modeling of induction linacs, reactors, targets, beam transport, BOP, and integrated commercial HIF power plants have been identified. A commercial power plant systems model that runs on personal computers was developed to facilitate wide-ranging tradeoff, sensitivity, and optimization studies. This model has been used to measure the relative value of improvements in physics understanding, conceptual designs, and technology. Limited only by the present understanding of HIF and the imagination of the project team, promising commercial HIF power plant configurations involving different degrees of optimism have been developed. Some of the insights gained in the development of cost/performance models have application to ICF in general. Some of the models are directly applicable to laser and light-ion fusion. Also, extensive interactions between reactor, accelerator, and target scientists and engineers have led to better understanding of the requirements and issues.

A consistent commercial HIF induction linear accelerator concept has been developed that incorporates the latest physics understanding and technological advances. A comprehensive, detailed cost/performance code has been used to develop a wide-ranging, multidimensional accelerator cost/performance database. Substantially lower linac capital costs than those estimated in previous studies are projected as a result of advances in induction linac science and engineering, materials, and industrial capability in recent years. The driver capital cost is now comparable to the sum of reactor plant and BOP capital costs for 1000-MWe plants, rather than completely dominating plant capital cost. The data has been fit with simple expressions to permit its incorporation into an integrated power plant systems code for performing design-tradeoff, parameter-sensitivity, and optimization studies. The integrated plant studies have revealed several important trends, including near-optimum COE's over wide ranges of linac design parameter values and substantial cost savings by operation with +3 charge state.

Accelerator-related R&D needs have been identified and priority recommendations have been made, with charge neutralization being assigned the highest priority and high priorities assigned to pulse shaping and compression and the use of much lighter ions with +1 charge. Additional opportunities for significant reductions in accelerator costs were identified.

Although great advances in target design did not result from HIFSA target studies, important benefits were obtained nonetheless. In particular, HIFSA target studies led to the formulation of target-performance models that relate important accelerator/reactor/target performance parameters for a wide variety of target concepts in simple, convenient, accurate ways to facilitate integrated HIF power plant studies. These models and the HIFSA target cost model are useful for laser fusion and light-ion fusion as well.

[18] Bangerter, R. O., Targets for heavy-ion fusion, to be published in special issue of **Fusion Technol.**
[19] Zuckerman, D. S., et al., A systems performance and cost model for heavy-ion fusion, to be published in special issue of **Fusion Technol.**
[20] Waganer, L. M., et al., Heavy-ion fusion systems assessment: an overview, to be published in special issue of **Fusion Technol.**

Table I. Design parameter value ranges for which estimated COE is within 5% of mimimum COE (one-reactor, 1000-MWe-net-electric plants with targets illuminated by +3 ions).

	Magnetically Protected	Liquid-Metal Jet	Granular-Wall	Wetted-Wall
Repetition Rate (Hz)				
Single-Shell	9-19	1-2	3-9	3-9
Double-Shell	7-19	1-2	3-9	3-7
Symmetric	13-19	NA	NA	5-9
Range-Multiplier	9-19	1-2	3-9	3-9
Advanced	7-19	1-2	3-9	1-9
Target Gain				
Single-Shell	20-45	125-200	50-125	50-150
Double-Shell	25-50	125-175	50-100	50-120
Symmetric	25-50	NA	NA	50-100
Range-Multiplier	50-75	175-200	50-125	75-150
Advanced	50-100	175-375	75-150	75-400
Pulse Energy (MJ)				
Single-Shell	2.25-5.00	7.25-11.25	3.00-7.25	3.50-8.00
Double-Shell	3.25-6.00	7.00-9.00	3.50-8.00	4.00-8.75
Symmetric	2.75-4.75	NA	NA	4.00-11.00
Range-Multiplier	1.75-4.00	7.00-9.50	2.75-5.25	3.25-6.00
Advanced	2.00-4.50	4.75-8.50	2.00-6.00	2.25-7.50
Ion Energy (GeV)				
Single-Shell	6-12	8-15	6-12	6-13
Double-Shell	5-11	8-14	5-12	5-12
Symmetric	7-9	NA	NA	5-11
Range-Multiplier	6-13	8-14	7-12	6-13
Advanced	5-10	6-14	5-11	5-12
Number of Beams				
Single-Shell	10-50	16-50	12-50	12-52
Double-Shell	8-30	8-20	8-36	8-40
Symmetric	22-50	NA	NA	18-60
Range-Multiplier	8-50	15-49	12-30	12-50
Advanced	10-44	10-60	12-52	10-60
(Ion Range)X(Spot Radius)$^{3/2}$ (g/cm$^{1/2}$)				
Single-Shell	0.01-0.03	0.02-0.04	0.01-0.04	0.02-0.04
Double-Shell	0.01-0.03	0.01-0.03	0.01-0.04	0.01-0.04
Symmetric	NA	NA	NA	NA
Range-Multiplier	0.01-0.04	0.03-0.04	0.02-0.04	0.02-0.04
Advanced	0.01-0.03	0.02-0.04	0.01-0.04	0.01-0.04

[18] Bangerter, R. O., Targets for heavy-ion fusion, to be published in special issue of **Fusion Technol.**
[19] Zuckerman, D. S., et al., A systems performance and cost model for heavy-ion fusion, to be published in special issue of **Fusion Technol.**
[20] Waganer, L. M., et al., Heavy-ion fusion systems assessment: an overview, to be published in special issue of **Fusion Technol.**

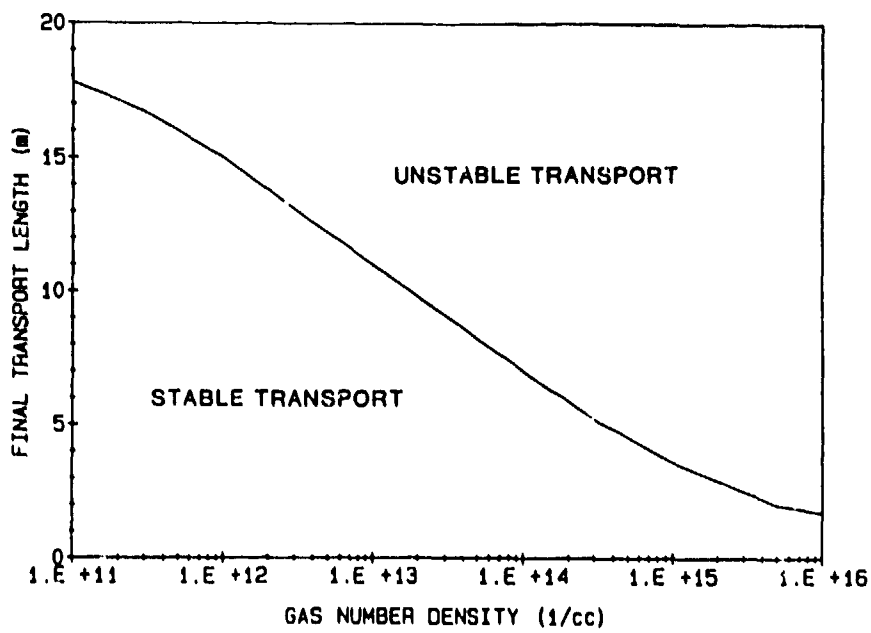

Fig. 1. Final beam-transport length for which 99% of +1, 10-GeV, mercury ions in a 10-ns, 0.5 MJ pulse focused by a 10-cm-bore final quadrupole magnet strike a 2-mm-radius target as a function of lithium vapor number density in an HIF reaction chamber.

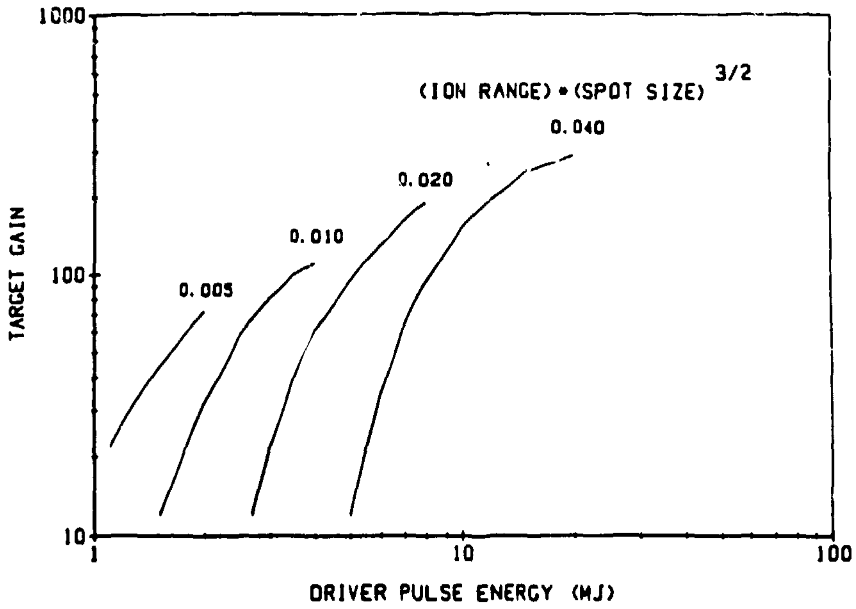

Fig. 2. Single-shell HIF target gain as function of driver pulse energy with (ion range)X(spot size)$^{3/2}$ in g/cm$^{1/2}$ as parameter.

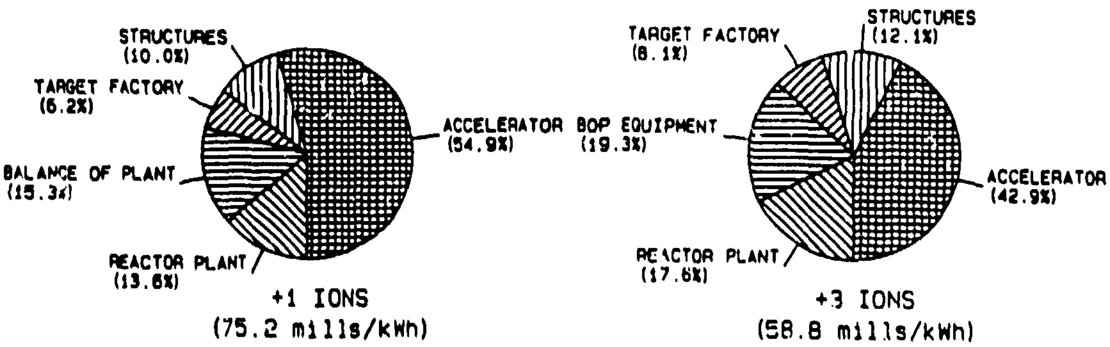

Fig. 3. Comparison of minimum COE and major-system captal-cost breakdown for induction linacs accelerating +1 and +3 ions and wetted-wall reactor-plant/BOP concept in 1000-MWe, single-reactor HIF power plants with single-shell targets illuminated from two sides by 16 beams of 130-amu ions with (ion range)X(spot radius)$^{3/2}$ = 0.03 g/cm$^{1/2}$.

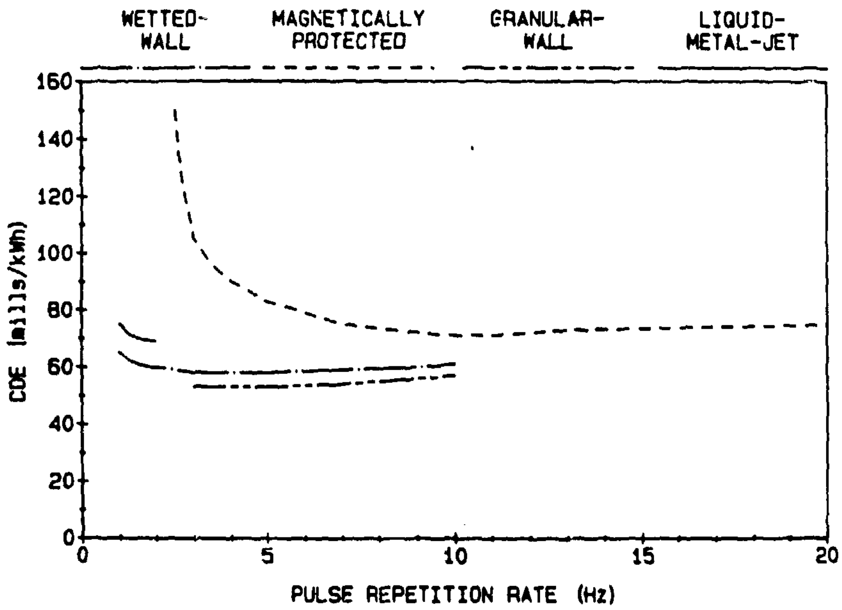

Fig. 4. COE as function of pulse repetition rate for for HIFSA reactor-plant/BOP concepts in 1000-MWe, single-reactor HIF power plants with single-shell targets illuminated from two sides by 16 beams of +3, 130-amu ions with (ion range)X(spot radius)$^{3/2}$ = 0.03 g/cm$^{1/2}$.

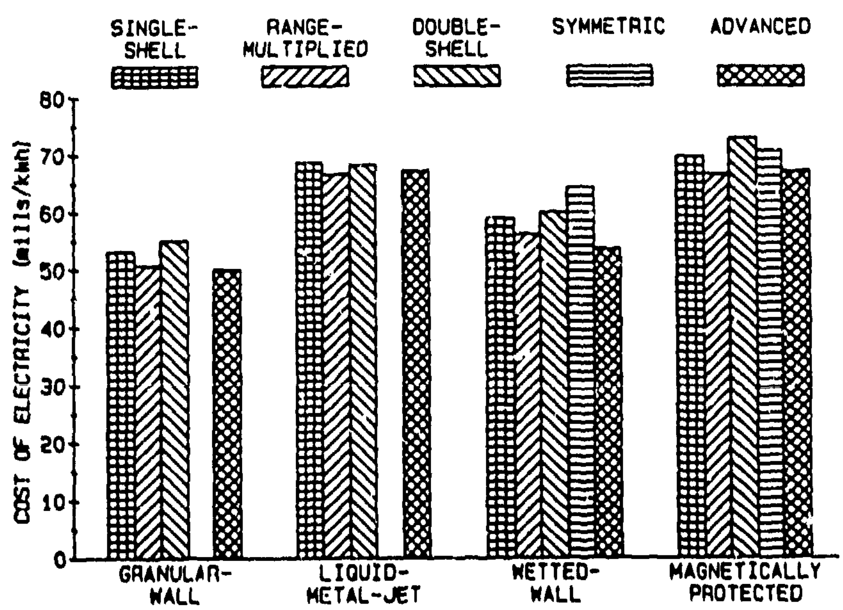

Fig. 5. Minimum COE for four HIFSA reactor-plant/BOP concepts in 1000-MWe, single-reactor HIF power plants and for five HIF targets illuminated by beams of +3, 130-amu ions.

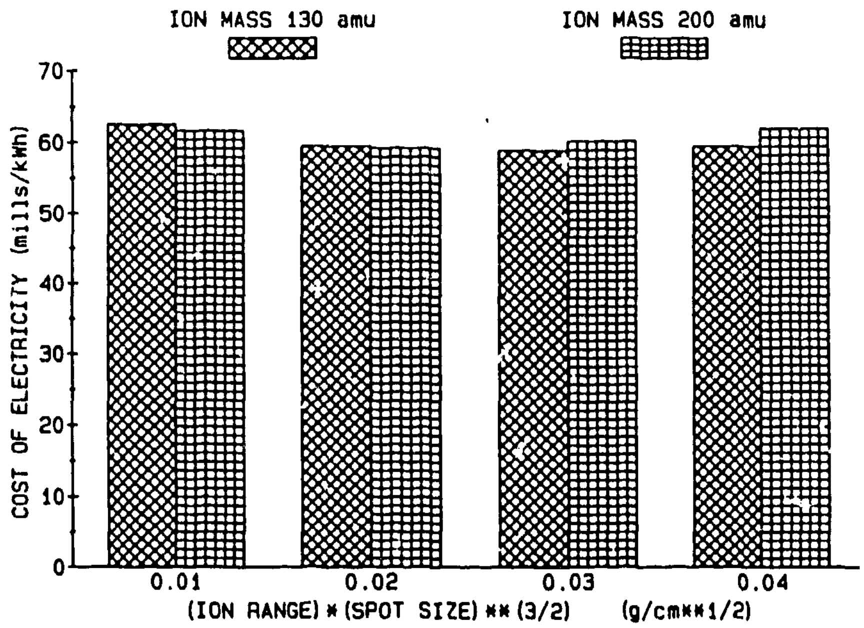

Fig. 6. Minimum COE as function of ion mass and (ion range)X (spot radius)$^{3/2}$ for wetted-wall reactor-plant/BOP concept in 1000-MWe, single-reactor HIF power plants with single-shell targets illuminated from two sides by 16 beams of +3, 130-amu ions.

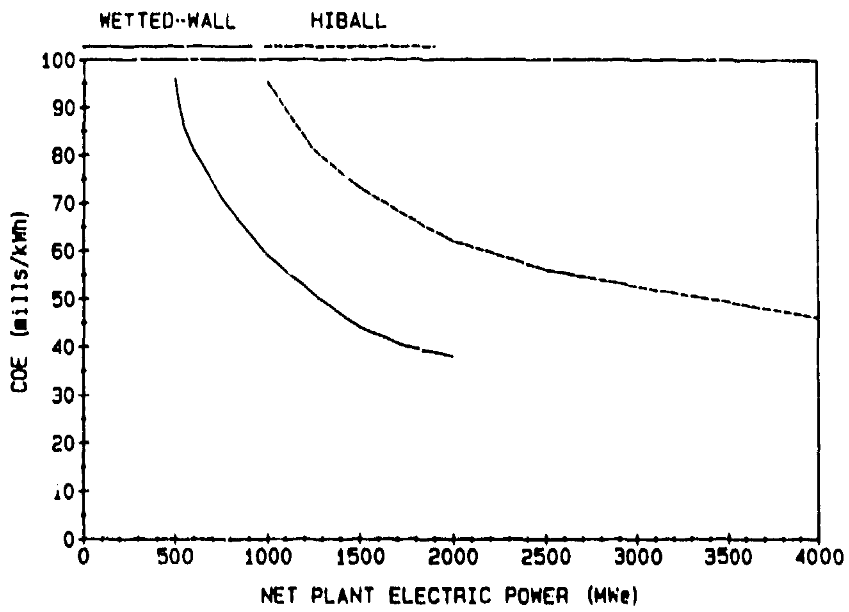

Fig. 7. COE as function of single-reactor HIF power plant size for wetted-wall reactor-plant/BOP concept with single-shell targets illuminated from two sides by 16 beams of +3, 130-amu ions with (ion range)X(spot radius)$^{3/2}$ = 0.03 g/cm$^{1/2}$.

Table I. Design parameter value ranges for which estimated COE is within 5% of mimimum COE (one-reactor, 1000-MWe-net-electric plants with targets illuminated by +3 ions).

	Magnetically Protected	Liquid-Metal Jet	Granular-Wall	Wetted-Wall
Repetition Rate (Hz)				
Single-Shell	9-19	1-2	3-9	3-9
Double-Shell	7-19	1-2	3-9	3-7
Symmetric	13-19	NA	NA	5-9
Range-Multiplier	9-19	1-2	3-9	3-9
Advanced	7-19	1-2	3-9	1-9
Target Gain				
Single-Shell	20-45	125-200	50-125	50-150
Double-Shell	25-50	125-175	50-100	50-120
Symmetric	25-50	NA	NA	50-100
Range-Multiplier	50-75	175-200	50-125	75-150
Advanced	50-100	175-375	75-150	75-400
Pulse Energy (MJ)				
Single-Shell	2.25-5.00	7.25-11.25	3.00-7.25	3.50-8.00
Double-Shell	3.25-6.00	7.00-9.00	3.50-8.00	4.00-8.75
Symmetric	2.75-4.75	NA	NA	4.00-11.00
Range-Multiplier	1.75-4.00	7.00-9.50	2.75-5.25	3.25-6.00
Advanced	2.00-4.50	4.75-8.50	2.00-6.00	2.25-7.50
Ion Energy (GeV)				
Single-Shell	6-12	8-15	6-12	6-13
Double-Shell	5-11	8-14	5-12	5-12
Symmetric	7-9	NA	NA	5-11
Range-Multiplier	6-13	8-14	7-12	6-13
Advanced	5-10	6-14	5-11	5-12
Number of Beams				
Single-Shell	10-50	16-50	12-50	12-52
Double-Shell	8-30	8-20	8-36	8-40
Symmetric	22-50	NA	NA	18-60
Range-Multiplier	8-50	15-49	12-30	12-50
Advanced	10-44	10-60	12-52	10-60
(Ion Range)X(Spot Radius)$^{3/2}$ ($g/cm^{1/2}$)				
Single-Shell	0.01-0.03	0.02-0.04	0.01-0.04	0.02-0.04
Double-Shell	0.01-0.03	0.01-0.03	0.01-0.04	0.01-0.04
Symmetric	NA	NA	NA	NA
Range-Multiplier	0.01-0.04	0.03-0.04	0.02-0.04	0.02-0.04
Advanced	0.01-0.03	0.02-0.04	0.01-0.04	0.01-0.04