THE DEVELOPMENT OF HEAVY-ION ACCELERATORS AS DRIVERS FOR INERTIALLY CONFINED FUSION

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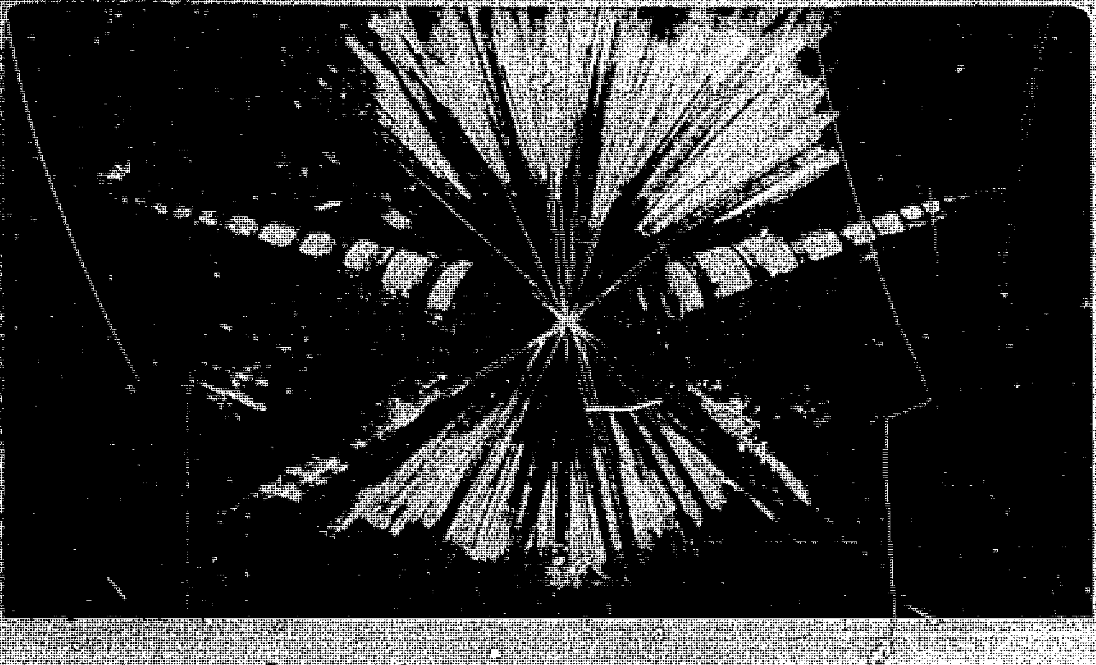

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PREFACE

This document is a compilation of material assembled for use as a reference in establishing a major R & D effort aimed at applying the technology of large-scale particle accelerators to the problem of providing a driver suitable for commercial power production from inertially confined fusion. In addition to work by the author, it contains several sections contributed by other workers in the field of Heavy Ion Fusion. Chapter 3 on the interaction of high-energy heavy ions with matter was conributed by Roger Bangerter. Chapter 4 by Lloyd Smith contains a description of the types of accelerators which have been considered, their advantages and limitations, and a summary of the status of relevant accelerator theory. The appendices contain descriptions of complete accelerator driver systems contributed by the staffs at Argonne, Brookhaven and Berkeley. Draft copies of the report were distributed to members of review committees and other workers in the field of inertial fusion. It is being printed at this time in response to the need for a source book for new workers in HIF.

Although the author's home institution is SLAC, the report is being published as an LBL document because the work has been supported through the Accelerator and Fusion Research Division of LBL. I wish to thank all those who contributed to the report, either directly or by discussions. In particular, I wish to thank Dr. Terry Godlove of DOE for his comments and encouragement. Finally, it is a pleasure to welcome new workers to this exciting field.

W. B. Herrmannsfeldt

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Chapter 1

INTRODUCTION AND SUMMARY

by W. B. Herrmannsfeldt

1.1 A STATEMENT OF PURPOSE

This document concerns the Heavy Ion Fusion (HIF) program for Inertial Confinement Fusion (ICF). It is intended to complement the Fusion Policy Plan presented to the House Science and Technology Committee on September 18, 1978 by John M. Deutch (Deutch [1978]).

There is probably no better place to look for an appropriate introduction than in the opening statement given by Dr. Deutch, which is quoted below verbatim:

> "Early in the next century, diminishing reserves of fossil and fissile fuels will force us to place increasing reliance on inexhaustible sources of energy. There are three such inexhaustible sources: fission breeder reactors, solar energy, and fusion energy. These technologies will require many years of development before they can generate power economically. Fusion is the furthest of the three from practical economic utility, but its potential rewards are great. Successful commercialization of fusion could provide the world with an energy source whose ultimate fuel (deuterium extracted from water) is essentially unlimited, and whose by-products would pose much reduced environmental problems compared to those of coal and fission power. Fusion power stations would pose no increased risks to the community (beyond those of ordinary fossil fuel plants) and would face no geographical limitations. Fusion hybrid reactors could be used to produce fissile fuel, or to produce other useful fuels, such as hydrogen."(Deutch [1978])

Because of the cost of the fusion research program, and because of the value to society of a successful outcome, it is important to determine as soon as possible whether controlled fusion can become a practical source of energy. To do this it is necessary to solve two classes of problems;

1. the physics questions, including;

   - a) confinement of plasmas, and
   - b) the heating of plasmas,

2. and the engineering questions, including:
   - a) designing workable power plants,
   - b) tritium breeding and containment,
   - c) reliability, safety, environmental acceptability, and
   - d) economic power production.

In addition to the Fusion Policy Plan (Deutch [1978]), comments and recommendations found in two reviews of the fusion program are important foundations for this document;

1. The JASON Study: Heavy-Ion-Driven Inertial Fusion (JASON [1978])
2. The Report of the Ad Hoc Experts Group on Fusion (Foster [1978])

1.2 DEFINITIONS OF ICF AND HIF

Brief definitions of the Inertial Confinement Fusion Program and the Heavy Ion Fusion Program may be of use to some readers:

1. The ICF process involves the deposition of a large amount of energy on a small pellet containing the fusion fuel. By heating the wall of the pellet, the pellet is caused to implode, heating and compressing the fuel, and igniting the fusion reaction. Achieving a sufficiently high energy multiplication (gain) to be effective requires burning a reasonable percentage of the fuel before the pellet can explode and disperse.

   The largest investment in the current program is in lasers which are used as the pellet driver, i.e., the device for providing the energy to heat and compress the pellet. Up to this point in the ICF program, this balance has seemed appropriate because it made it possible to achieve high incident power on the pellets with modest incident energy . The application of ICF to commercial power requires relatively high input energy to achieve adequate gain from reasonably priced pellets. The efficiency and repetition rate of the driver are crucial parameters.

2. A recently identified type of driver, meeting the apparent requirements for commercial fusion power plants, adapts particle accelerator technology to the problem of accelerating intense beams of heavy ions. The process is called Heavy Ion Fusion (HIF) even though it is not the heavy ions which are being fused. There are several potential advantages to HIF;

   a) Heavy ions have a very short, well defined range in matter, which results in efficient classical coupling of the particle energy to the wall of the pellet. (This will be covered in Chapter 3.)

   b) Heavy ion beams, with a low charge state, can carry large amounts of energy with relatively modest current and at low kinetic energy per nucleon.

   c) The high-current particle accelerators which are of interest have inherently moderately high electrical efficiency. To maintain this efficiency throughout the system, it is necessary to operate at reasonable repetition rates (≥1Hz) and to use efficient components in subsystems (e.g., use superconducting beam transport magnets).

   d) Accelerator systems can readily achieve more than adequate pulse repetition rates.

   e) Accelerators can be made highly reliable. Accelerator systems in operation routinely achieve 80-90% operational availability in spite of the fact that existing systems are in research applications and do not have the built-in redundancy that one would put in an accelerator driver for a power plant.

   f) A mature base of technology exists from the accelerators built for basic research. Existing machines must meet the simultaneous needs of multiple users, each with different beam requirements, which is more difficult than the requirement anticipated for a fusion driver of a single, dedicated and unchanging function.

   g) Heavy ion accelerators make a good match to the needs of a commercial power plant because;

i) It is relatively easy to achieve the necessary beam energy, even to about 10MJ.

ii) To overcome space charge effects on the ion beam, it is necessary to have fairly high particle energy. This results in needing fairly large pellets in order to stop the high energy ions.

iii) Larger pellets, requiring more beam energy for ignition, have higher confidence level designs for achieving adequate gain.

1.3 A SUMMARY OF THE STATUS OF THE ICF PROGRAM

The ICF program is newer than the Magnetic Fusion Energy (MFE) program. There are two principle reasons for pursuing the ICF option;

1. Confinement is based on entirely different physical principles than those used for magnetic confinement.
2. Engineering advantages result from the fact that ICF drivers can be designed nearly independently of the reactor design because the driver can be physically separated from the reactor system. (This is especially so for HIF, but may not be true for certain light particle drivers.)

The largest single segment of the present ICF program is for the development of glass lasers. Their main purpose is for steps leading to an early demonstration of scientific breakeven. However, glass lasers are generally acknowledged to be inappropriate as drivers for commercial power plants because of low efficiency and difficulty with adapting to high repetition rates. There is a high-power carbon dioxide laser program at LASL to demonstrate the potential of gas lasers as drivers for commercial power plants. There is also a high-power electron and light ion program at Sandia to show possibility of adapting these systems as drivers. Programs in advanced laser development and long lead technology including reactor design and pellet fabrication are under way in several laboratories and industrial firms.

1.4 THE STATUS OF HEAVY ION FUSION

1.4.1 The HIF Program

The first public suggestions to apply high energy accelerator technology to the generation of the needed beams came from accelerator physicists at two high energy physics laboratoriies; ANL and BNL. Direct DOE funding for HIF began in April 1977. The FY1979 budget for HIF is about $3.5M shared between three major laboratories (ANL, BNL and LBL) plus a few smaller contracts. The ICF community has held three annual workshops;

1. Claremont Hotel, Oakland in 1976 (LBL 5543) (this was before formal funding was initiated)
2. Brookhaven Lab in 1977 (BNL 50769)
3. Argonne Lab in 1978 (ANL 1978)

The references for the workshops, which are the proceedings of these meetings, constitute the principal body of documentation in the field and will be repeatedly cited in the following chapters. The concepts of HIF were independently reviewed by a JASON panel in February 1978 which found "nothing within the scope of our study that would in principle bar such a system from delivering the energy and peak power required to ignite the fuel pellet."(JASON [1978])

1.4.2 The Accelerator Physics Community

Contrary to an opinion expressed by some observers of science, the field of accelerator physics is anything but a stagnant area in need of just any new machine to build...good projects abound and the competition for the time and interest of scientists in the field is intense. It is because of the outstanding opportunity that fusion offers to the future betterment of all mankind that so much enthusiasm exists for HIF. In high energy physics (HEP), the field from which HIF was spawned, large construction projects are underway on the east coast (ISABELLE, a 400GeV superconducting proton-proton storage accelerator at BNL), in the midwest (the TEVETRON, a 1000GeV superconducting synchrotron at FERMILAB), and on the west coast (PEP, a 15GeV positron-electron storage ring being jointly built by SLAC and LBL). A similar list could be compiled of new ideas which are being actively studied included electron-proton colliding beams (PEP II) and proton-antiproton colliding beams at Fermilab. Other major accelerator projects underway in the U.S. include electron storage rings for synchrotron light at BNL and the Univ. of Wisconsin, projects related to neutral beam injection into Tokamaks, the CESR electron storage ring at Cornell, the high intensity accelerator being built for a neutron source at Hanford by LASL, and two electron linear induction accelerators being built at LLL.

As a result of this competition, only a small part of the accelerator community has been involved in HIF. Very significant progress has been made in evalulating design concepts, determining theoretical limits to the transport of high intensity beams, and finally evolving to a unified concept in which either of two types of linear accelerators are found to be promising candidates for the HIF application. Although either the high-current induction linac, or the rf linac with accumulator rings will fill the HIF requirements, the choice between these two approaches is not trivial. Synchrotrons, which were the third major candidate for an HIF driver, have received less attention because the potential for cost savings does not presently appear as great as it did when somewhat higher ion energies were being considered. Also, the curtailed budget levels do not permit much effort to be spent on problems which are peculiar to synchrotron scenarios, such as ion-ion cross sections and the requirement for better vacuum. One confidently expects that an appropriate effort, such as that outlined in the "staged program option," would result in new ideas that would improve the cost and performance projections of all of these systems significantly beyond present designs.

1.5 THE ROLE OF HIF IN THE DOE FUSION POLICY PLAN

According to the Fusion Policy Plan, the driver for the Engineering Test Facility (ETF) is to be chosen during the 1986-7 period. The program chart for the Fusion Policy Plan is shown in Fig. 1. A heavy ion accelerator system should be one of the candidates for the ETF driver. Its energy would probably be in the 1-5MJ range. Such a machine could be upgraded in energy, repetition rate and efficiency, to become the driver for the Experimental Power Reactor (EPR). Although the EPR is scheduled to be started about 1997, a successful heavy ion ETF driver could be converted to become the EPR driver in a much shorter time.

The present HIF program is an element in filling the need for an expanded engineering base. It draws on physics and engineering concepts up to 50 years old, and on a net investment in engineering, construction and development of $1-2B in the postwar HEP program.

1.6 DEFINE HIF PROGRAM OPTIONS

1.6.1 Fast Program

The HIF driver could be built rapidly because of the advanced state of accelerator technology. An appropriate schedule, after the decision to begin, would be as follows;

Preliminary design, R & D, build prototypes	2 years
Final design, site preparation, test prototypes	1 year
Construction	4 years
Operational checks and debugging	1 year

Such a plan would be justifiable if;

1. a high-priority national requirement could be satisfied, (e.g., the HIF accelerator would become the principal driver for doing pellet physics experiments),

2. and the HIF driver would be "reactor adaptable," i.e., could be upgraded to become the driver for the ETF and EPR stages of the program,

3. or there was found an alternative source of funding (e.g. collaboration with industry or a foreign government).

A necessary precaution would be to require that tests, particularly during the prototype stage, would establish complete feasibility of each stage beyond reasonable doubt.

A schedule similar to that described here would be a very fast program considering the present level of HIF funding. It would be a higher risk effort than a slower, staged program in which each step was made after the previous step had succeeded in meeting the required performance. Certainly, a very rapid build-up from the present level of HIF accelerator R & D would be needed. Two benefits that could be expected to result from such an effort are;

1. The total cost of a fast program, assuming success in meeting requirements, would be less than the cost of a comparable staged program.

2. A fast-paced, large-scale effort would attract the serious attention of the scientific community, and the best workers in the relevant fields could be recruited.

1.6.2 Staged Program

The path to a high-efficiency HIF driver can be appropriately charted with several technical levels, or stages, which one must achieve before committing the next larger increment of funds. Such a staged program is illustrated in Fig. 2. A very preliminary version of such a plan follows:

1. Stage 0 2 years at \$3-5M/year (the present level)
   Conceptual design and systems studies; including very limited preliminary R & D on critical components of each candidate system. Continue accelerator theory studies and low-cost experimental tests of theoretical predictions of the behavior of high intensity beams.

2. Stage 1 One year at \$10M and 3 years at \$25M/year plus about \$5M/year for equipment
   Accelerator Qualification; build critical subsystems, particularly injection systems. Continue the R & D stage on the rest of the driver and do detailed design work for the Heavy Ion Demonstration Experiment.

3. Stage 2 One year at \$40M and 2 years at \$50M/year
   Heavy Ion Demonstration Experiment (HIDE); construct sufficient amounts of each different part of the system to establish all technical, operational and cost factors. Test beam propagation in a scaled experiment. Test target coupling in high temperature matter (≥20MJ/g).

4. Stage 3 3 years at \$150M/year
   Megajoule driver; the Engineering Test Facility (ETF); If chosen as the ETF driver, the HIDE facility would be expanded and completed to the 1-5MJ level.

5. Stage 4 3 years at \$200M/year
   EPR driver; the Experimental Power Reactor; The Megajoule driver is upgraded to become the EPR driver.
   Typical parameters;

Beam Energy	3-10MJ
Particle Energy	10-20GeV
Peak Beam Power	300-600TW
Average Beam Power	150MW
Efficiency	15-30%
Pulse Repetition Rate	15pps

If this schedule is followed beginning with Stage 1 in FY1980, the Megajoule driver would be available by about 1989. If, after completion of Stage 1, a decision were made to push for earlier availability of the Megajoule system, two to three years could be saved between Stages 1-3 by a faster funding schedule. Such a schedule, as illustrated in Fig. 3, would be equivalent to that described above under the heading of "Fast Program." The total cost would be the same or slightly less. (Considerably less if inflation is considered.)

1.6.3 Delayed Program

The third option, labelled "delayed program," is essentially the present level of funding, $3.5M/year, continued for FY'79 and FY'80. A number of projects that had just been started in expectation of modest budget increases that would permit them to be carried out, have been stopped because of the decrease in funding. The net effect on the continuity of the research, and on the abilities of the laboratories to retain vital personnel, may be worse than just to delay HIF. The present level of funding is estimated by comparison with accelerator R & D in HEP, to be too low by about a factor of three for driver R & D at the present stage. At the present level, the funding is probably "subcritical" to what is required to make the necessary advances over the next few years. This funding level delays indefinitely the determination of whether heavy ion accelerators can be used as drivers for commercial ICF power plants. The DOE policy on fusion projects a total expenditure of some $18 billion in the next two decades to determine if fusion can be a practical energy source. By supporting HIF at the level proposed for the staged program, rather than at the present level, it should be possible to get answers to the questions of practicality of ICF several years sooner than projected. The net monetary savings alone makes the faster program worthwhile.

1.7 HIGH ENERGY PHYSICS PROGRAM SUPPORT

When HIF work was initiated by scientists in HEP laboratories, their efforts were encouraged by the HEP program as an important spin-off application of HEP technology. Later, as the effort grew, it was identified at the level of about $1.5M as a share from HEP to help get the new concepts off the ground. The Office of Laser Fusion provided the balance, about $3.5M in FY'78. Actually, the total contribution from HEP was significantly higher since pieces of equipment not immediately needed by HEP have formed the backbone of the HIF R & D at each of the three HIF laboratories. Examples of loans from one laboratory to another:

1. LBL loan of rf equipment and ion source to BNL.
2. FNAL loan of insulators to LBL

Other examples of uses of existing equipment:

1. Many components from the LBL electron ring accelerator experiment are being reused for the HIF program.
2. ANL obtained a surplus Dynamitron from a DOD lab
3. BNL made bunching tests on the AGS
4. LLL loan of induction cores and vacuum chambers to LBL

Also, scientists at non-HIF laboratories, notably FERMILAB, have made very significant contributions to the program. As HIF enters its fourth year, these voluntary contributions continue unabated, but after due notice, the HEP program does not have funds budgeted for HIF for FY'79 and beyond. Not surprisingly, the progress that can be made with recycled equipment is limited. That limit appears close at hand; the logical extension of the progress, mostly in ion source and low energy accelerators, will require new equipment very soon.

Thus it is the fact that the Laser Fusion Office did not increase the HIF funds, rather than that it cut them, that has resulted in the drop in the level of HIF support. There is also, of course, severe competition for the funds for laser fusion, and as the aforementioned reviews indicate, a great deal of careful study of the position and direction of the ICF program. This option plan is designed to establish a coherent heavy ion fusion program, and to demonstrate how that program fits within the Fusion Policy Plan.

The Ad Hoc Experts Group on Fusion spoke eloquently on the need for ICF to broaden its base of engineering, particularly for driver technology, before committing too much of its resources to extending existing technology of questionable application (Foster [1978]). The HIF community believes these remarks were directed precisely at the kind of promise HIF can demonstrate for inertial fusion.

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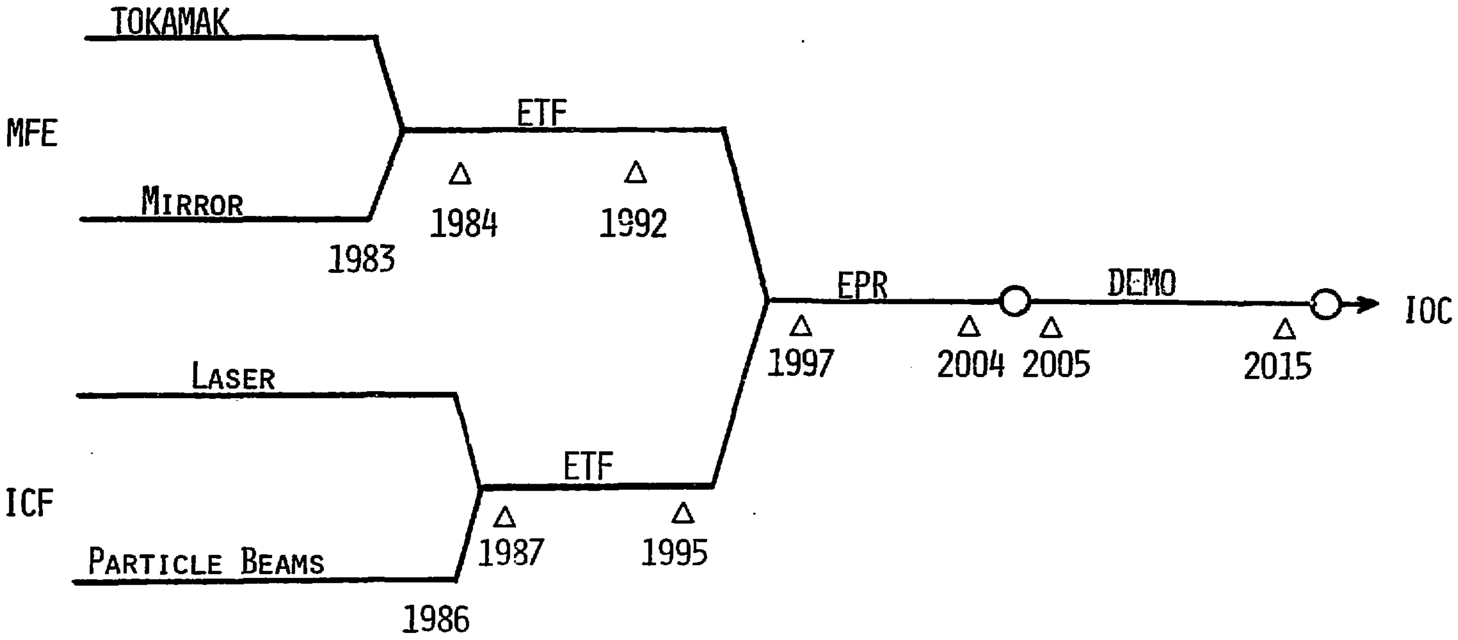
FIGURE 1: FUSION DEVELOPMENT PLAN



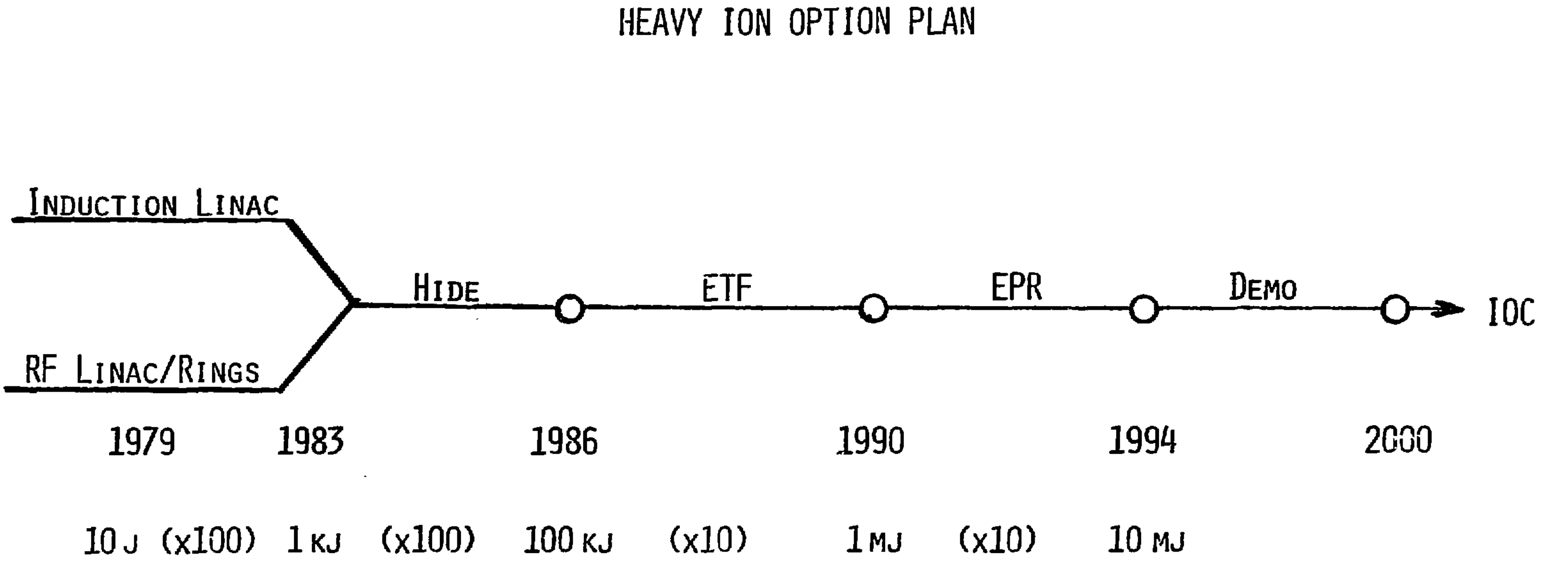


Figure 2: HIF Staged Development Strategy

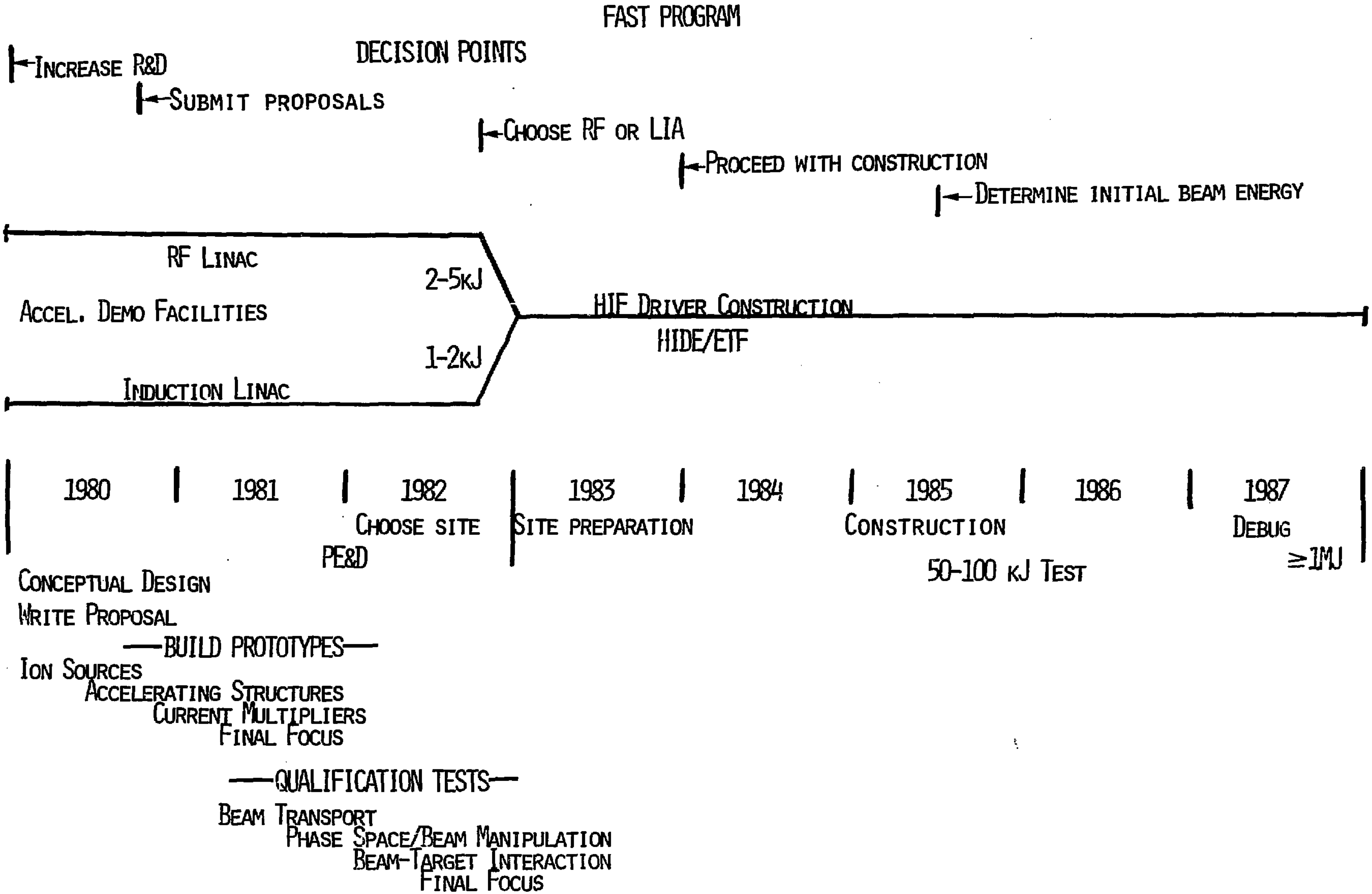


Figure 3: Accelerated Schedule Leading to a 1 MJ Driver by 1987

Chapter 2

COMMERCIAL APPLICATION OF INERTIAL FUSION ENERGY

by W. B. Herrmannsfeldt

2.1 THE ECONOMICS OF ICF POWER

2.1.1 Introduction

This section will attempt to answer the following question; "if there exists a reasonable technical basis for proceeding with the R & D towards the development of an Inertial Confinement Fusion (ICF) power system, is there any possibility that electricity made with such a system would be affordable?" The significance of this question can best be appreciated if one asks what the proper program strategy should be if the answer is clearly and emphatically negative. Then, probably, one should choose among the following options;

1. Abandon all pretext of an energy program and concentrate only on the military aspects.

2. Revert to a purely research mode in driver and pellet development, and downgrade reactor and systems R & D, until further developments give a more positive answer to the question.

If the answer is "yes," even marginally, then one would be encouraged to pursue the R & D to test the concepts. Note that even a marginally economic fusion system could still be successful if adapted as a fission-fusion hybrid or as a fission fuel breeder. Although the economics of hybrid systems is beyond the scope of this paper, it seems probable that the most economic pure fusion system is most likely to provide the most economic hybrid system.

The question of whether such a technical basis exists is the subject of the next two chapters of this paper. To answer the question of affordability, an economic analysis of ICF power production will be presented using conventional techniques of cost prediction for power plants. Comparisons with the methods and results found in the literature for other fuels will also be presented.

2.1.2 Capital Charge Rates

Because the cost of fuel used for generating electrical energy by fusion is very low (about 0.006mills/kWh for lithium and deuterium (Holdren [1978])), nearly all the cost of electricity results from capital charges and from plant operation. Operation is likely to be of the order of 10% of the power cost and can thus be readily added as a "tax" on the capital charges. The capital charges can be found from

$$Ce = Ct \cdot R/(365 \cdot 24 \cdot Cf \cdot Pn) \qquad (1)$$

where Ct is the capital cost of the entire facility,
R is the annual fixed charge rate,
Cf is the capacity factor, and
Pn is the rated net power of the plant.

Most comparisons of power costs similar to that being attempted here use about 15% for the annual fixed charge rate. One finds studies from 13% (Ford [1976]) up to 20% (Rossin [1978]). Since the purpose of this paper is more for comparison than for an absolute estimate, a level of 15% will be assumed for the fixed charge rate. The reader must scale appropriately in any comparison of estimates using different rates.

One also finds other authors using capacity factors anywhere in the range from 60% to 70%. The argument for the lower value is based on recent experience with large, new nuclear plants. The argument for the higher value, besides a desire to appear more competitive, is that after the technology matures, the more capital intensive plant, with lower fuel cost, will be operated for base load as much as possible. Since the purpose of this study is to compare ICF technology to other mature technologies, after the ICF approach has also matured beyond the initial models, it seems appropriate to use the compromise value of 65% for the capacity factor. Again, the reader may have to make adjustments when comparing results from different studies.

A simple energy flow model is shown in Fig. 4. The net power of the plant is given by

$$Pn = (1 - f)P \qquad (2)$$

where P is the total electrical power generated and
fP is the recirculating power to the driver.
The total power is given by

$$P = fP\eta g\epsilon \qquad (3)$$

where η is the driver efficiency,
g is the pellet gain, and
ϵ is the thermal conversion efficiency of the turbine plant.

By limiting ϵ to a conservative 33%, allowance is made for an unknown fraction of recirculating power for pumps, etc., in the reactor system. This relatively low efficiency is typical of nuclear systems which run at lower temperatures than do fossil fuel plants. The reason for this is a matter of materials technology that might be totally irrelevant to an ICF plant. However, because this is more a question of technology than of economics, the more conservative value of 33% will be used here. Combining Eqs. 2 and 3 yields

$$Pn = (\eta g \epsilon - 1) fP \qquad (4)$$

which, since fP is the power into the driver, can be rewritten as

$$Pn = (\eta g \epsilon - 1) nE/\eta \qquad (5)$$

where n is the pulse repetition rate, and
E is the pulse energy from the driver in megajoules.
Finally, by substituting from Eq. 5 into Eq. 1, and inserting the suggested values for the parameters, one finds

$$Ce/Ct = 26\eta/((\eta g/3 - 1)nE) \quad (\$/kWh\text{-}\$G) \qquad (6)$$

In Eq 6, the capital cost has been divided through to get an expression depending only on the physical parameters.

The relationship between gain and driver energy can be found for some selected pellets designed by the group at LLL (Bangerter [1979]). The expression

$$g = 200(E^{0.4} - 0.5) \qquad (7)$$

fits data points at 1 and 4MJ, and is probably reasonably applicable up to about 10MJ for a family of single shell targets. A warning provided with these results is that it may be necessary to reduce the expected gain by about a factor of two in a real environment. Higher gains are possible, but would probably require more complicated double shell pellets. Plots of the curve of Eq. 7, and curves a factor of two higher and lower, are shown in Fig. 5.

Since the capital charge for electric power is found to be inversely proportional to the repetition rate, it is interesting to explore the practical upper limits on n. To obtain about 4000MWth, which is approximately the thermal power needed for a 1 GWe plant, one would need between 1pps (at 10MJ per pulse) and 40pps (at 1MJ per pulse) to stay within the range of validity of Eq. 7. The 1MJ driver, would appear to be the easier driver to build, but it requires an average output power of 40MW compared to the average of about 10MW for the 1pps driver. Repetition rate does not necessarily have a large impact on the cost of the driver. Although at some level there are certainly cost penalties for very high average beam power, (additional cooling capacity, etc.) repetition rate is mostly a question of employing appropriate technology. For the reactor system, one expects that most of the effects of high repetition rate would be beneficial since the peak blast intensities are reduced. This permits the construction of smaller reactor chambers and requires less drastic means for protecting the chamber walls. Other implications of high repetition rate impact the pellet system. The allowable upper limit for the cost of each pellet is reduced, but in the absence of any estimate of pellet costs, there is no way to assess the significance of this limitation. It is probable that pellet cost is dominated by the capital cost of the pellet factory. The difference between a 1pps system ($2 \cdot 10^7$ pellets per year) and a 40pps system (10^9 smaller pellets per year) would not permit grossly different technologies to be used. The pellet factory would have to be fully automated in either case. If one reactor is used, at a reasonable insertion velocity of about 100m/s, the pellets would be only 2.5m apart at 40pps. This implies a limit on reactor vessel size, but because the blast is proportionately less intense, it may not be incompatible with other constraints. Fortunately, the required repetition rate drops off rapidly with higher energy, as shown in Fig. 6, so that the need for very high repetition rate to achieve 4000MJ is limited to only the low-energy, low-gain cases.

In Fig. 7, the capital charge ratios from Eq. 6 are plotted using the gain curve from Eq. 7. Curves are shown for driver efficiencies of 3%, 6%, 12% and 25%, covering the efficiency range for drivers which have been suggested for ICF power systems. Similar curves in Fig. 8 are plotted for the high and low pellet gain functions for drivers with efficiencies of 25% and 6%.

The plots in Figs. 7 and 8 show an asymptotic limit of 19.5mills/(kWh-$G). Somewhat surprisingly, this limit is closely approached for all driver energies at moderate efficiency. It is also approached for lower efficiency drivers at higher pulse energies. Only lower energy-low efficiency drivers have capital charge ratios that are significantly higher because they are operating just above practical breakeven. A driver with efficiency greater than 25% may, if developed, cost less because it needs less utility services, but the capital charge ratio would not be significantly lower because of the approaching asymptotic limit.

2.1.3 Capital Costs of ICF Facilities

2.1.3.1 Indirect Costs

The total cost of an ICF facility can be expressed as

$$Ct = Cd + Cr + Cp \qquad (8)$$

where Cd is the cost of the driver,
Cr is the cost of the reactor, including the turbine plant, cooling system, etc., and
Cp is the cost of the pellet factory including the tritium related equipment.

For any construction project, the direct costs of construction must be multiplied by a factor to account for various indirect costs. The basis for computing this factor for a power plant is very different from the way it is calculated for a research facility to be built with government funding. The four elements of the indirect factor are:

1. Engineering, Design, Inspection and Administration (EDIA),
2. Contingency,
3. Escalation (Inflation), and
4. Interest on the funds spent during construction.

For power plant construction, the equivalent of EDIA, including special construction tooling, is typically 24% of the direct construction cost (Lee [1976]). For power plant estimates, a contingency factor of 12% is common (Lee [1976]).

Escalation has to be anticipated by the designers of a research facility when seeking funding from the government. However, in comparing power plant costs and the resulting rates, it is more useful to compute the bus-bar cost of power in current year dollars. Inflation can then be put in at an appropriate rate to compare power costs calculated for any two different times. Thus escalation will be omitted at this stage of this study in order to be consistent with the methods used in other reports, e. g., by Rossin and Rieck (Rossin [1978]).

Interest on funds spent during construction, i.e., before operation commences, must be added to the construction cost of a power plant. The construction time, the interest rate, and the spending curve are all needed to calculate this factor. One can reasonably hope that the construction times would be less than the decade or more that has been the recent experience of nuclear plants. Lee [1976] uses 52% of construction cost (direct plus EDIA and contingency), for interest charges, equivalent to almost five years at 9%. This implies a ten year construction project, with a linear spending curve, or its equivalent.

In summary, the indirect multiplier can be found from:

1. EDIA; 24% of direct construction cost,
2. Contingency; 12% of direct construction cost,
3. Escalation; omitted for now,
4. Interest; about 52% of construction costs including EDIA and contingency,

The resulting indirect factor is 107% which will be rounded to 100% for this study.

2.1.3.2 Heavy ion drivers

Fairly detailed computer optimized estimates have been made for the cost of an induction linac driver similar to the system described in Appendix B. The latest estimate for a 1MJ heavy ion induction linac is $350 (Hoyer [1979]). Other estimates by groups at ANL and BNL for rf linac systems with storage ring current multipliers are very similar; any differences may be less than the uncertainties. The cost of the driver can be expressed as

$$Cd(\$G) = (0.35E^{0.4} + f(\text{rep rate}))\bullet(2.0) \quad (HIF) \quad (9)$$

where the factor of 2.0 accounts for the indirect costs. The 0.4 power dependence on energy has been found to be a good approximation in several estimates between 1 and 10MJ by all three laboratories. The expression is in FY1979 dollars. The added "rep rate" function is required only for driver systems operating at repetition rates higher than are generally assumed. For 0.1 to 10pps, it has been assumed that there would be no cost increment. For the following calculations, at 20pps a penalty of 10% will be added and at 40pps the penalty will be 20% of the total driver cost. Generally a small fraction of the cost of a facility even depends on average power. Recent construction experience has found the direct costs proportional to average beam power to be only about $300/kW (PEP [1978]). This cost would amount to about 1% of the cost of the 1MJ, 10MW heavy ion driver. Thus, these penalty allowances would appear to be conservative, but in any case, are not very significant to the resulting cost of power. The nominal expected efficiency of any of the heavy ion accelerators is around 25%.

2.1.3.3 "Modular" drivers

Other driver candidates include various types of lasers and accelerators for either electrons or light ions. Generally these devices have in common the trait that higher pulse energy, beyond some threshold which is usually well below one megajoule, is obtained by replicating the basic module rather than just by making the whole device larger. These machines will be called "modular" drivers in this discussion.

There are no preliminary designs, with cost estimates, for high repetition rate modular drivers available in the literature. Since many of the components, such as pulsers, cooling systems, etc., will be similar in capacity, it may be that any modular driver would have a similar cost to that of a low energy heavy ion accelerator. With the benefit of R & D in this new area, the cost might be reduced to, for example, half that of a 1MJ heavy ion accelerator. This is reasonable to expect because the low velocity part of any of the heavy ion accelerators that have been proposed appears to be relatively expensive. The energy scaling exponent is almost certainly different for energies above that of the basic module. The scaling rule that has been suggested for large carbon dioxide lasers is the 0.8 power (Frank [1978]). Ignoring the "rep rate" function, because there is no technical basis for any part of this estimate anyway, and assuming the same cost at 1MJ as the heavy ion accelerator, the cost of the modular driver is

$$Cd(\$G) = (0.35E^{0.8})\bullet(2.0) \qquad \text{(modular)} \quad (10)$$

2.1.3.4 Reactor and power plant

There are no appropriate published cost estimates for ICF power plants. Conceptual design work at Livermore (Maniscalco [1978]), Los Alamos (Booth [1978]), and earlier studies which were reviewed by EPRI [1976], have concentrated on exploring possible technical solutions to the combination of requirements facing the reactor designer. For the purpose of this paper, it will be initially assumed that the cost of the ICF reactor system is the same as that of a comparable light water reactor (LWR), including all cooling, turbines, controls, containment vessels, etc., but not including the driver, tritium handling equipment and pellet factory. The heart of the LWR, the Nuclear Steam Supply System (NSSS), generally accounts for not more than 20% of any total cost estimate. Thus, since it is assumed that all the rest of the facility is essentially the same, the uncertainty in the cost estimate is concentrated in a small fraction of the total.

There are many published estimates for the cost of a LWR plant. One of the more recent ones, made on approximately the same basis as the driver estimate above, is by Rossin and Rieck (Rossin [1978]) for dual 1200MWe plants at $692/kWe in FY1977 funds. Escalated for two years at 10%, this comes to $1 billion per plant. Other published estimates are within a few percent of this, probably depending on regional variations.

The objective of this study has been to define the cost of a nominal 1GWe plant. The power industry seems to be standardizing on a nominal 1300MWe for the NSSS (Ford [1976]). The turbine systems are presumably optimized to match this level. Working backwards, assuming a thermal conversion efficiency of 33%, the thermal requirement is 3.9GWth, hence the nominal 4GWth that was initially chosen as the thermal power requirement for this study. Differences between the nominal 1GWe and the possible 1.3GWe are in the fraction of recirculating power to the driver system. By using the approach of Eq. 6, the cost of power delivered accounts for the recirculating power, i.e., what is not recirculated is available for distribution. Thus, the term Cr is compatible with the total estimate for a 1200MWe plant, escalated to 1979 dollars, and Cr = 1($G).

2.1.3.5 Pellet factory and tritium handling equipment

The term Cp represents systems for which there is no design on which to base a cost estimate. It could be argued that pellet cost is like a fuel charge and that the facilities should not be included in the capital cost for the plant. However, since there are no such facilities, and since the tritium handling equipment must be installed on every reactor, even those not designed to breed tritium, at least part of the total is a legitimate capital cost. If dual ICF reactors are built on a site, the pellet factory costs could be split between them, but no such detailed accounting is appropriate at this time. The Livermore group has suggested $100M apiece for the cost of the pellet factory and for the tritium handling system. Intuitively, one feels that if the pellets can be mass produced at all, these numbers must be about right. However, even if they are low by a factor of two, the cost of electricity would be only affected by about

10%, which is less than the error due to the uncertainties in any of the other estimates. Thus, it will be initially assumed that Cp = 0.2($G).

2.1.3.6 Total ICF plant cost

The total cost of the ICF power plant, found by making the indicated substitutions in Eq. 8, is

$$Ct(\$G) = (0.35E^{0.4} + f(\text{rep rate}))2.0 + 1.2 \quad (\text{HIF}) \quad (11)$$

for the heavy ion system. For the modular driver system it is

$$Ct(\$G) = (0.35E^{0.8})2.0 + 1.2 \quad (\text{modular}) \quad (12)$$

The expressions in Eqs. 11 and 12 are plotted in Fig. 9. Also shown on Fig. 9 is a "half-price" curve of Eq. 12 with the driver cost divided by a factor of two.

2.1.4 The Cost of ICF Generated Power

By multiplying the costs in Fig. 9 by the appropriate rates from Eq. 6, the family of electricity costs shown in Figs. 10 through 14 are obtained. An operating "tax" of 10% has been included. This "tax" would generate about $30M/year for a plant selling electricity at 50mills/kWh and operating at a capacity factor of 65%.

The most striking feature of the results in Fig. 10 is that electricity costs for 25% efficient drivers are essentially independent of driver energy over a very wide range; from 1 to beyond 4MJ. The rates are also very weakly dependent on pellet gain over the same region as shown by the area between the high- and low-gain curves in Fig. 10. Only by significantly changing the plant costs can the indicated rates be very much changed. For example, a reduction of 10 to 20 mills results from reducing the driver cost by 50%, which could be accomplished by operating two reactors from one driver. As a worst case example, if the costs are $1 billion higher than estimated here, power rates would be 25 to 30 mills higher.

In Fig. 11, the cost curve for the heavy ion accelerator, Eq. 11 has been used, with the nominal gain curve, to calculate the cost of power using driver efficiencies of 3%, 6%, 12% and 25%. In Fig. 12, the same expression has been used, with the nominal gain curve, to show the cost dependence on efficiency for several different energy drivers. The modular driver cosst function, Eq. 12, has been used with the nominal gain curve to show the dependence on efficiency in Fig. 13. Rates for the lower efficiency drivers, are not only substantially higher, but also show a very strong dependence on pellet gain. In Fig. 14, the 6% efficiency case has been plotted for the modular cost function, Eq. 12, showing the high-, low-, and nominal-gain cases.

2.1.5 Comparison of Power Costs

Power costs for new generating plants, (i.e., built with current dollars) are given for the Northern Illinois area by Rossin and Rieck (Rossin [1978]). Their data is reproduced here in Table 1.

TABLE 1

Bus-bar costs for future plants in 1977 dollars

	Nuclear	Oil	Coal*
		(mills/kWh)	
Fixed return (R=20%, Cf=60%)	26	15	24
Operation and Maintenance	2	1	3
Fuel (includes coal inventory)	7	30**	16
Totals	35	46	43

* The difference between high- and low-sulfur coal, with scrubbers, is only 1 mill. The high-sulfur case is quoted above.

** The reference gives 26 mills for oil without scrubbers, but quotes actual experience for 1977, with "mostly imported" oil at 29.6mills/kWh.

For direct comparison with the results found above for ICF, the data from Table 1 are adjusted to R = 15%, Cf = 65%, and escalated for two years at 10%. The results are shown in Table 2. The continuation of this table shows the cost, and cost increments for various assumptions, for different ICF parameters. The increments are found by comparison with the 1MJ heavy ion case, which is the lowest cost ICF system found. The examples are all for the 3MJ driver case, which has been commonly used in other studies, and which is near the practical minimum for the modular example with 6% driver conversion efficiency.

TABLE 2

Bus-bar costs for future plants in 1979 dollars

	mills/kWh	
Nuclear (R=15%, Cf=65%)	33	
Coal (R=15%, Cf=65%)	44	
ICF (1MJ heavy ion driver)	49	
ICF options with heavy ion drivers		increment
a) 3MJ heavy ion driver as estimated	53	+4
b) If total is $1B higher than estimated	76	+27
c) If driver cost is half of LBL estimate	40	-9
d) Same as a) with low-gain targets	55	+6
e) Same as a) with high-gain targets	50	+1
ICF options with modular drivers		
f) 3MJ modular driver as estimated	81	+32
g) If total is $1B higher than estimated	109	+60
h) If driver cost is half the given estimate	57	+8
i) Same as f) with low-gain targets	118	+69
j) Same as f) with high-gain targets	70	+21

Note that the driver costs can be reduced by a factor of two either by substantial technical improvements resulting from the R & D program, or by operating two reactors, alternately, from one driver. The LWR costs referenced for this study are all for dual reactor stations. Therefore, for comparison, dual reactors must be assumed in this study. Although all driver costs have been given for one driver per reactor, except for the high repetition rate system, the heavy ion drivers should have no trouble serving two reactors.

The effects of escalation, which have been omitted from the above calculations, have two rather opposite implications. The first is that any new power plant, built with inflated costs, will raise the cost of power to all consumers who get any share of their power from that plant. This tends to inhibit new construction to provide facilities beyond immediately demonstrable need.

The second effect is that fuel costs generally escalate faster than general inflation, for about the same reasons as given above. That is, new fuel producing facilities are needed, and the cost of these raises fuel costs for all customers. This has the effect of making fuel intensive plants progressively less economic, and acts to promote construction of newer, more capital intensive plants. This implication of inflation eventually will make up for a small, presently perceived, difference between ICF power and coal, as it has already allowed fission to bypass fossil fuels for economy. It is probably not a significant effect if the cost differences are large, but if coal continues to escalate 3% faster than general inflation, fifteen years from now the above calculations would show coal power as expensive as fusion for all except the pessimistic cases with increments greater than 20 mills/kWh.

2.1.6 Conclusion

The question posed at the beginning of this section, "is ICF power affordable?" can now be answered. If the cost estimates given here are not much too low, ICF power from a heavy-ion accelerator system should cost between 5 and 10 mills more than power from a new coal plant. One would expect this difference to shrink with time as coal prices rise faster than general inflation. Furthermore, this difference, which is largely independent of a wide range of assumptions, is less than the difference between the power costs from new coal and new LWR plants. Since it is not an insurmountable deterrent for new coal plants, it should not be insurmountable for ICF.

On the other hand, power from a driver with efficiency in the 3% to 6% range costs at least 25mills/kWh more than power from a new coal plant, and only comes close to the lower end of this range if one makes optimistic assumptions about pellet gain. One exception to both of the above statements is if the driver cost is cut in half. Then, if all the other assumptions work out, the heavy ion driven system could actually produce power for less than the cost of coal produced power. Another exception would be for an entirely different mathematical model to apply. This would occur if, for example, fission-fusion hybrid systems are considered; a task well beyond the scope of this paper.

2.2 SMALL (FEW HUNDRED MEGAWATT) POWER PLANTS

One does hear suggestions that the electric power industry would prefer much smaller fusion reactors. In view of the evidence that small fission power plants are being shut down because they are uneconomic, these suggestions should at least be questioned. One possible rationale for small fusion installations is that, as in the case of earlier fission power plants, the very first reactors might not be gigawatt sized units. Some lower power units would be built from which to scale up to full size units. Indeed, the Fusion Policy Plan (Deutch [1978]) calls for essentially just such a step in the Experimental Power Reactor.

It appears certain that the capital cost of fusion power plants of any type will be greater than that of equivalent fission plants. Thus there appears to be no rationale for projecting a future power industry consisting of many small fusion plants scattered about the countryside.

2.3 BEAM REQUIREMENTS IMPOSED BY REACTOR DESIGNS

It is useful to attempt to determine what can be deduced about the characteristics of fusion power reactors, particularly as those characteristics affect the design of ICF drivers.

2.3.1 Pure Fusion Power Reactor

The pure fusion power reactor would be of the type discussed in the first section of this chapter on the economics of fusion power. The reactor chamber would be quite large, 5 to 10 meters in radius, in order to absorb the repeated blasts of neutrons, electromagnetic radiation and debris. The radius of the chamber determines the minimum standoff distance for the last focusing elements. From the standoff distance, one can deduce the necessary beam quality. If, as it will be shown later in the HIF case, the required beam quality is better than can be delivered by the accelerator, it is necessary to divide the beam into a number of less intense beams. It will, in fact, turn out that the number of beams needed to achieve adequate beam quality is significantly higher than the minimum needed to provide adequately symmetric illumination of the pellet.

The environment in the reactor vessel may be important for the final transport of the ion beam to the target. There appears to be no question that the beams can be made to hit the required spot size if the reactor chamber is evacuated. If there is a substantial pressure, such as the vapor pressure from liquid lithium, then theoretical and experimental studies are needed to resolve the final transport questions. However, it is interesting to note that if the lithium temperature is maintained at around 600°F, i.e., somewhat higher than the coolant temperature in a light water reactor (LWR), then the vapor pressure is in the 10^{-5} Torr range, adequate for the vacuum requirements for beam transport. An accelerator capable of a definitive test of beam transport in a gas or plasma at a pressure ≤ 1Torr would have many of the characteristics needed for an ICF driver. Thus it now appears that such tests would have to be part of a development program such as that described in Chapter 5. However, it appears certain that some pure fusion reactor scenarios exist with evacuated chambers. Liquid metal getters can be used for fast pumping, and first wall protection schemes compatible with vacuum conditions have been described by Hovingh [1976]. Critical questions of materials, radiation damage, first wall lifetime, and cost, all remain to be studied.

2.3.2 Tritium Generating Reactor

It appears certain that the first generation of fusion reactors will require some mixture of tritium-deuterium fuel. The use of "advanced" fuels, i.e., without tritium, is attractive mainly because it eliminates the complication of separating, purifying and storing tritium. However, even advanced fuel reactors will result in unburned tritium "ash" in the residue. Thus the environmental problems of tritium containment will be part of any fusion plant, for either magnetic or inertial confinement.

The critical tritium question is "how much?" or rather, how little tritium needs to be mixed with the deuterium in the fusion fuel. In the case of ICF, if sufficient beam energy is supplied to the pellet, the reaction should propagate with significantly less than a one-to-one D-T mixture. With a lower tritium fraction, the inventory of tritium and the investment in tritium handling equipment can both be reduced. Calculations to show the dependence of pellet gain on the D-T mixture have shown only a small drop (≤ 10%) in going from a one-to-one mixture to a two-to-one D/T ratio (Skupsky [1978]). While it is possible that only the tritium ash from the pure fusion reactor may be needed, a more likely scenario is that some reactors are designed for and dedicated to tritium breeding. A tritium breeding reactor designed for the maximum production of tritium could yield approximately twice as much tritium as required to sustain the reactor itself with a one-to-one D-T mixture (Monsler [1978]).

The tritium breeding reactor is likely to borrow heavily on the existing technology for generating tritium in fission reactors. Although much of this technology is classified, it is common knowledge that the tritium is generated by neutron absorption in lithium. To aid in handling the tritium, particularly to minimize the tendency to permeate through metals, such as the stainless steel plumbing, the tritium is kept as cool as is practical.

A tritium breeding fusion reactor based on existing technology would not also be used as a power reactor. There may be a beryllium, or lead, or refractory metal blanket for neutron multiplication. The interior of the reactor chamber might not be much different from that of the pure fusion power reactor, except that the ambient temperature could be lower. If the liquid lithium "waterfall" concept is used, and the lithium is maintained at about 200°C, (just above melting) the vapor pressure is reduced to $< 10^{-5}$Torr.

2.3.3 The Tritium Breeding-Fusion Power Hybrid

The reactor designs usually presented as part of ICF scenarios are of the tritium-fusion hybrid class (Maniscalco [1977]). They usually use a lithium blanket, sometimes in a "waterfall" configuration, to serve the double purpose of providing a first surface shield and a high solid angle for the lithium to be exposed to the flux of neutrons.

2.3.4 Electro-nuclear Breeding Reactor

Electro-nuclear breeding of fissile fuel, rather than pure fusion, may be the key to unlimited, inexhaustible energy for the future. There is every reason to believe that the safety record of the fission reactor industry, especially when compared to that of the fossile fuel industry, will eventually convince the general public about the safety of nuclear power. The other critical issues of fission, proliferation and waste disposal, have technical solutions.

The principle uncertainty for fission reactors is the continued availability of enriched fuel at reasonable prices. The fast breeder reactor should in theory solve the fuel problem except for two serious drawbacks;

1. It is generally felt to be more prone to catastrophic accidents, and

2. The breeding rate is too slow to make it possible to fuel non-breeding reactors in any quantity.

Thus there has recently been increased interest in the construction of systems for electro-nuclear breeding. Earlier studies have been underway in Canada for a number of years. These studies generally conclude that electro-nuclear breeding is an attractive alternative to fast breeder reactors. With some new concepts of insitu enriching of fuel rods, perhaps as many as three or four times (Grand [1978]), there would be no need for either enrichment or reprocessing facilities. This at once greatly improves the economics and eliminates the problems of proliferation by diversion of weapons materials. Unfortunately, the cost of operating such a powerful accelerator, makes the cost of the resulting fuel relatively uneconomic, (though not as uneconomic as fast breeder reactors).

An electro-nuclear breeding accelerator obtains about one neutron from every 10MeV of beam energy. These are relatively low energy neutrons. By contrast, about 80 percent of the energy from a D-T fusion reactor is in 14.1MeV neutrons. By the use of a beryllium and/or refractory metal multiplier blanket, the flux of neutrons can be further enhanced (Rose 1961]). Even without such enhancement, at a pellet gain of two, the yield of neutrons per MeV of input beam from an ICF reactor would be comparable to that from the accelerator breeder. However, to achieve comparable flux as that proposed in the Brookhaven study, the pellet gain should be about 60 if one 10MJ pulse per second is assumed. The proposed accelerator breeder is designed to provide fuel for three light water reactors. The ICF driver could, in theory, serve 15 similar fuel breeding facilities, providing fuel for 45 light water reactors. In practice, the need for tritium will require some fraction of the driver pulses. If a lower ratio of tritium is used, then the neutrons from D-D collisions would account for an appreciable part of the flux. These neutrons are at a lower energy and may be less able to be multiplied.

In the absence of a comprehensive study, such as that made for the accelerator breeder, the optimimum values cannot be assigned to the various factors described above. However, it is apparent that with only a modest pellet gain, a very interesting electro-nuclear breeder could be designed. It is also difficult to guess at all the characteristics of the reactor chamber as they apply to the ICF driver except to point out that, as in the case of the tritium generator, first wall protection will be a primary consideration. The reactor chamber could be kept relatively cool and at pressures low enough to avoid beam transport problems.

2.3.5 The Fission-fusion Hybrid

Combining the electro-nuclear breeder with the power generating capability of a fusion reactor has the advantage of greatly reducing the fusion gain needed to yield net output power.

2.4 GENERAL DISCUSSION

We have tried to survey the range of reasonable reactor scenarios to find what characteristics of the driver can be deduced. The survey is admittedly superficial, partly because of limitations on time and resources, but certainly also because very little significant reactor design work has been done for ICF. The work that has been done appears to be tailored to show that marginal, (low energy-low efficiency) drivers could be used in a contrived fusion scenario. The history of ICF has been highlighted by attempts to make a pellet burn with whatever driver characteristics are available. By contrast, what is clearly needed is an adequate driver with which to study the properties of a range of pellet designs. The HIF driver would be the tool that could provide the definitive tests for ICF.

2.4.1 Reliability Discussion

If, in particular, a single driver provides beam to several fusion reactors, then the questions of reliability of critical components of the driver are crucial. Most linear accelerator systems, including those being proposed for HIF drivers, can operate with some acceleration stages turned off. Standby units are available with the next pulse should a fault be detected with one of the accelerating units. Indeed, the particle energy of the beam is normally adjusted by varying the number of standby units. Only the injector and front end or "low-beta" part of the linac is essential. These essential components, which comprise only about 5% of the total driver cost, can be replicated for reliability.

The trend in recent years has been toward power parks consisting of several generator facilities, each of about 1GWe capacity. For example, facilities consisting of clusters of up to eight 1GWe fission reactors are planned for Brazil, Iran and Saudi Arabia. The needs for security, a cadre of skilled operators and technicians, the pellet fabrication facility, etc., all lead to the conclusion that fusion power plants of the next century will be very large facilities. To mention just one very good reason; it is generally much easier to get governmental permits for one large facility, or to enlarge an existing site, than to arrange for several small or medium sized sites.

Another consideration is that reliability in power plants may not be as important in the future as it is today. Almost all electricity today is generated for high quality applications. It is simply too expensive to use electricity for most low quality applications, such as building heating, desalinization of water, hydrogen generation, etc. In the "intensive-electrification" scenarios studied for energy systems of the next century (ERDA-48), electricity must be used for many applications that are covered by fossil fuels today. Recalling that only solar energy, electricity, and waste heat from power plants will be available after fossil fuels run out, one recognizes that there will be both a much larger power grid than exists today, and many more interruptable users.

2.4.2 Tritium

A substantial case can be made for considering the tritium breeding reactor, rather than a power reactor, to be the logical first application of controlled fusion. A neutron converting lithium to tritium is more valuable than a neutron used only for its kinetic energy converted to heat. One can even envisage a scenario of magnetic confined fusion reactors becoming customers for ICF produced tritium.

Another aspect of the tritium problem is that, if substantial amounts of power are generated from pure fusion, lithium could become the limiting natural resource. This is because the lithium inventory in some fusion reactor designs is quite large and not because so much lithium will be converted to tritium. In fact, the identified U.S. terrestrial lithium, without resorting to obtaining it from seawater separation, could run D-T fusion power plants at ten times the 1976 U.S. electricity generating rate for 1000 years (Holdren [1978]). The lithium inventory problem would be solved if a few, dedicated, tritium breeding reactors were used rather than requiring a large lithium inventory in every fusion power reactor.

The tritium inventory needed for a fusion power plant has been estimated for some magnetic confinement systems. Although some designs, particularly those using the D-D reaction, may have a much smaller inventory, the typical number is 250MCi per GWe (Holdren [1978]). This is equivalent to about 25kg of tritium and would permit operation at the 1GWe level for about four days from a plant in which all the energy comes from the D-T reaction. The inventory is further broken down into "active" and "reserve" parts, the later consisting of about 60% of the total, is maintained in cold storage to permit continued operation when the tritium recovery system is down. The active part, which would be currently undergoing separation and preparation for injection into the reactor, would be the only part assumed potentially vulnerable to a sudden release.

2.4.3 Safety and Environmental Considerations

The traditional aim of fusion power is to provide an inexhaustable source of energy with a minimum of safety and environmental hazards. Some such hazards have been identified and these will be briefly discussed below.

The major new problem created by pure fusion is the handling of a large tritium inventory. Following Holdren [1978] along the lines of the previous section, if the "active" 100MCi were suddenly released, it would produce only about one percent of the number of early fatalities and injuries of the comparable fission reactor accident considered in the Rasmussen report (WASH 1400). Holdren points out that a further five-fold decrease in the tritium inventory, such as would be permitted by a reduced percentage of tritium in the pellets, would reduce to zero the prompt fatalities from a worst case tritium release. If, however, the accident involves the accidental release of quantities of LiOH from lithium reacting with water, the toxic hazard is far greater than the hazard from radioactivity (Booth [1977]).

A possibly more difficult problem is the one of "chronic" release of tritium which escapes into the biosphere. The daily loss of inventory should not exceed about one part per million in order to stay below present NRC "design objectives" for fission power reactors (Holdren [1978]). Designs are claimed for magnetic confinement that can theoretically achieve better containment than this implies, but practical experience, and application of these designs to ICF, are both required. Because tritium diffuses through metals faster at elevated temperature, tritium breeding fission reactors are kept relatively cool and are not simultaneously used for power generation.

The higher energy neutrons from fusion (about 14MeV) makes neutron shielding more difficult for fusion than for fission. The necessary barriers of concrete are practical and no major design effort appears needed for ICF. However, neutron activation of reactor materials does present a design problem. The effect of the release of activated materials in the event of a catastrophic accident also needs to be evaluated. Material lifetimes in such intense neutron fluxes are known to be limited. It is here perhaps more than in any other area, that ICF has an advantage over MFE. The simpler ICF reactor, without large external magnets for confinement, and with the driver far removed, has fewer sensitive materials in the vicinity of the intense flux of neutrons.

In the absence of any fission-fusion hybrid scheme, the containment and shutdown problems of fission reactors do not apply to fusion power. Even if fission fuel breeding is incorporated, as long as the fuel is kept cool, i.e., no attempt is made to extract fission energy to operate a power plant, it is easy to design in such a way as to assure safe shut down if any problems occur. This is perhaps the single best reason to avoid the fission-fusion hybrid in first generation fusion scenarios.

Accelerator safety is a well understood engineering discipline. Interlocks, personnel protection, and machine protection systems are in satisfactory use at all large research accelerators. In spite of the unprecedented power levels needed from an HIF driver, the accelerator shielding problems are less severe than those at any HEP laboratory. This is because the principal radiation hazard in HEP laboratories is from nuclear fragments due to the high energy per nucleon of the incident beam. Although the ion energy is high for HIF, the per nucleon energy (about 100MeV) is quite low and shielding is relatively easy.

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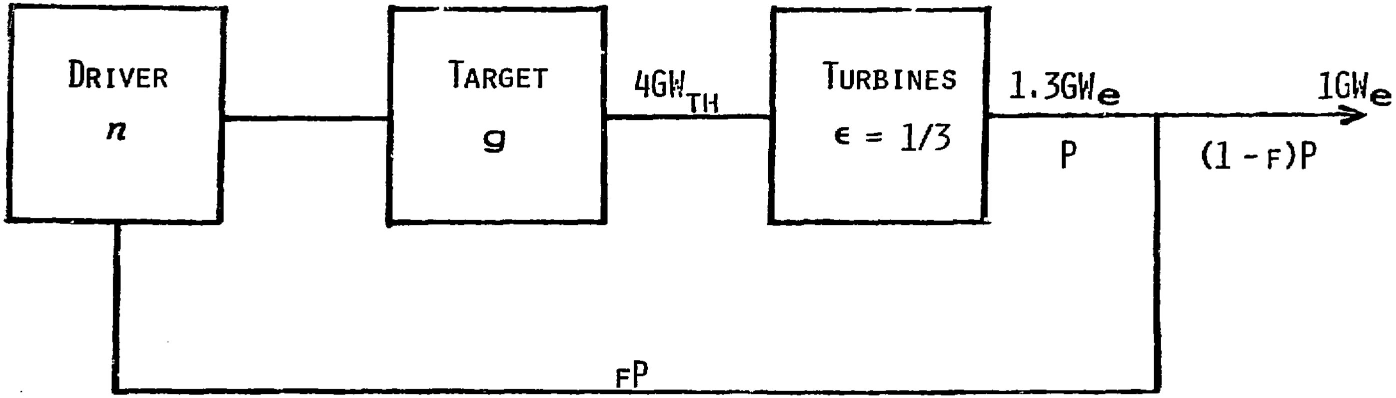
FIGURE 4: ENERGY FLOW IN AN ICF SYSTEM



$F P n g \epsilon = P$

$F = 1$ FOR NO NET POWER

$F \leqslant 0.25$ FOR ≥ 1 GW_e

$n g \geqslant 12$ FOR $1GW_e$

Figure 5: Pellet Gain Functions

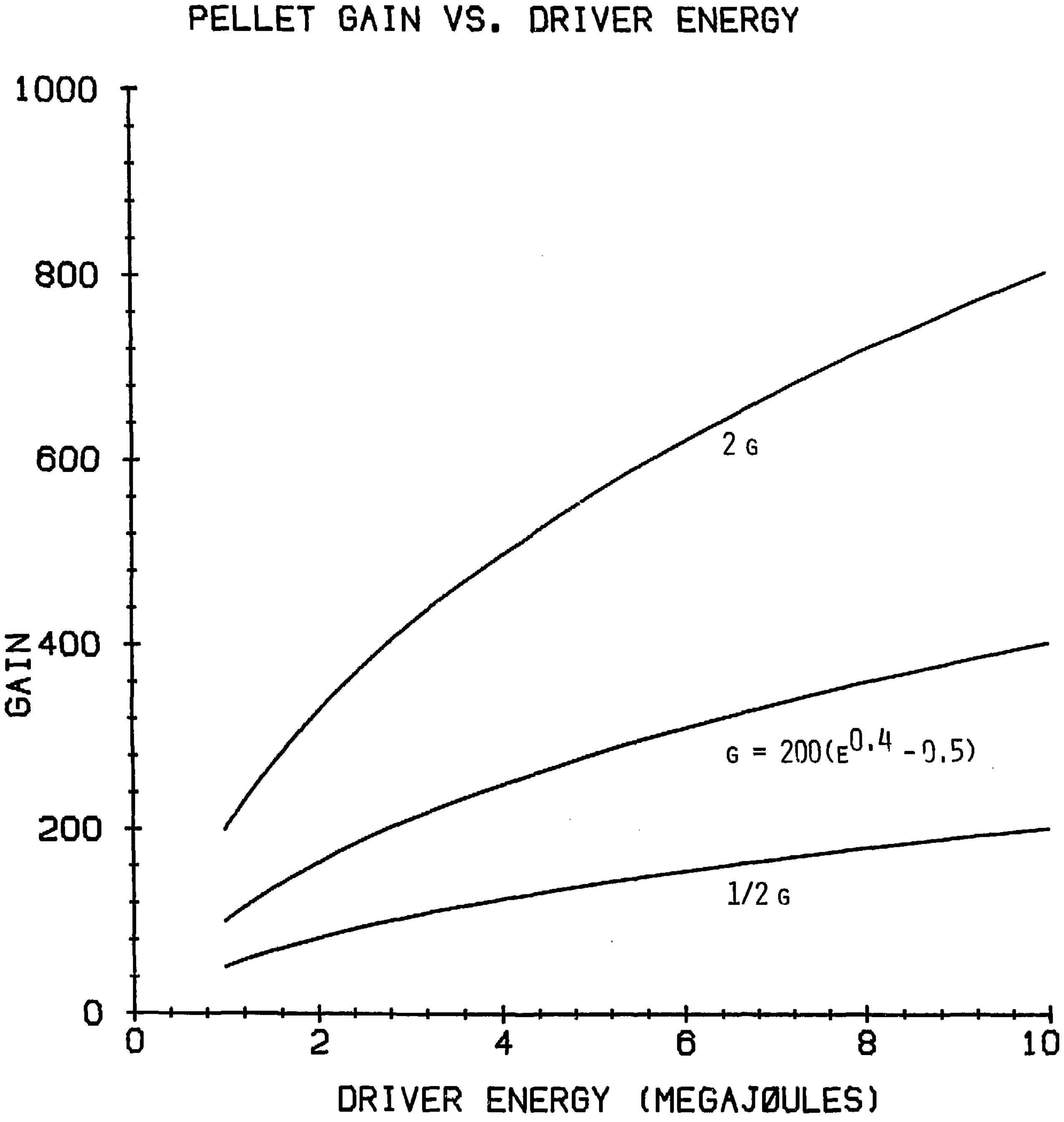


Figure 6: Pulse Repetition Rate for a Nominal 1 GWe Power Plant

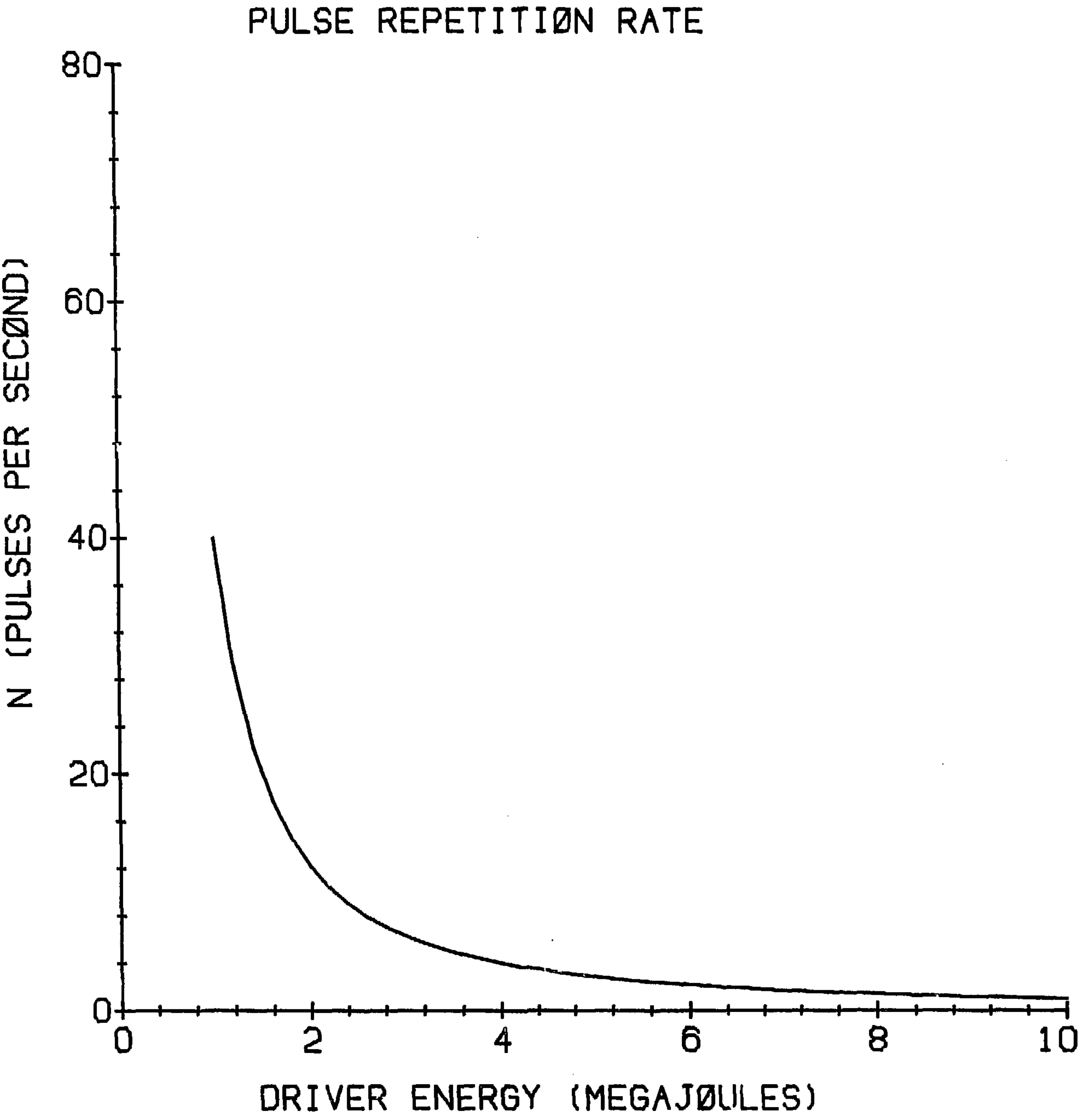


Figure 7: Capital Charge Rates for Driver Efficiencies of 3%, 6%, 12%, and 25%

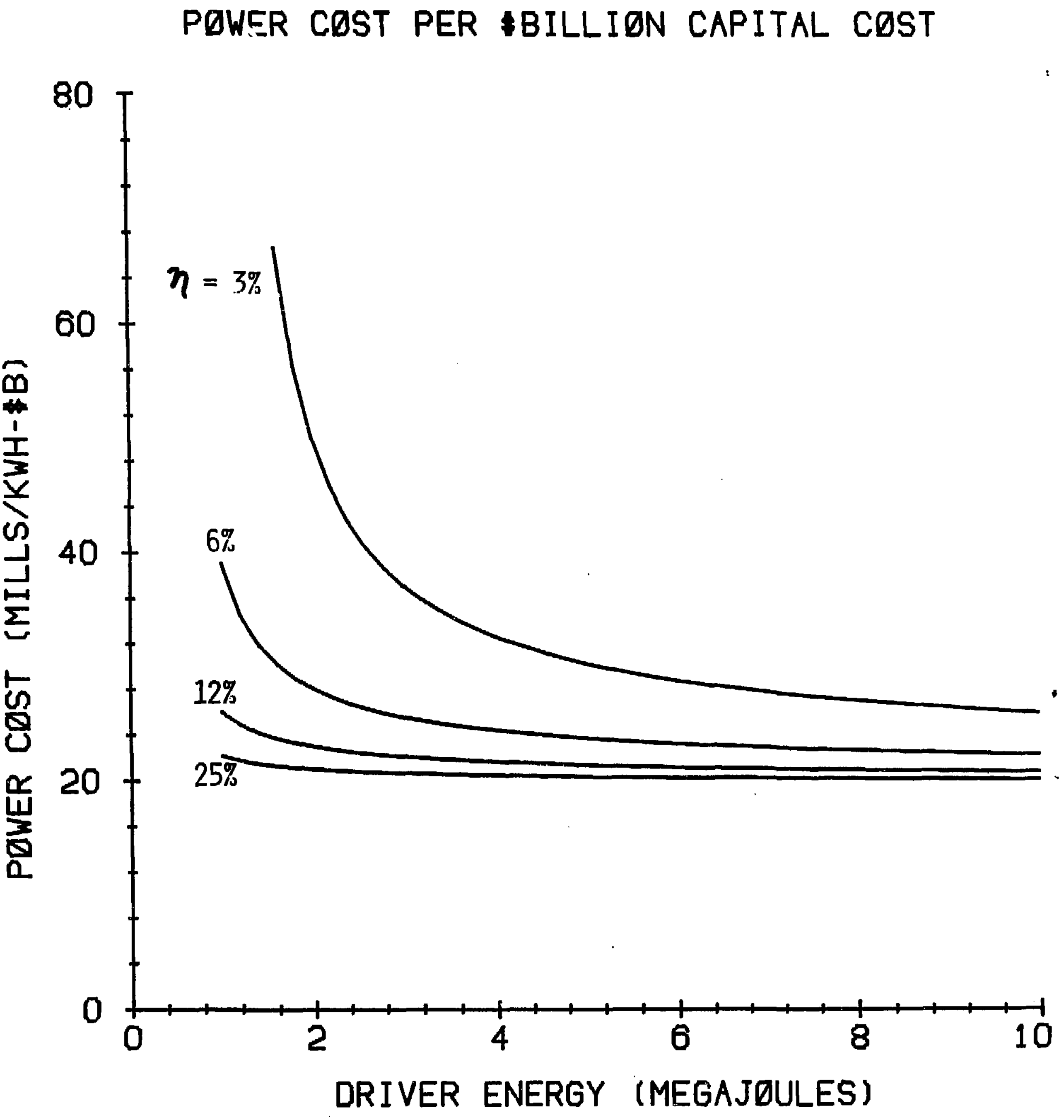


Figure 8: Capital Charge Rates for 6% and 25% drivers for the High- and Low-Gain Functions

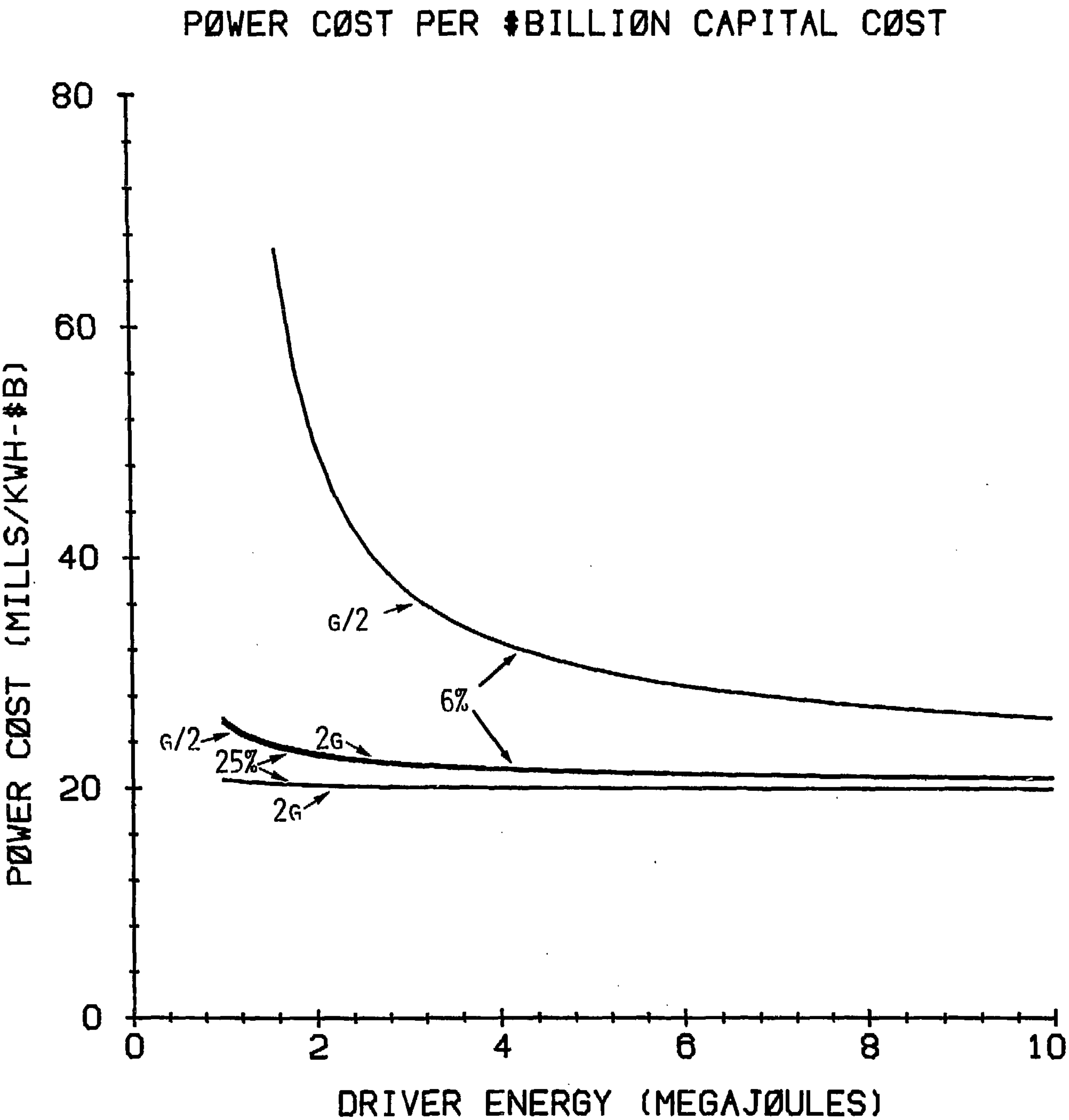


Figure 9: Total ICF System Capital Cost for HIF Driver, Modular Driver, and "Half-price" Modular Driver

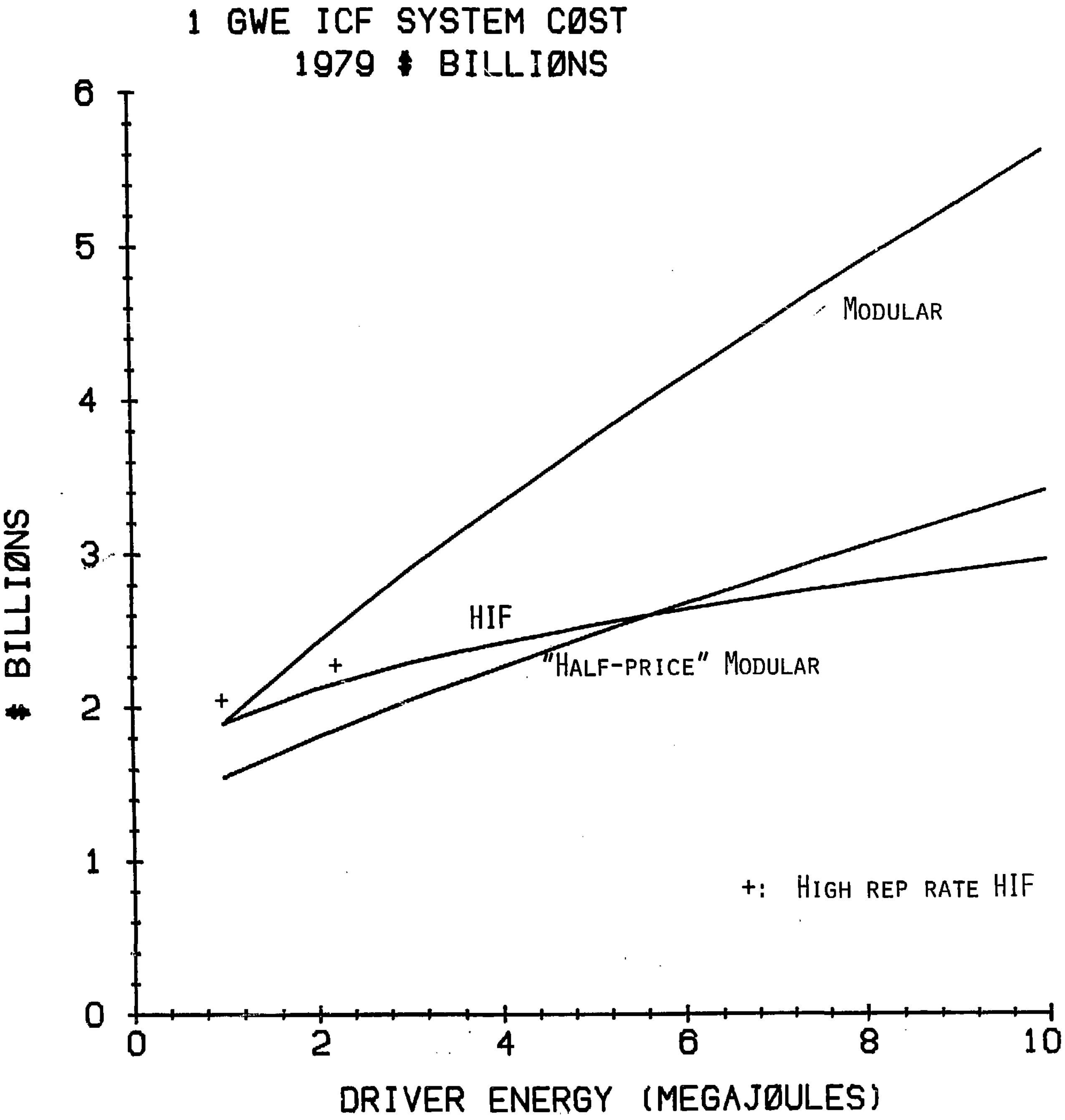


Figure 10: Cost of Electric Power with 25% Efficient Driver for Low-, Nominal-, and High-Gain Pellets

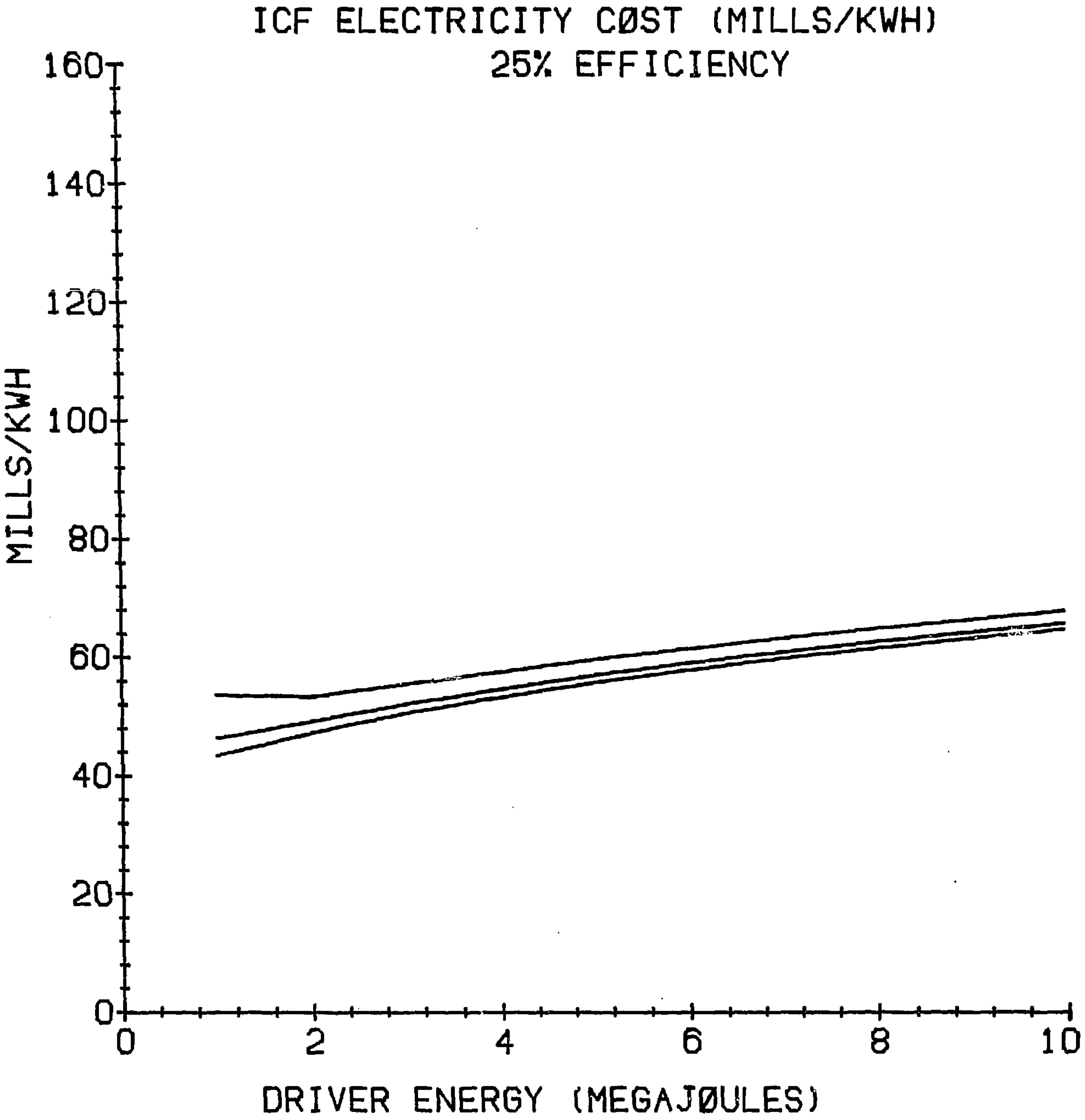


Figure 11: Cost of Electric Power for Nominal-Gain Pellets Using the HIF Cost Function

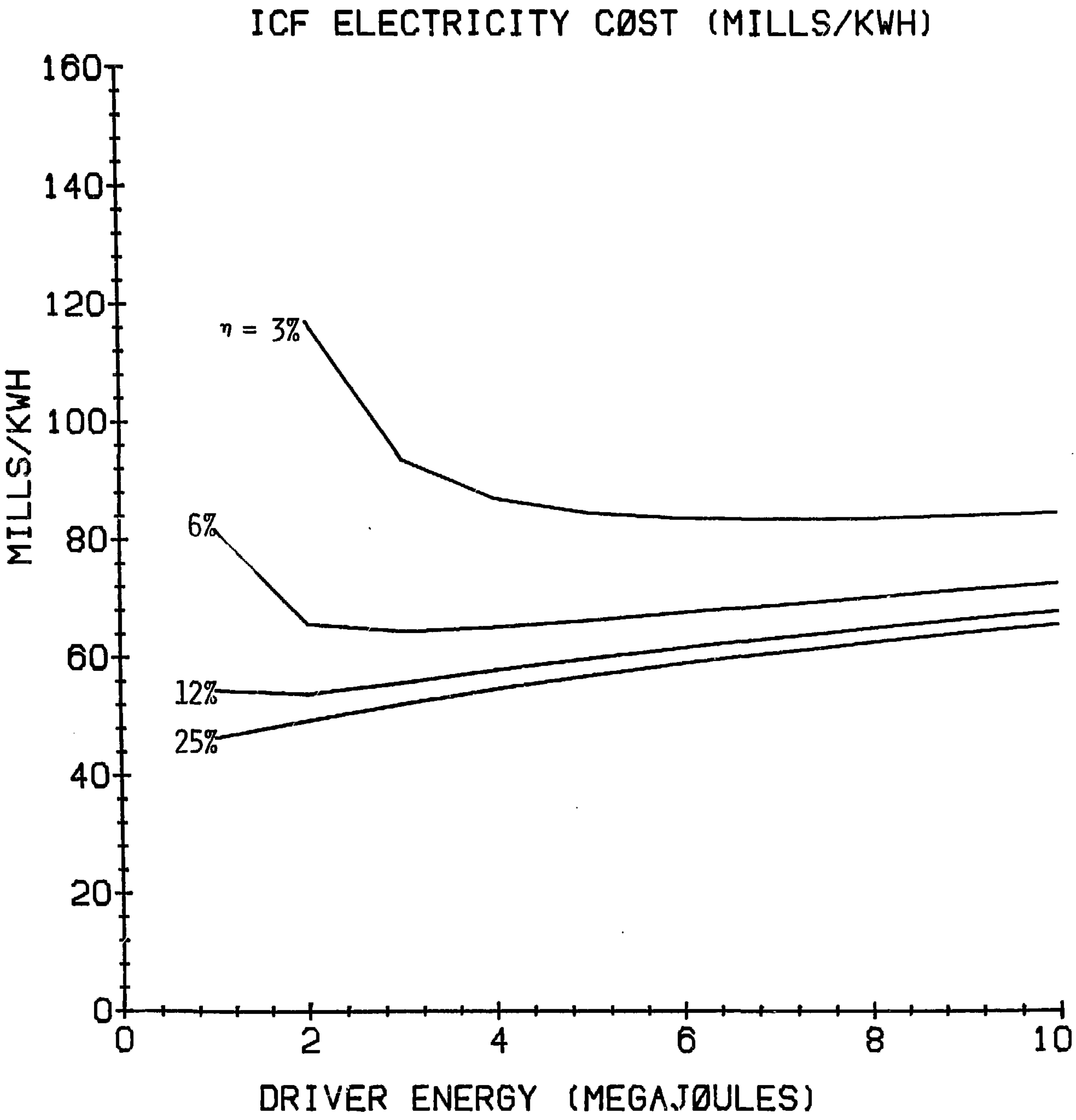


Figure 12: Cost of Electric Power for Nominal-Gain Pellets Using the HIF Cost Function

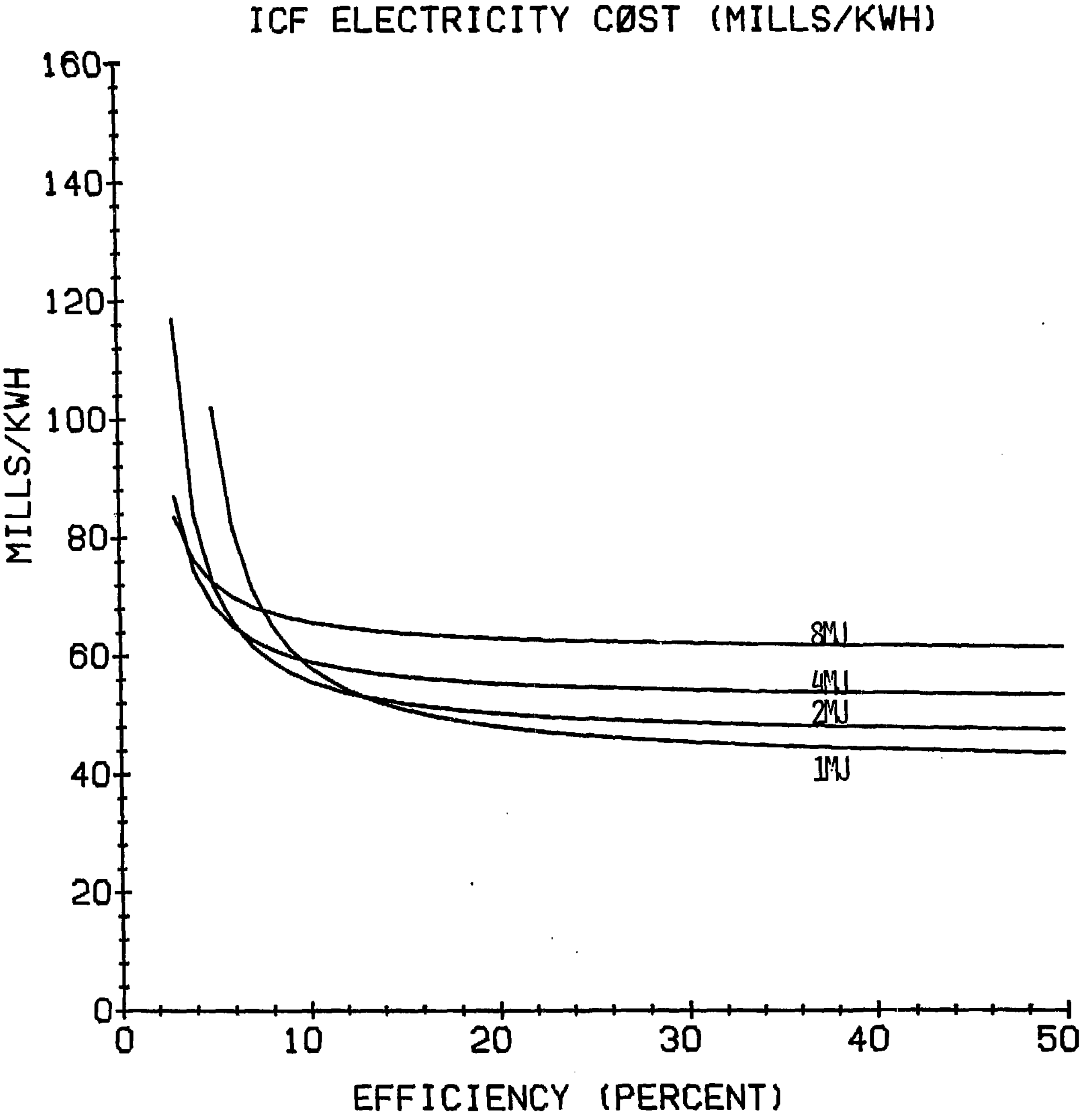


Figure 13: Cost of Electric Power for Nominal-Gain Pellets
Using the Modular Driver Cost Function

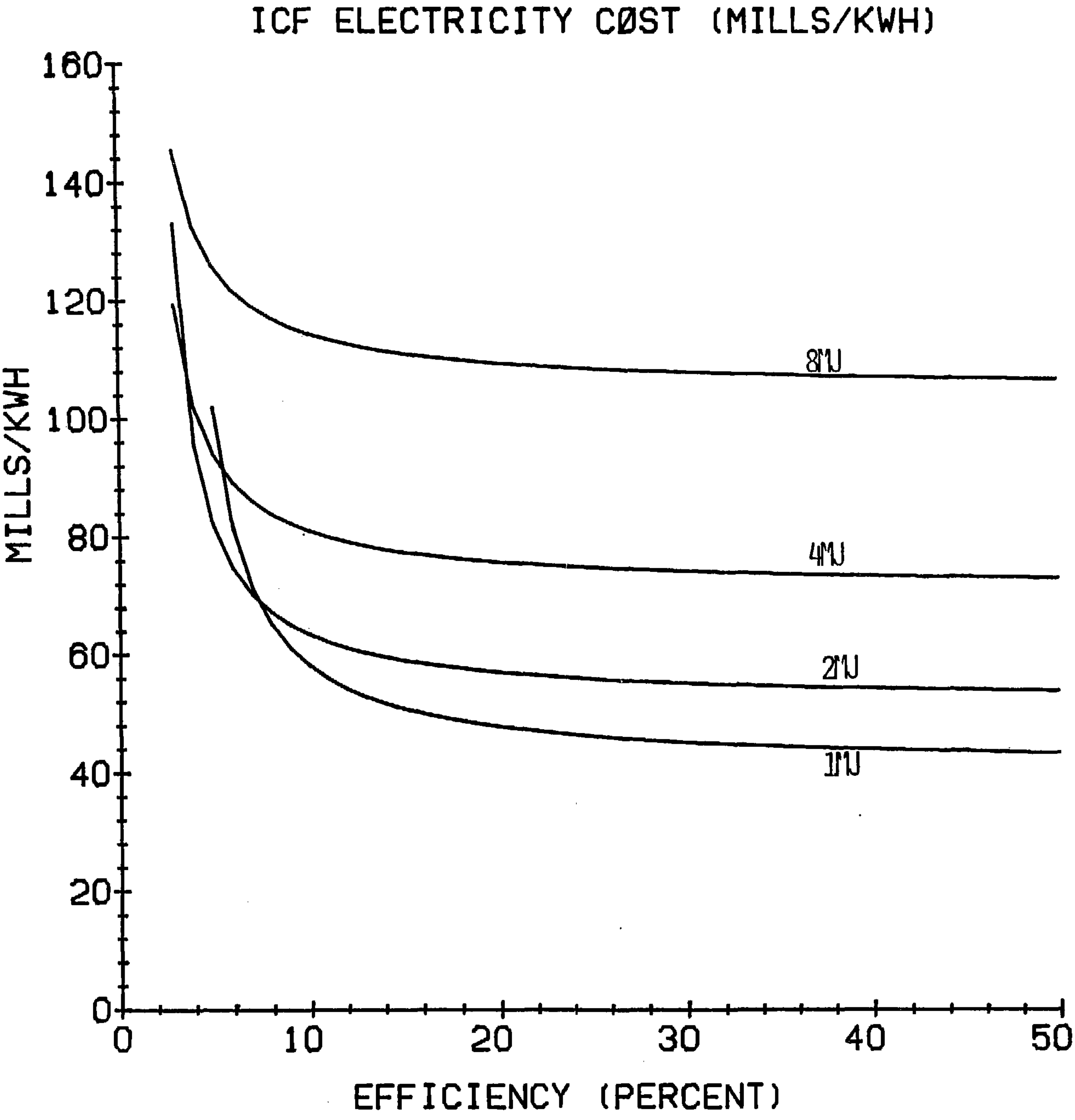
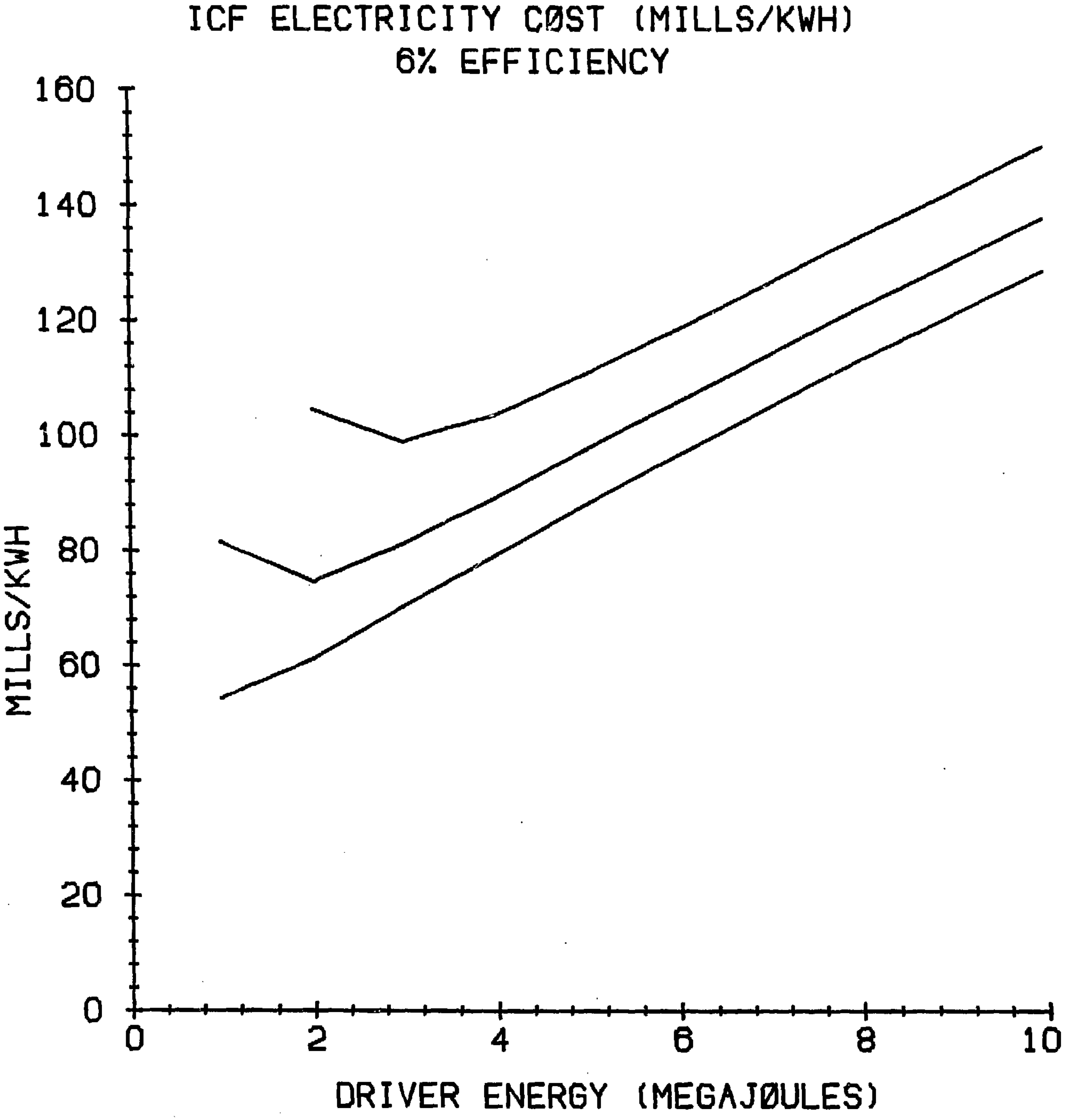


Figure 14: Cost of Electric Power with 6% Efficient Modular Driver for Low-, Nominal-, and High-Gain Pellets



Chapter 3

IONS AS ICF DRIVERS

by Roger O. Bangerter

3.1 THE BEAM-TARGET INTERACTION IN HEAVY ION FUSION

The beam-target interaction in laser fusion has proved to be a very challenging problem. It is therefore natural to be concerned about the beam-target interaction in heavy ion fusion. Much of this concern seems to arise from the feeling that a beam capable of target ignition is in some sense "intense" and thus qualitatively different than the low-intensity beams with which we are familiar in nuclear science. For example, we will show that for typical target and beam parameters the electron density in the target is roughly nine orders of magnitude larger than the density of beam ions. Furthermore there are about 1000 Debye lengths between beam ions in the target so that one might expect the beam ions to behave independently. These statements are simply an manifestation of the fact that for heavy ion fusion each particle carries a large energy (about 10GeV). This can be contrasted with light ion (proton) or electron beam fusion where the expected particle energy is 1-10MeV or with laser fusion where each photon carries an energy of about 1 eV.

However, there are some ways in which heavy ion beams must be considered intense. Collective effects are important in the propagation of the beam in the accelerator and through the combustion chamber to the target. This is discussed in Chapter 4; Heavy Ion Accelerators.

There are two classes of ion beam physics that must be considered: electromagnetic and nuclear. Recent accelerator design effort has been directed toward accelerating heavy ions to a maximum of about 20GeV. At this energy the calculated range of a heavy ion is much less than a nuclear collision length so that only a small fraction of the incident ions will produce nuclear reactions (Silberberg [1977]). Furthermore, nuclear processes are unaffected by the state of matter in the target so that measurements of cross sections with low intensity beams are directly applicable. The only area of conceivable uncertainty involves electromagnetic phenomena.

The electromagnetic interaction of low intensity ion beams with ordinary matter has been reasonably well understood for about 60 years. The calculated energy loss of heavy ions in matter (or range) is in excellent agreement with experiments (Tarle [1978]) (Northcliffe [1963]). However, experiments with heavy ion beams at the appropriate energies, intensities, and matter temperatures, have never been performed. Some additional relevant experiments might be performed at existing heavy ion accelerators, but it has not yet been possible to obtain fusion intensity beams. The continuing experiments in light ion fusion are also relevant to heavy ion deposition and may provide early verification of ion stopping predictions in hot matter.

In order to achieve fusion conditions, it is necessary to deposit $\geq 2 \cdot 10^7$J/g in the target (Bangerter [1977]). Thus for a given target size, less total energy is required if the range of the incident ions is short. On the other hand, there are significant accelerator design considerations that push one in the direction of high ion kinetic energy and therefore long range. Any anomalous effect that shortens the range of the ion would be welcome. Conversely, if the range of the ions were significantly larger than calculated it would increase the cost of the heavy ion accelerator. The estimates presented in the appendices show accelerator costs increasing as (output energy)$^{0.4}$. Thus if the range were 25% too long, one could compensate by increasing the output energy by 25% to achieve $\geq 2 \cdot 10^7$J/g. This would increase the accelerator cost by about ten percent. This represents the worst case because it might be possible to redesign the target or accelerator to reduce the cost penaly. Fortunately, fundamental physical arguments indicate that the range will not be significantly larger than calculated.

As an ion passes through matter, it transfers energy to the ions and electrons in the matter through binary Coulomb collisions. It may also lose energy through excitation of plasma waves or other collective processes (Jackson [1962]). In the following considerations, we will place an upper limit on the range of ions by making the pessimistic assumption that only binary Coulomb collisions with electrons contribute to the energy loss. As a by-product we will also obtain an expression for the spectrum of the energetic electrons produced by an ion beam, and discuss preheating in the target.

The cross section for scattering of electrons by ions with charge Z is given by the well-known Mott cross section.

$$\frac{d\sigma}{d\Omega} = \frac{Z^2 e^4}{4p^2 v^2 \sin^4\left(\frac{\theta}{2}\right)} \left[1 - v^2 \sin^2\left(\frac{\theta}{2}\right)\right]$$

where P is the three-momentum of the incident particle, v is its velocity, and O is the scattering angle. The speed of light is set equal to unity. Assuming that the electron is initially at rest (or moving slowly), it is convenient to express this cross section in terms of the final kinetic energy of the electron in the laboratory,

$$T = m\beta^2\gamma^2(1 - \cos\theta)$$

where m is the electron mass, beta is the ion velocity, and, as usual,

$$\gamma = (1 - \beta^2)^{-\frac{1}{2}} .$$

Making the transformation of variables, we obtain

$$\frac{d\sigma}{dT} = \frac{2\pi Z^2 e^4}{m\ {}^2}\left[\frac{1}{T^2} - \frac{1}{2m\gamma^2 T}\right].$$

Note that the maximum electron kinetic energy, Tmax, is given by setting $\cos\theta = -1$, so that

$$T_{max} = 2m\beta^2\gamma^2$$

For nonrelativistic ions, $2m\ {}^2T >> T^2$ so that the electron spectrum produced by nonrelativistic ions is given by

$$d\sigma/dT \propto 1/T^2$$

As usual, this diverges as T → 0, corresponding to an infinite impact parameter, and it is necessary to impose some Tmin. Physically, Tmin is determined by atomic binding energies or Debye screening, depending on the state of the stopping medium. In addition to the electrons having the $1/T^2$ spectrum, there can also be a component associated with the incident ion if it is not fully stripped when it hits the targets. Since these electrons have about the same velocity as the incident ion, their kinetic energy is down by the ratio of the sum of their masses to the ion mass. Thus they contain only a negligible fraction of the beam energy and can be ignored.

Using the electron spectrum we have performed detailed Monte Carlo calculations of target preheat. These calculations are somewhat dependent on specific target designs and beam energies, but indicate that electron preheat is not a problem.

We now return to the question of energy loss. The energy loss of an ion per unit length is calculated by integrating d /dT between Tmin and Tmax yielding,

$$dE/dx \propto Z_{eff}^{2}\left[\,\ell n(T_{maz}/T_{min}) - \beta^{2}\right]/\beta^{2}$$

Note that we have replaced Z^2 by $Zeff^2$ since the ion may not be fully stripped.

In order to obtain values for the parameters in this expression, we consider typical beam and target parameters. In particular, we will assume that a 10^{14} watt, 20GeV heavy ion beam (A about 200) is incident on a target having an electron density of $10^{24}/cm^3$ (approximately equal to solid density) at a temperature of 200eV. The beam radius is assumed to be ≥ 1mm. With these values, the ion density in the beam is $\leq 2\cdot 10^{14}/cm^3$. The Debye length is about $3\cdot 10^{-8}$cm and the thermal speed of the target electrons is about 0.03 c. For the typical speed of an incident ion, we take the value after it has lost one half of its initial energy, approximately 0.3 c.

It has been experimentally established that Zeff is a function of ion velocity (Betz [1962]) (Brown [1972]). As one might expect, an ion is stripped to the point that the orbital velocities of the remaining electrons are about equal to the velocity of the ion. Brown and Moak (Brown [1972]) find that the experimental data for a variety of projectiles and targets are well approximated by $Zeff/Z = 1-1.034\exp(-137\beta/Z^{0.69})$. Thus for $\beta \geq 0.3$ even heavy ions are more than 80% ionized and the dependence of Zeff on b has become very weak. Although the experiments have been performed in cold matter, the fact that Zeff depends only on β and not on other target characteristics implies that in the plasma case Zeff will depend on the relative velocity of the ion with respect to the target particles. In our case β is an order of magnitude larger than βe which is in turn 2 or 3 orders of magnitude larger than the thermal velocity of the target ions so that temperature effects on Zeff should be small. In fact, in the limiting case where $\beta \ll \beta e$, Zeff is increased relative to cold matter by thermal ionization.

In obtaining dE/dX, we should also integrate over the appropriate thermal electron distribution. It can be shown that this is important only for $\beta \leq \beta e$ (Spitzer [1962]).

For $\beta = 0.3$, Tmax is about 100keV. In a plasma the electric field of the incident ion is expected to be screened at distances greater than the Debye length. Thus, for free electrons, Tmin is determined by setting the impact parameter equal to a Debye length. In this case, (Jackson [1962])

$$T_{min} = \frac{2Z_{eff}^2 e^4}{[illegible]} \lesssim 10^{-2} \text{ keV} .$$

Since the electron density is about $10^{23}/cm^3$ and the Debye length is about $3 \bullet 10^{-8}$cm there are only a few electrons in a Debye "cube". For this reason collisions with impact parameters less than the Debye length must be unscreened binary collisions. We can ignore β^2 compared to ln(Tmax/Tmin) since Tmax/Tmin≥10^4. The energy loss due to plasma excitation at impact parameters larger than a Debye length has been calculated by Jackson [1962]. The net effect of this additional loss is equivalent to multiplying Tmax/Tmin by $[1.123\beta/\omega p \lambda D]^2$ where ωp is the plasma frequency. For our assumed conditions this increases the value of Tmax/Tmin by a factor of 290. Thus even in the worst case where Tmax=10^4, binary collisions alone account for $\ln(10^4)/\ln(290 \bullet 10^4)$ = 62% of the total dE/dx. This represents a minimum energy loss rate that is independent of a detailed understanding of the plasma physics.

Our ability to calculate this minimum energy loss rate depends on only three obvious or well-tested assumptions:

1. Validity of the Mott cross section.
2. Weak dependence of Zeff on target conditions for relevant beam and target parameters.
3. Binary nature of collisions for impact parameters less than a Debye length (especially since there are only a few electrons per Debye cube).

Since the ions must lose energy through binary collisions that account for most of the energy loss, the only way the range can be significantly longer than calculated is for some mechanism to exist that accelerates the ions. To compete with the binary collisions, the accelerating field would have to add about 20GeV to a heavy ion in about 1cm (range about $1g/cm^2$ → 1cm at density = $1g/cm^3$). Assuming Zeff ≤ 100, this would require a minimum electric field of $2 \bullet 10^8$V/cm over a distance of about 1cm.

Since the only source of energy is the ion beam this would require a chain of events whereby the ion beam could accelerate itself. In any case $2 \bullet 10^8$V/cm fields are rather inconceivable. Joule heating results in a power dissipation per unit volume given by E^2/η where E is the electric field and η is the resistivity of the plasma. Following Spitzer [1962] we calculate $n=10^{-3}$ ohm-cm for a high-Z plasma and $\eta=10^{-5}$ ohm-cm for a low-Z plasma. Since the total power deposited by the beam is only about $3 \bullet 10^{15}W/cm^3$ the Spitzer resistivity would have to be wrong by more than 3 to 5 orders of magnitude before such fields become energeticaly possible.

In order to simplify the analysis we have considered only free electrons. For typical conditions high-Z targets are only about 40% ionized so that there is also a contribution to dE/dx from bound electrons. Energy transfer to bound electrons is well understood from our experience with ordinary matter (Northcliffe [1963]), but two modifications are required in the partially ionized case. The average binding energy of the electrons is increased and impact parameters greater than the Debye length are excluded. Neither of these modifications fundamentally alters the physics of the situation.

If the beam strikes matter at all, we are confident that it will stop as predicted. If the beam carried a large amount of momentum, it is conceivable that it could sweep the target material out of its way. Very simple calculations show that the effects of momentum deposition by a heavy ion beam are negligible compared to the thermal pressure developed by energy deposition. In conclusion, it seems unlikely that fusion-intensity ion beams will have significantly less energy loss than predicted.

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Chapter 4

HEAVY ION ACCELERATORS

by Lloyd Smith

The purpose of this chapter is to provide some orientation in accelerator technology as applicable to the HIF application. The various components will be briefly described, certain essential concepts will be defined, and the aspects requiring new development will be pointed out. More detailed information can be found in the proceedings of the three workshop sessions and in reports issued by various laboratories.

4.1 PRINCIPAL COMPONENTS

4.1.1 Injectors

4.1.1.1 Ion Sources

The production of ions for acceleration is a more complex process than the production of electrons, which can be obtained in copious amounts from a conventional cathode or field emission source. The method that has been used for over forty years is to establish a gaseous discharge in a small, enclosed volume; ions of the desired species are extracted by applying an electric field to the plasma surface. Currents of heavy ions, adequate in intensity and brightness for injection into an rf linear accelerator, can be readily obtained in this way. Other types of accelerators require much higher currents than the rf linac and for this reason development work is under way or contemplated on contact ionization sources, the use of pulsed diodes, and multiple arrays of conventional sources. All of these methods have yielded high currents in other applications, but their compatibility with a subsequent accelerator has not been demonstrated.

4.1.1.2 Pre-accelerators

The typical ion source operates with extraction voltages of some tens of kilovolts, at which level the velocity of the ions is low and the mutually repulsive space charge forces are too great to permit acceptance by any of the main accelerator systems. Consequently the ion source is housed in a terminal maintained at high dc voltage, most commonly provided by the voltage multiplying circuit first used by Cockroft and Walton in 1932. A voltage of 750 kilovolts is convenient and standard for proton accelerators; higher voltage would be desirable for intense heavy ion beams, but the practical upper limit is probably a few million volts (Van de Graaff accelerators are not able to meet the high current requirements).

4.1.1.3 Low-beta Accelerators

For the proton machines of HEP, dc acceleration to less than 1MeV is adequate for injection into a conventional rf linac even at intensities of several hundred milliamperes. Heavy ions at that energy are moving more slowly by an order of magnitude (thus the term "low-beta", beta being the symbol for the ratio of ion speed to the velocity of light) so that even though the current may be only 50mA or less, another element must be added to the accelerating chain. This element represents a new development in accelerator technology and absorbs much of the current effort in all three of the U.S. laboratories involved.

The problem lies in the fact that if oscillating electric fields are used for acceleration (one of the few available options), the efficiency of acceleration and maintenance of beam quality are strongly increasing functions of the ratio of velocity to oscillation frequency, so that for exceptionally low velocity, an exceptionally low frequency must be used. The use of a resonant cavity is precluded because of its enormous size and power consumption; a different electrical configuration is needed which will also provide space for adequately strong focusing elements to overcome the transverse space charge forces. A favored candidate is the Wideroe structure, invented in 1928, but abandoned later when power sources at high frequency became available. The Wideroe was resurrected in recent years by GSI in Darmstadt, where a modern version works well for heavy ion acceleration, but is still at a very low current and at a frequency substantially higher than what is required for the HIF application. A similar machine is under construction at LBL. Somewhat different configurations, specific to high current acceleration of heavy ions, are being explored at ANL and BNL.

For the induction linac to be used as a single pass device, with a single bunch traveling from ion source to pellet, it is desirable to start with such high currents that continuously oscillating fields are not attractive; instead a series of electrodes pulsed on and off as the bunch passes is being developed. The electrodes, called drift tubes, are made as large as is necessary to let the entire bunch be shielded inside as the potential of the drift tube is switched to form an accelerating field at the next gap. The electrotstatic focusing system, which is used to confine the beam transversely, is effective for a charge density up to about 10uC/m³. The charge needed for HIF, up to about 200uC, would require drift tube sections with up to about 20m³ of active volume. Longitudinal focusing can be provided by shaping the accelerating voltage pulse.

4.1.2 Main Accelerators

Although there are many types of accelerators which can provide particle beam energies suitable for HIF, all but a few have limitations which preclude their use. The cyclotron, for example, has served well in heavy ion research for many years, but is inherently a dc device, providing currents in the microampere range. Its variant, the synchrocyclotron, is restricted to even lower intensities. Apart from the three devices described below, a number of schemes have proposed, and some are in an experimental stage, to accelerate ions in intense bursts by means of electric fields from even more intense streams or bunches of electrons. As of this writing, nothing of this sort has reached a stage of development which permits evaluation of applicability to HIF.

4.1.2.1 Rf Linacs

The type of rf linac best suited to HIF is called the Alvarez structure, the first of which was built by Louis Alvarez at the end of World War II, exploiting the then new developments in radar transmitters. In its present form it consists of a succession of cylindrical cavities, resonant at frequencies from about 50 to 200MHz in their lowest mode, in which there is a uniform axial electric field. In each cavity is suspended a succession of smaller cylinders ("drift tubes") adjusted in length so that as the ions pass through the cavity, they are shielded from the electric field in its decelerating phase. In order to provide the transverse containment for the beam, focusing magnets or electrodes are contained in each of the drift tubes. Rf power to maintain the accelerating field and to supply energy to the ions is coupled into the sides of the cavities from multi-megawatt power amplifiers.

Every high energy proton accelerator has an Alvarez linac in its chain of accelerators, and so the behavior of this type of accelerator is very well known. Average electric fields of a few MV/m are conservative and appropriate to this application. Average currents approaching an ampere are feasible, providing the beam is properly prepared in the preceding low-beta accelerators.

4.1.2.2 Induction Linacs

The first induction linac was built by N. Christofilos in 1958. In spite of its relative newness, the induction linac is attractive for HIF because of its high current capability. With the induction linac it is possible to make a single-pass system from ion source to pellet, achieving current multiplication by compression during acceleration. The accelerating action can be described as analogous to a transformer; there is a ferromagnetic ring with a one-turn primary and the beam acts as a one-turn secondary winding. Actually, pulsed power terminology is more accurate and more relevant to induction linac technology. An energy source (capacitors, Blumlein line, or other) is connected by a switch (spark gap) to a transmission line which enters the non-resonant accelerating module from the side.

The line voltage, power, and impedance are seen by the passing beam on one side of the transmission line while the ferromagnetic material on the other side presents a high impedance which prevents the energy from entering the side away from the beam. Accelerating capability, expressed as the product of gap voltage times pulse length, is limited by saturation of the ferromagnetic material, which is in turn determined by the amount of material present. A high repetition rate is achievable because the energy per module us much less than in the typical pulsed diode. The voltage wave form can be precisely controlled because the beam current is independent of voltage; however, the line characteristics must be matched to the anticipated current.

Transverse focusing for the induction linac is provided by magnets placed between accelerating modules. In contrast to the rf linac, in which beam intensity is limited by the rate at which the cavity stored energy can be replaced, the induction linac works best when the pulse length is short (to decrease the amount of ferromagnetic material needed for a given voltage) and the current is high (to increase the efficiency of supplying energy to the beam). Therefore it is important to compress the bunch as rapidly as possible during acceleration by shaping the voltage wave form. The ability of the focusing fields to contain high currents, a subject to be discussed in a later section, becomes a dominant factor in the design of an induction linac.

4.1.2.3 Synchrotrons

The work horse in HEP applications for the past twenty years has been the alternating gradient ("strong focusing") proton synchrotron. This machine consists of an array of bending and quadrupole magnets closing on itself around an approximately circular path. Accelerating cavities on a more modest scale than in an rf linac are distributed arount the ring. Ions are injected into the ring from a linac or smaller synchrotron, after which the magnetic fields are increased in strength. In accordance with the principle of phase stability, discovered by McMillan and Veksler 35 years ago, bunches of ions are locked in step with the rf frequency and gain energy from the rf cavities, and the frequency is modulated upward to correspond to the rotation frequency demanded by the increasing magnetic field. At peak magnetic field and ion kinetic energy, the ions can be extracted from the ring, usually by pulsing special magnets, and the beam can be used for physics experiments. This process can be repeated, up to about once per second for ramped magnetic fields, or at 10 pulses per second or more with magnet power supplies based on resonant circuits.

Although the synchrotron is the simplest and most economic means available for achieving high kinetic energy, and total energies on the order of a megajoule seem feasible, peak current is severely restricted except under highly transient conditions. The tolerable range of transverse ion optical oscillations is quite low because the repetitive circulation of the beam permits resonant interaction with magnetic field imperfections and resulting catastrophic loss of beam. Consequently, a substantial change in transverse frequency due to space charge forces is unacceptable. It follows that the beam must be extracted in many small bunches, complicating delivery to a target pellet.

The energy efficiency of a synchrotron is inherantly low because of the power required by the magnets. In short, due to limitations of current, repetition rate, and efficiency, for the presently accepted target requirements, the synchrotron seems the least likely candidate for the main accelerator, in spite of its basic simplicity, economy of construction, and long history of reliable performance. The synchrotron principle might still be applied in an intermediate scenario, for example as an inexpensive means of increasing the energy of an accumulated beam.

4.1.3 Other Components

In addition to the accelerating systems, an number of other components are required to provide current amplification and to deliver the ions to the target. Those currently under consideration are described in this section.

4.1.3.1 Accumulator Rings

The current expected from a single conventional ion source and low-beta accelerator is of the order of 25mA. By using several such units funneling together in pairs to form a tree-like collection of rf linacs, a current of perhaps 500mA can be achieved at the high kinetic energy end. Such a manipulation has never been experimentally tested but appears on paper to be feasible. Even so, the problem remains to reach the kiloampere level. An obvious step in that process is to have the linac feed one or more accumulator rings. These rings would consist of arrays of bending and focusing magnets, similar to a synchrotron in appearance, but operating at constant field strength, thus eliminating the expensive pulsed power requirement. They would probably use superconducting magnets to reduce electrical power requirements. The linac beam can be injected into an accumulator ring for as many as a hundred turns. The resulting circulating current would then be about 50 amperes. Another potential application of accumulator rings is to match the low energy end of an induction linac to an ion source.

4.1.3.2 Linear Compressors

The final stage of compression of bunch length and corresponding increase in instantaneous current is probably most easily achieved by using induction accelerator modules in which the voltage waveform is such that the early-arriving ions are decelerated slightly and the late ones strongly accelerated. The ions then drift freely, contained transversely by quadrupole magnets, until the faster ions catch up with the slower ones at the target. The induction accelerator modules can be located in the accumulator rings and/or in the transport lines following beam extraction from the rings.

4.1.3.3 Beam Transport Lines

At each stage of transfer from one type of accelerator to another, from accelerator to accumulator rings, and from rings to the target, the beams are guided by a succession of focusing magnets, most probably superconducting quadrupoles. Such lines are standard equipment in HEP installations, mostly still using iron-copper quadrupoles, but shifting toward superconducting magnets as that technology matures and the cost of electric power rises. These transport lines are mentioned here because they will probably be numerous and will contribute substantially to the capital cost of a HIF facility. The present picture of the target is that of an object with two or more spots which must be hit with the beam. Various constraints on beam properties to be discussed later tend to favor the use of multiple beams. Just how many beams will be manageable in practice is a subject of current debate, but there probably will be several lines approaching the target on each side of a two-sided symmetrical configuration.

4.1.3.4 Final Focusing

A small but important part of each transport line to the target is the last set of two or three quadrupoles whose function is to concentrate the beam on a spot a few millimeters in diameter located five or ten meters from the last quadrupole. In contrast to the transfer line, in which an aperture of the order of ten centimeters is adequate, beam optics constraints require an expansion to perhaps as much as a meter in diameter in the final lenses. At that size, fortunately, space charge forces are relatively unimportant and remain so in the reactor vessel even without the charge and current neutralization that would be provided by a background plasma. This is because the ions, which are of fairly high energy and are quite hard to bend, are highly concentrated for only a very short distance near the target. However, the lenses must be of high quality, comparable to the best that has been achieved in quadrupoles for other applications. A more fundamental problem is that of aberrations; chromatic because of the momentum spread in the beam, and geometric (analogous to spherical aberration in light optics) due primarily to the non-linear fringing fields at the ends of the quadrupoles. Means for compensating for these effects are being investigated, but it may well turn out that the properties of the final lens systems will dictate the entire accelerator complex (beam quality, number of beam lines, number of accumulator rings, etc.) since the fraction of beam striking the target is a direct multiplier on overall efficiency.

4.2 BEAM LOSS MECHANISMS

In operations such as the combining and splitting of beams, physical structures such as electrodes or current carrying sheets must often be located in places where they may intercept some fraction of the ions. This problem is well known and the losses can be restricted to a few percent in a predictable way. Also well known is the phenomenon of catastrophic loss due to failure of some component. Places at which the beam has sufficient energy to damage the vacuum chamber or other components are protected by suitable protection collimators or beam dumps which are blocks of material, cooled if necessary, and capable of absorbing the beam energy. Radiation hazards should be minimal for the types of accelerators being considered since at these kinetic energies, the range of the ions is much less than the nuclear mean free path. Thus the ions are stopped by atomic collisions, resulting in heating the stopper, rather than by nuclear interactions which, with faster ions, can result in the emission of nuclear fragments.

There are two other loss mechanisms which are not as well understood because of uncertainties in some atomic cross-sections. If an ion in colliding with a molecule of residual gas, gains or loses an electron, the change in radius of curvature in bending magnets or quadrupole lenses, will drive it into the wall of the vacuum chamber. A significantly good vacuum is thus required to prevent significant losses. Because the ions spend a relatively long time in circular machines, the vacuum required in accumulator rings and synchrotrons is in the range 10^{-10} to 10^{-11}Torr, which is achievable with present day techniques. In the linear accelerators, either the rf linac or the induction linac, vacuum requirements are usually determined by voltage breakdown limits and pressures $\leq 10^{-7}$Torr, which are needed, are adequate for the beam loss criterion. There is no reason to believe that heavy ions lost to the walls will cause more secondary emission problems than are known with proton beams, but an experimental check of this subject should be made at some time.

The second bothersome loss mechanism is intra-beam charge exchange. Within a bunch, the ions are in constant collision with each other as they oscillate back and forth. If such an encounter leads to a change in charge state, the ion will be lost to the wall of the vacuum chamber. The probability of such an event is poorly known as no experimental data exists. Present best estimates lead to lifetimes of the order of one second. This is on the border line for success or failure for some otherwise attractive schemes using accumulator rings with singly or doubly charged ions. Some improvement can be expected if some specific ionization states are chosen to leave the ion in a closed shell, such as Xe^{+8}. There is an urgent need for experimental information in this area.

4.3 THEORETICAL CONSIDERATIONS

This section deals with some matters of principle which are well known and set the framework for design requirements, and also with some new questions specific to HIF which strongly influence design but which are not easy to answer experimentally until intense high heavy ion beams are available.

4.3.1 Phase Space Constraints

From ion source to target, the forces applied to the ions to contain and accelerate them, and the forces exerted by the ions on each other, are electro-magnetic in nature and are derivable from the formalism of Hamilton. If individual particle encounters are neglected compared to the long range collective forces, (an excellent approximation for accelerators), then Liouville's Theorem reduces to the statement that the volume occupied by the required number of particles in the six-dimensional space of three coordinates, and the corresponding components of momentum, is a constant of the motion. The area of the projection of this volume onto a plane defined by one coordinate and its corresponding momentum component is called the emittance of the beam in that degree of freedom; horizontal, vertical or longitudinal. The product of the three emittances is the six dimensional volume and is also a constant of the motion.

This theorem provides a powerful necessary condition on choice of design. If the transverse emittances at the final lens are limited by geometric aberrations, and the longitudinal emittance is limited by pulse duration and allowable momentum spread, and the maximum number of beams is limited by practical considerations, then the ion source and low-beta accelerator must supply the required number of ions in a phase volume less than the product of the final three emittances and the number of final beams. If this is not achieved, no degree of complexity or ingenuity in the intervening hardware can produce the desired result.

Unfortunately, the theorem does not establish a sufficient condition. In practice, it is impossible to carry out the various required beam manipulations without stirring some "air" into the six-dimensional volume, much as the volume of an egg is increased by beating it. According to the present knowledge of ion sources and low-beta accelerators, and presently specified target parameters, the necessary conditions are satisfied by a comfortable margin. Nevertheless, a substantial accelerator experiment is needed to determine how well the dilution of phase volume can be controlled. The nature of the problem is well known from experiences with research accelerators, but in that field there has been little incentive to achieve high efficiency and there has been no experience with the beam intensities required for HIF.

4.3.2 Space Charge Limit in Circular Accelerators and Accumulator Rings

As mentioned in the section describing synchrotrons, circular machines are quite sensitive to the ratio of transverse oscillation frequency, determined by the strength of the focusing quadrupoles and the defocusing effect of the space charge, to the rotation frequency. For example, an integral number of oscillations per turn is disastrous because the corresponding Fourier component of errors in guide field strength or quadrupole position will quickly drive the oscillations of the particles to an amplitude exceeding the vacuum chamber dimensions. Even if the tune is kept well away from an integer, the tolerance on quadrupole position is a few tenths of a millimeter; a large synchrotron is one of the finest examples of precision surveying. At half-integer tune, errors in quadrupole strength cause the oscillations to be linearly unstable and at smaller fractional values, non-linear instabilities arise, but in this case the amplitude growth is limited by the slightly non-linear character of the unperturbed oscillations. For reliable and reproducible performance, the tune is usually controlled by correcting elements to within a few hundredths of an integer.

If the space charge forces on all the particles were the same, the tune could still be controlled by correcting elements. However, the particles must be bunched in azimuth either for acceleration or as a means of current amplification before subsequent extraction. In this situation, particles at the center of the bunch experience stronger defocusing forces than those at the ends, and external compensation for all particles simultaneously is not possible. Analysis of particle motion including the forces between particles is quite complicated, but rough estimates combined with extensive experience indicate that the maximum tolerable tune depression is about one quarter of an integer. The formula used for introducing this constraint into synchrotron or accumulator ring design is derived by assuming a uniform space charge density, which gives rise to a linear self force, and computing the resulting decrease in oscillation frequency. The decrease in tune, $\Delta\nu$, is approximately

$$\Delta\nu = \frac{I}{I_\alpha}\,\frac{R}{\epsilon_n}\,\frac{(BF)}{(\beta\gamma)^2}$$

where I = average circulating current,
R = machine radius,
I_α = Alfven current = mc^3/Ze,
ϵ_n = transverse emittance/mc,
(BF) = bunching factor = peak/average current, and
m = ion mass.

This expression can be written in various ways to demonstrate explicit dependence on charge state, stored energy, magnetic guide field, etc. In the form given as applied to injection into a synchrotron of fixed radius, it shows that circulating current can be increased only by lowering the charge state or increasing the emittance or injecting at a higher kinetic energy. Such changes require a more expensive injector, larger synchrotron aperture and more elaborate subsequent manipulation to reduce the final emittance per beam on target to an acceptable level. Thus the restriction $\Delta\nu \leq 0.25$ accounts in large part for the multiplicity of synchrotrons and accumulator rings called for in various design studies.

4.3.3 Beam Transport Limits

As mentioned in the section describing the induction linac, there is a cost premium on keeping the bunch length and instantaneous current as high as possible. Also in any scheme, instantaneous currents of the order of kiloamperes are required in the final approach to the target. A question, outside of any experience in high energy accelerator technology, then arises; what level of current can be transported for long distances in a quadrupole beam line without serious degredation in longitudinal or transverse emittance? Much theoretical and experimental work has been done on the transport of electron beams in klystrons and other devices, but in those applications beam emittance is of little interest. As a result, almost no information existed on this subject prior to the beginning of interest in HIF.

Considerable theoretical effort has been addressed to this matter since the beginning of the HIF program, and that primarily to transverse stability; only recently has a computer program to study longitudinal motion been developed. The problem of transverse motion fortunately can be parameterized in such a way that all cases can be treated by a set of dimensionless equations with one parameter related to beam intensity. The transportable current (in amperes) can be written (Maschke [1976]) (Courant [1976]) as;

$$I = 3.7 \cdot 10^{6} \left(\frac{A}{Z}\right)^{1/3} B_q^{2/3} (\beta\gamma)^{5/3} (\epsilon_n)^{2/3} F$$

where A, Z = atomic weight and charge state,
B_q = quadrupole field at the edge of the beam (in Teslas),
$\pi\epsilon_n$ = emittance/mc (in meter-radians)
F = "figure of merit" (of order unity). This expression was originally derived assuming uniform space charge density (micro-canonical distribution function in the four-dimensional transverse phase space), in which case the figure of merit is determined unambiguously by the geometry of the quadrupole channel and the dimensionless space charge parameter. The same functional form in fact applies to any distribution, with suitable interpretation of emittance and edge of the beam.

The problem then reduces to the question of what value of the space charge parameter (and corresponding value of F) either avoids the instabilities entirely or leads to an acceptable growth in effective emittance. Stability of the micro-canonical distribution has been investigated analytically and both that distribution and others have been investigated by computer simulation. The transverse motion appears to be unstable for quite a variety of cases, leading to emittance growth of factors of two or three; at very high intensities a slower rate of growth appears to go on indefinitely. To avoid instability completely, F must be about 0.5 for a channel half-filled with quadrupoles, dropping to F about 0.2 for a 10% filled quadrupole channel. Clearly, experimental information is needed, either from a scaled experiment or from the first accelerator test facility.

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Chapter 5

HEAVY ION FUSION IMPLEMENTATION PLAN

Three possible schedules for implementation of a HIF facility will be examined in this chapter:

1. The first, labelled the "fast" program, would complete a 1-3MJ driver by about 1986 if a strong R & D effort was undertaken beginning in 1979. Thus the fast program could result in making up the perceived difference between the status of ICF and MFE, at least insofar as the driver system is concerned.
2. The second, labelled the "staged" program, would take two to four years longer, but would entail substantially less risk. Assuming that HIF funding is increased to an appropriate level by FY 1981, the staged program would approximately achieve the schedule suggested by Deutch [1978] (see Fig. 1) and Battelle [1978] for the decision point for the ETF driver.
3. The third, labelled the "delayed" program, extends indefinitely the time required to determine if the HIF approach can succeed in the role of the driver for a commercial fusion power plant. The delayed program, if continued at the same pace beyond FY 1980, appears to be too slow to meet the DOE schedule for choosing between alternative driver candidates.

5.1 CONSTRUCTION SCHEDULE

Since the ultimate aim of this plan is the construction of large accelerator facilities for use as ICF drivers, it is useful to explore how such construction should occur. An HIF driver, of good efficiency and high repetition rate, could be built rapidly, partially because of the advanced state of accelerator technology. A rapid construction schedule is practical because;

1. In any large accelerator, most of the cost is for items whch are replicated many times. Also, if

one includes housings in this category, most of the cost is for products of conventional technology which are readily available from industrial sources.

2. The relatively recent appearance on the market of mini-computers for process control, (which owes much of its technological inspiration to accelerator-related applications) has had the effect of standardizing the hardware components of accelerator control systems. This was historically one of the expensive "custom" engineering tasks on every accelerator.

3. Once the main accelerator is under construction, the engineering staff is able to turn its attention to the details of the special systems such as the beam transport interfaces between major portions of the accelerator system. This dual use of staff has been repeated several times on big accelerator projects. It results in substantial personnel savings by reducing the number of parallel engineering projects.

4. Large accelerators not only can be built rapidly, but for economic reasons, they should be. The surest way to increase costs on a large technological project is by a long, delayed construction schedule. It has been by necessity that all large research accelerators of recent years have been "on time" and "under budget."

The statement that the HIF driver could be built rapidly is <u>not</u> equivalent to a statement that construction should start in the immediate future. There are two classes of R & D that should be carried forward for at least two years before a decision to begin construction would be appropriate:

1. The first of these is in the general scope of the present ICF program, particularly in pellet and reactor systems studies. It is demonstrably true that the vast majority of ICF pellet studies have been tailored to suit lasers which, as a generic class, have relatively low energy, high power pulses. A great deal of effort from the HIF community has gone into trying to match the laser parameters in the 100 kJ, 100TW range. It turns out that this is a particularly poor match for the characteristics of heavy ion accelerator drivers. Larger targets, requiring pulses of higher energy and relatively modest peak power, are a much better match for accelerators and also, apparently, are more appropriate for commercial power reactors (Battelle [1978]).

Systems studies are also needed to identify the characteristics of practical, economic reactors. Designs suitable for use with high energy charged particle drivers may be quite different from reactors designed for use with lasers or light, low energy charged particles. In particular, although there appear to be pressure regions in which the final transport process is stable, there appears to be no uncertainty about the stability of this process in a vacuum. Thus work on an evacuated reactor vessel could avoid needless complications for the HIF driver.

2. The second class of needed R & D is for the injection and low-beta part of the heavy ion accelerator. The acceleration of high-intensity, low charge state, heavy ions is an essential departure from past experience. As in any area of technology, one expects to make considerable improvement in subsequent designs after some experience. Also, the results of tests with the injector and low-beta accelerator may profoundly affect the design of the main accelerator. Even though the low-beta part of the complete accelerator represents a small fraction of the total cost, R & D and experimental verification in this area may pay large dividends in the final system.

Assuming that the R & D suggested above has been completed, the appropriate construction schedule can be patterned after the schedules for other accelerators and other similar scale projects. An example of such a schedule, beginning with the onset of construction funding, is the following;

1. Year 1; Preliminary design, R & D, build prototypes.

2. Year 2; Final design, site preparation, test prototypes.

3. Year 3; Begin construction, design special items.

4. Year 4; Finish conventional facility construction, begin installation of accelerator components.

5. Year 5; Finish installation, preliminary checkouts.

6. Year 6; Operational checks and debugging.

This total construction schedule is six years, including one year before actual groundbreaking and one year for finishing touches while debugging is in progress. Including the two years of R & D, the total period needed is eight years.

5.2 PROGRAM OPTIONS

5.2.1 Fast Program

The schedule described above, which will be called the "fast" program, is probably within about one year of the optimum period needed to construct a 1-3MJ driver along the lines of the systems described in the appendices. However, at the present time, there are significant drawbacks to following a fast schedule, including:

1. the financial impact that a strong commitment to a single approach would have on other avenues of fusion research,
2. questions about the design of pellets that may be resolved with the existing ICF program, and may indicate different ranges of parameters for HIF drivers,
3. the possibility of missing some cost-saving innovations that might be demonstrated by a broader based accelerator R & D effort, and
4. the risk that the accelerator may not be able to perform to theoretical expectations. Assurance against such an eventuality is contained in the "staged" program described below.

If in spite of the aforementioned drawbacks, the necessary political, technical and financial conditions could be simultaneously met, the fast program has the advantage of the lowest cost for the driver. Also, the speeded up schedule makes for the lowest total cost to determine whether ICF power is an attainable goal. The conditions that need to be met include:

1. Politically: it would require recognition that an accelerated ICF program committed to the HIF option is a proper strategy, particularly if by such a program, other fusion approaches are curtailed or even stopped.
2. Technically: it would require evidence from other parts of the ICF program that HIF has persuasive advantages over other drivers, as well as a high probability of success.
3. Financially: it would require financial support beyond the present DOE-ICF program. In addition to expansion of the DOE-ICF program, funding could be obtained from other sources such as by collaboration with industry and/or foreign governments.

The DOE-ICF program could be supplemented by support from the utility industry, (for example, through the Electric Power Research Institute, EPRI). It could also be increased by a combined program to investigate the electro-nuclear breeding of fissile fuel with either large accelerators or with neutrons from fusion reactions. Other possibilities include the collaboration with foreign governments on the (unclassified) driver part of the program, or with other U.S. agencies interested in pulse power systems.

5.3 THE STAGED PROGRAM

The program towards a heavy ion fusion accelerator system may be divided into the following chronological periods;

1. Conceptual design and system studies; including R & D on critical components and experimental tests of theoretical predictions of high intensity beam behavior.

2. Accelerator qualification; including source qualification, construction of prototype components and conceptual design of the accelerator systems for the HIDE and ETF facilities described below.

3. Heavy Ion Demonstration Experiment (HIDE); including the construction of adequate amounts of each subsystem to establish all technical, operational and cost factors. HIDE also includes beam propagation and target coupling tests at the 20MJ/g level.

4. Engineering Test Facility (ETF) Driver; including upgrading HIDE to the 1MJ, 100TW level for scientific breakeven tests.

5. Experimental Power Reactor (EPR) Driver; including further upgrades (to the 3-10MJ, 300-600TW level if that is appropriate) with high repetition rate and high efficiency.

6. Commercialization; including continued accelerator system improvements.

If for each of the chronological periods listed above, a corresponding "milestone" is established, then one can specify technical levels, or stages, which one must achieve before committing the next larger increment of funds. This process very much reduces the risk of a failure at some level causing a large waste of resources because all substantive technical questions are scheduled for resolution at the earliest possible stage. A very preliminary version of such a plan follows:

1. Stage 0 The present period; funding at $3-5M/year
   Accelerator theory and conceptual design; Build and test ion sources. Do very limited R & D on low-beta accelerators. Due to budgetary limitations, conceptual design activities have had to be restricted to consideration of only the two most promising driver candidates (rf linac plus accumulator rings and single-pass linear induction accelerator), and only the most critical problems; a very narrow program.

It would be unfortunate if it turns out to be mandatory to select a leading and an alternative HIF driver candidate at this stage of program funding, before there exists scientific evidence upon which to base such a decision. However, if this decision is forced, one would expect that an impartial ad hoc advisory panel would be formed; that it would be charged with considering the entire ICF driver program to rank all of the potential power plant driver candidates; and that until such time as large construction commitments have to be made, DOE would endeavor to maintain viability of the best of these driver candidates by funding their respective R & D programs.

2. Stage 1 One year at $10M and 3 years at $25M/year plus about $5M/year for equipment. The first year is a transition year for staffing and designing experiments. The funds are assumed to R & D operations. However, about $10-15M per year could be designated construction funding, so long as the total of approximately $30M per year was maintained. Design and construct accelerator qualification facilities and do conceptual design for HIDE, ETF (≥ 1MJ), and EPR; including preliminary R & D on critical components of each candidate system. Continue accelerator theory studies and experimental tests of theoretical predictions of the behavior of high intensity beams.

   Design and build a significant accelerator qualification demonstration for each of the two most promising heavy ion driver candidates. By definition, the accelerator qualification experiments should be a significant step, in both energy and current, beyond the low level experiments of Stage 0. They should be aimed toward providing a convincing demonstration that the design concepts for the driver are well founded and are scalable. Approximate goals, as perceived at this time, are;

   a) For the single pass, induction linac; a beam energy of approximately one kilojoule seems a suitable point from which to extrapolate to HIDE from the Stage 0 experiments. It is anticipated that all of this work will be properly R & D operations plus equipment. LBL has made a rough estimate of $8M per year including about $2M for equipment.

   b) For the rf linac approach; a linac "tree" (of at least two branches) with frequency jumping and longitudinal phase space matching, followed by a 200MV linac, followed by a low-energy, ultra-high-vacuum, storage ring, would test the critical questions. ANL has made a preliminary estimate of $35-50M for this work, depending on certain options (e.g., going only to 100MV), of which an unknown fraction is equipment. The ANL estimate is contained in a proposal for doing this work as a construction project using existing facilities being vacated as the ZGS is shut down at ANL. However, if it is possible to begin the project sooner as an R & D effort, that option would be preferable. The balance of the listed funds, (about $4M operating and $1M equipment) would be primarily for source and low-beta accelerator development.

During the third year, a decision would be made to determine the accelerator system to be built for HIDE (Stage 2, below). This decision would commit the HIF accelerator community to join forces. If another accelerator system still appears to offer ultimately superior advantages for a power plant driver, it may be supported at an R & D level as an alternative approach.

The logic for the Staged Program is illustrated by the HIF Engineering Development Scenario in Fig. 15. Phase I in the figure corresponds approximately to Stage 1 in this description. There is a decision point after Phase I depending on the success of pellet physics at that time, i.e., roughly 1983. If the pellet physics program has been successful and the pellets are well understood, it would be appropriate to design and build HIDE in such a way as to make it upgradable to become the ETF and eventually the EPR drivers. That path is assumed in the following discussion. However, if the pellet physics is less well defined, it might be appropriate to develop HIDE into a facility just to do pellet experiments, continuing to a 1MJ HIDE-upgrade or HUP, to do high-gain pellet experiments. The implications of this decision cannot be defined this early, but may include the speed of funding and the location of the HIDE and HUP facilities.

3. Stage 2 One year at $40M and 2 years at $50M/year
   During the first year, finish qualification evaluation and initiate construction of HIDE. Also during the first year, organize the consolidation of the HIF community for the HIDE project. Continue R & D stage on the rest of the driver and do detailed design work for HIDE. Continue R & D on alternative approach if one is chosen. During the next two years, construction of the Heavy Ion Demonstration Experiment (HIDE); construct sufficient amounts of each different part of the system to demonstrate all technical, operational and cost factors. Test beam propagation in a scaled experiment. Test target coupling at the 20MJ/g level.

4. Stage 3 3 years at $150M/year
   Megajoule driver: the Engineering Test Facility (ETF); If chosen as the ETF driver, the HIDE facility would be expanded and completed to the

1-3MJ level.

5. Stage 4 3 years at $200M/year
Multi-megajoule driver; the Experimental Power Reactor; The 1MJ driver is upgraded to become the EPR driver.
Typical parameters;

Beam Energy	3-10MJ
Particle Energy	10-20GeV
Peak Beam Power	300-600TW
Average Beam Power	150MW
Efficiency	20-30 %
Pulse Repetition Rate	15 pps

If this schedule is followed beginning with the onset of Stage 1 by FY 1980, the HIDE facility would be available by 1987. The megajoule driver could then follow as early as 1990. If a decision were made to push for earlier availability of the 1MJ system, two to three years could be saved between Stages 1-3 by a faster funding schedule. The total cost would be the same or slightly less. (Considerably less if escalation is considered.)

When the above schedule is compared with the Fusion Development Plan in Fig. 1 (Deutch [1978]), it is noted that the time required to advance from the ETF decision point to the operational ETF is reduced from about nine years to three, or perhaps four to allow for the onset of construction. Similarly, the time to build the EPR is reduced from seven years to three or four. These reductions are possible because the HIF accelerator is assumed to have been designed from the outset to be upgradable at each stage and to eventually meet the requirements anticipated for a commercial power plant.

5.3.1 <u>Delayed Program</u>

The third option, labelled "delayed program," is essentially the present level of funding, about $3.5M/year, continued beyond FY 1979. A number of projects that had just been started in expectation of modest budget increases that would permit them to be carried out, have had to be stopped because of the decrease in funding. The net effect on the continuity of the research, and on the abilities of the laboratories to retain vital personnel, may be worse than just to delay HIF. When compared with the accelerator R & D effort in HEP, the present level of funding of HIF driver R & D is estimated to be too low by about a factor of three for the task at hand. At the present level, the funding is "subcritical." It is urgent to at least restore the cuts that were suffered between the FY 1978 and FY 1979 budgets in order to return the HIF effort to criticality.

This funding level delays indefinitely the determination of whether heavy ion accelerators can be used as drivers for commercial ICF power plants. It will certainly cause the HIF option to be inadequately developed by the time a decision should be made on the choice of a driver for the ETF. The DOE policy on fusion, projects a total expenditure of some $18B in the next two decades to determine if fusion can be a practical energy source. By supporting HIF at the level proposed for the staged program, rather than by delaying it at the present level, it should be possible to get answers to the questions of practicality of ICF several years sooner than projected.

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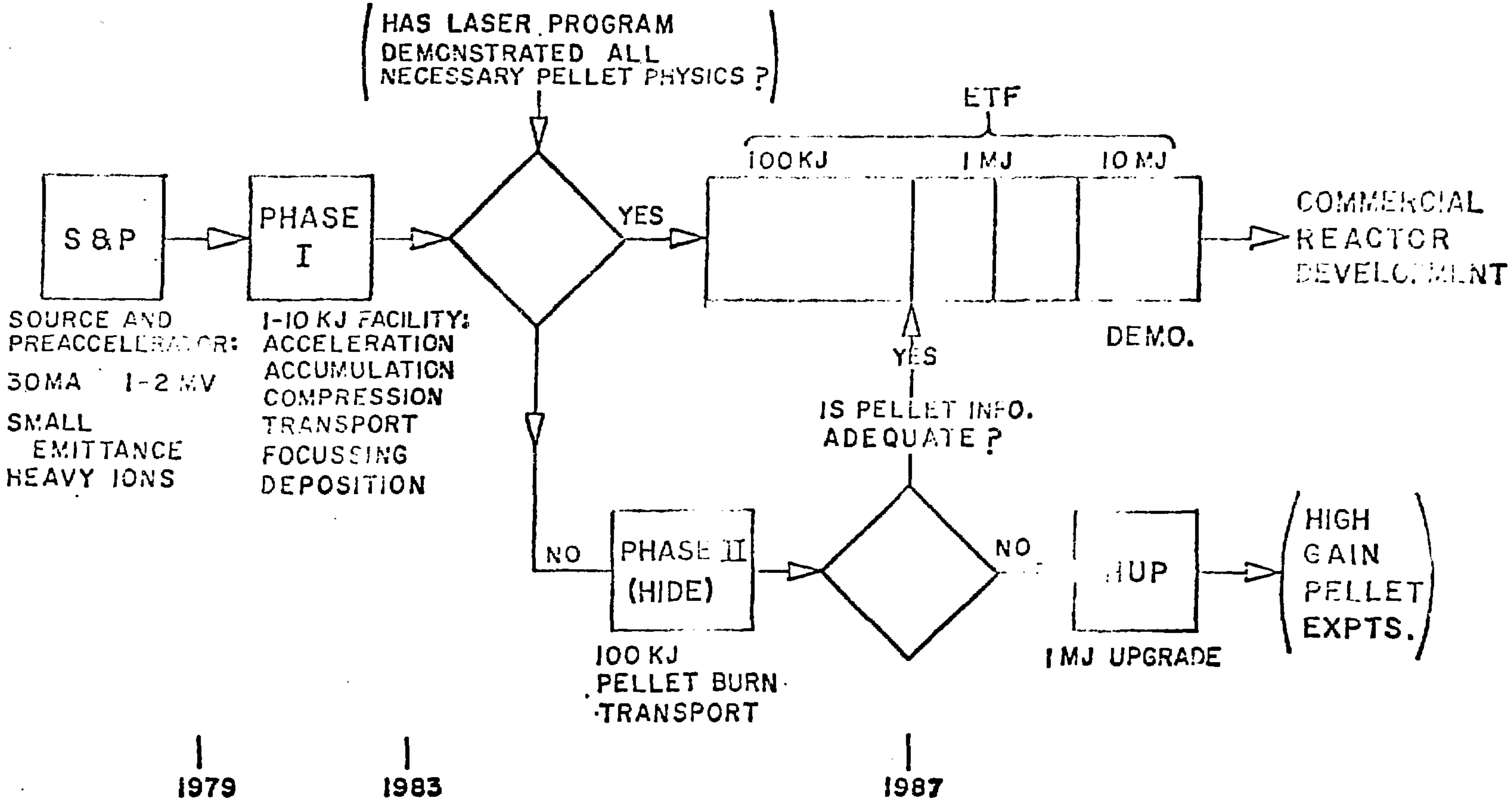
FIGURE 15

HEAVY ION INERTIAL FUSION

ENGINEERING DEVELOPMENT SCENARIO



Appendix A

DRIVER WITH ACCUMULATOR RINGS FED BY AN RF LINAC

A.1 1MJ DRIVER

This section briefly summarizes a reference design (Arnold [1978]) for a 1 megajoule heavy ion inertial fusion driver based on a radio-frequency linear accelerator. This system has a high repetition capability (greater than 20 per second) and high efficiency.

In the linac system described here, 128mA (electrical) of Hg^{+8} is accelerated with a 2.5GV linac to 20GeV. Transverse stacking (4x4) x (4x4)=256 is performed using intermediate delay rings. Ion currents of 24 A are then accumulated in 18 storage rings. One extraction beam line per storage ring is used, with external linear-induction bunchers, to supply a final compression factor of 74. A spot size on target of 1mm radius is possible, with a reaction chamber radius of 5 meters and a port radius of 21cm, providing a specific energy deposition of 20MJ/g. The momentum spread on target is very small, (dp/p)=0.035%.

A.1.1 System Description

A.1.1.1 Ion Sources

Two parallel sources of Hg^{+1} are used, with normalized emittances of 0.01mr-cm and currents of 50mA. These feed, through dc pre-accelerators and bunchers, into two low-beta linacs operating at 12.5MHz and capturing 40mA each.

A.1.1.2 Linac

At an energy between 10 and 20MeV, depending on the choice of stripper, the Hg^{+1} is stripped to Hg^{+8} with a 20% particle efficiency, giving 64mA (electrical) Hg^{+8} in each branch. These ion bunches are injected into alternate rf buckets of a 25MHz linac section, which then carries 128mA(e). At appropriate energies in the subsequent linac, frequency shifts to 50, 100, and 200MHz are performed, with a final kinetic energy of 20GeV. We allow a transverse emittance dilution of a factor of 6 in the linac. At the linac output, every 8th rf bucket is filled; the bunch width is $dt=4.7\cdot10^{-11}$ sec.

A.1.1.3 Debuncher

To conserve most of the momentum resolution attainable in the linac, a long debuncher follows the linac. A shear-enhancing set of cavities, operating at about 1GHz and 20MV peak-to-peak, is followed by a drift space of 450 m. At the end of the drift, a shear-stopping set of cavities applies 20MV in the opposite phase, relative to the bunch, at a frequency of 25MHz. The result is debunching by a factor of 107, giving a bunching factor BF=1/4 to begin the transverse stacking manipulations.

A.1.1.4 Delay Rings and Combination of Beams

Transverse stacking of (4x4) x (4x4)=256 is necessary, with minimal emittance dilution, to achieve the required 24 A(e) of circulating Hg^{+8} with a net efficiency of 74%. The normalized emittance is 2.1mr-cm in the final storage rings. The stacking scheme is illustrated in Fig. 16.

Four beams are combined after each of a sequence of four delays. The first and second delays use four 180 degree bends and maximum delay-line lengths of 1.36km and 340m respectively. The third delay uses three rings and the fourth delay uses four rings for storage times amounting to about 60 and 250 turns respectively. Each delay thus allows stacking the beam in one transverse dimension by a factor of four. The overall result is an increase in beam current (neglecting beam losses) by 256, and an increase in transverse emittance in each plane by (4•1.45), where the factor 1.45 is the dilution factor expected based on the experience of the CERN PSB group with the booster for their synchrotron.

The 256-fold current amplification allows reaching the space charge limit of 24 A in the storage rings while losing 25% of the linac beam during the amplifying manipulations.

The bunch length from the debuncher output is allowed to increase (shear) a factor of two during the transverse stacking process; the bunching factor in the last delay array and in the final storage rings is set at BF=1/2. This process sacrifices a factor of two in attainable longitudinal phase space density (dp/p), but the system produces a satisfactorily small value which should be quite sufficient to avoid chromatic aberration problems in the final focus.

The delay rings (as well as the final storage rings) have a rotation time of 0.88 usec, an average radius of 18.5M, and an average dipole field of about 2 T. The delay rings, and the storage rings during the fill cycle, operate on a harmonic number h=22, with single turn injection.

The rings in each array are filled sequentially; then the beams are simultaneously extracted, combined with the beam from the previous array (except for the last array) using four septum magnets, and the combined beam is used to fill one ring at a time in the next array.

A.1.1.5 Storage Rings and Bunchers

The 18 final storage rings are filled sequentially, using one-turn injection, with successive 22 bucket bursts from the last delay array. The bunching factor is BF=1/2.

After each ring is filled, the 22 circulating bunches are adiabatically debunched and rebunched using rf cavities into one 440 nsec bunch, maintaining BF=1/2. At extraction time, the bunches in all storage rings are simultaneously extracted into beam lines that pass through an external linear-induction compressor. The latter provides a final compression factor of 74 (above the space-charge limit), with 122MV. The bunches are restored in the rings for the first part of the collapse and the collapse is completed during passage through the beam lines leading to the target chamber.

Economy is obtained in the bunch compressors by stacking the group of 9 beam lines (from each half of the final storage ring array) in a common compressor aperture, using integrated 3 x 3 quadrupole arrays.

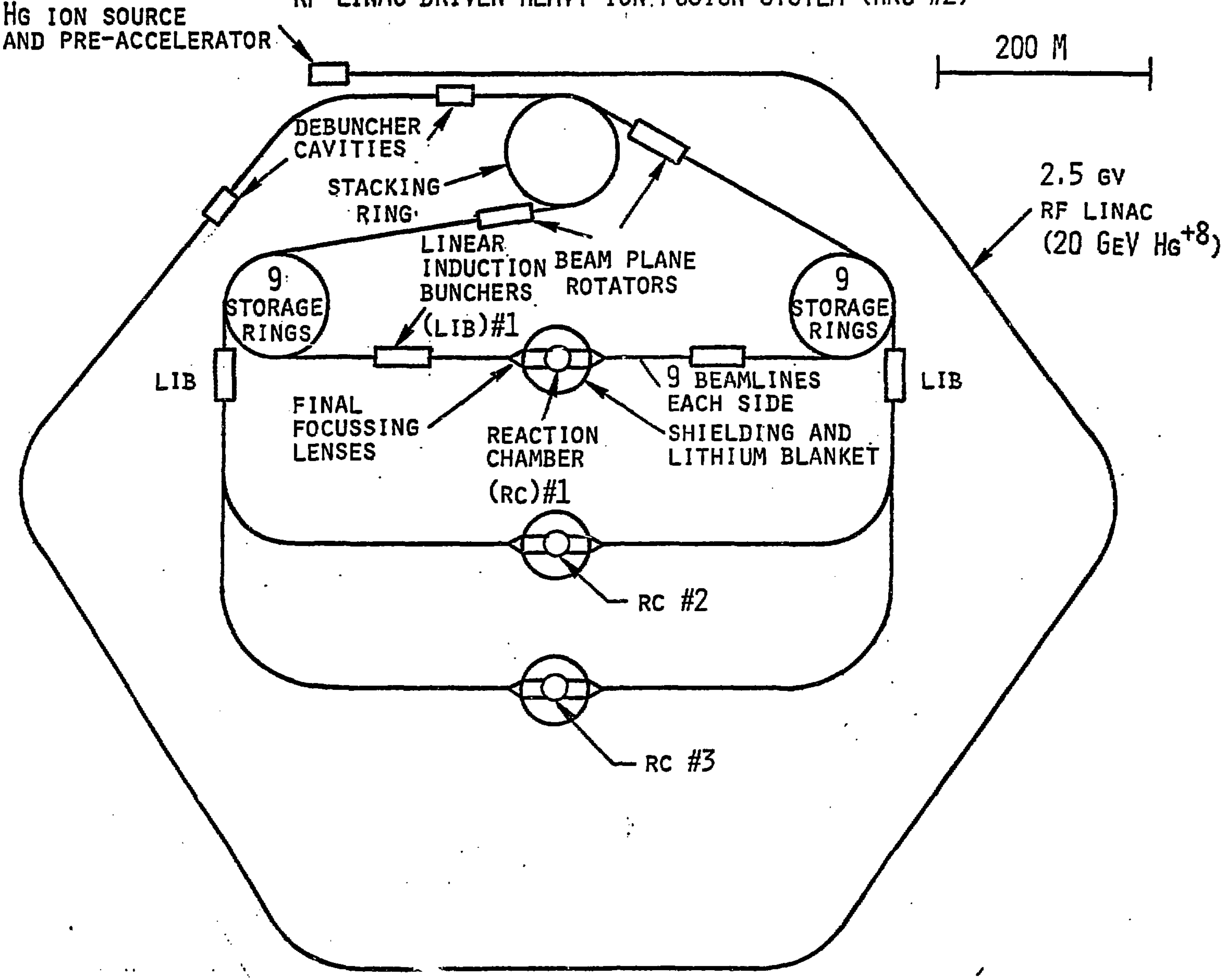
A.1.1.6 Final Transport and Focusing

Transport of 160 Terawatts (unshaped 1MJ pulse 6 nsec long) in 18 beam lines, i.e., 9TW per beam, requires an average quadrupole field of 4 Tesla (50% packing factor), with Hg^{+8} at 20GeV, with un-normallized emittance of 2.1mr-cm.

A target spot radius of 1.06mm is allowed for 1MJ of 20GeV Hg, which has a range of 0.7 g/cm, maintaining 20MJ/g specific deposition. With the un-normalized emittance 4.4mr-cm, we require a minimum port radius of 21cm for a 5m radius reaction chamber. The momentum spread of the beam after final compression is calculated to be $(dp/p)=0.00035$.

FIGURE 16

RF LINAC DRIVEN HEAVY-ION FUSION SYSTEM (HRC #2)



A.2 10MJ ACCELERATOR SYSTEM

The following section is taken from a conceptual design developed by Maschke [1978]. A Heavy Ion Accelerator system is described which is based upon existing technology, and which is capable of producing 150MW of average beam power in 10MJ, 200TW bursts, 15 times per second. It consists of an rf linac which accelerates doubly ionized uranium ions to an energy of 20GeV. Then by utilizing the well known procedure of multiturn injection, a 6.6-msec-long burst of linac current is stored in eight separate "accumulator" rings. At the conclusion of the filling process, a pulsed rf system bunches the beam in each of the eight rings simultaneously. As the bunches decrease in length, they are then extracted from the rings and transported for about 1km to one of five "boilers", in which the thermonuclear pellet has been placed. The eight beams (2 opposing clusters of four beams each) are then focused simultaneously onto the pellet.

A.2.1 General Description

For the purpose of this study, it has been assumed that uranium ions are accelerated. Any one of several other ions including xenon, mercury, gold or bismuth could have been used without having a significant effect on the design. The ions start out of a rather conventional source, and are accelerated first in a 500kV high-gradient dc column. A beam of 50mA of U^{+1} is produced at the end of the column. It would be preferrable to have a higher current, and a higher voltage. Both choices here are made because they are rather conservative and do not represent a significant extrapolation from electromagnetic isotope separation experience. The design current for the linac is 160mA, obtained by starting with eight linacs of 20mA each. As the ions gain energy, the bunches of beam are combined, until finally all the current is in a single structure. The accelerator starts out as a cascade of eight 2MHz Wideroe linacs, injecting into four 4MHz Wideroe linacs. At about 6MeV the beam is stripped to U^{+2}, with about 50% efficiency, i.e., the current of U^{+2} is still the same as it was for the U^{+1}. At about 13MeV, the beams are combined into two 8MHz Wideroe structures. At 30MeV, the beams of 80mA each are combined in a 48MHz Alvarez linac. At 120MeV this beam is matched into a 96MHz Alvarez, and at 480MeV into a 192MHz Alvarez. The 192MHz structure is continued until the final energy of 20GeV is reached.

At this point the beam is injected into a very long (6.3 kilometer) "multiplier" ring. Ten turns are injected into this ring by means of multiturn injection into the horizontal phase space. At the completion of the 10 turn filling, the beam is extracted, the horizontal and vertical phase planes are exchanged via a series of skew quadrupoles, and the beam is multiturned into the aperture of a multiplier ring of 100 meter radius. We have now a current amplification factor of 100. This beam is now transferred to one of the eight waiting accumulator rings. The linac beam could have been multiturned directly into the accumulator. However, because small losses occurring during multiturn injection could affect the vacuum, and since the vacuum requirement in the multiplier rings is at least an order of magnitude less than for the accumulators, it is safer to have separate rings for this purpose. The stacking arrangement is illustrated in Fig. 17.

After all eight accumulator rings are filled the beams are bunched with a low frequency (1st harmonic of the rotation frequency) pulsed rf system. This starts a longitudinal "implosion" of the bunch which carries the beam a factor of ten over the "space charge limit" of the accumulator. This is possible because of the transient nature of the implosion. When the beams are extracted, another factor of five increase in the current occurs in the 1km drift from the accumulator to the boiler. At this point the eight beams are simultaneously focused onto the pellet, with an instantaneous current of 2500 amperes in each of the beams.

The entire cycle takes 6.6ms, and is repeated 15 times per second. The beam is transported alternatively from one boiler to another. Each boiler is fired 3.75 times per second.

A.2.2 Detailed Accelerator Design

No substantive effort was made in this study to optimize the design in any real sense. Rather, the emphasis was put on exhibiting a design that requires the least departure from existing technology. It is important to remember that it is only within the past year that a development effort has been started to advance the state of the art in the area of heavy ion accelerators for inertial fusion. Therefore a similar study, started in a few years from now, could be expected to incorporate many new features which are at present only in the "concept" stage.

A.2.2.1 Preinjector and Ion Source

For purposes of this study a 500kV Cockcroft-Walton accelerator is taken for the dc terminal. This is a conservative choice between a desire for high voltage to alleviate space charge problems versus a fear of breakdown and contamination damaging a higher voltage accelerating column. Extensive experience at GSI at 320kV indicates that one could easily go somewhat higher in voltage. If 400kV had been chosen for the terminal voltage, the overall design of the facility would not be altered appreciably. Ion sources of a type suitable for injection into a preinjector acceleration column have been developed for protons with currents on the order of an ampere. Child's law, from which one calculates the space charge limited extracted current, requires that the current vary inversely with the square root of the atomic number. This means that we might expect currents about 15 times smaller for heavy ions. The performance assumptions made here require a beam of about 40mA from each of eight accelerating columns. Isotope separation sources, developed over the past 35 years, have routinely produced heavy ion beams of currents higher than required here. For purposes of this study, U^{+1} has been selected as the ion to be accelerated in the "pre-stripper" portion of the accelerator. The final choice would be decided on the basis of rather subtle differences between species. Isotopic purity, ion-ion cross sections, stripping considerations, etc., will all play a role in the final choice. None of these considerations are expected to make a significant difference in either the design of the facility or its performance. If a particular species was found to have unusually small ion-ion charge-exchange cross section one might chose to alter the scenario to take advantage of the resulting longer beam lifetime in the accumulator rings. However, using a geometric cross section as an upper bound, the system considered here loses only about 1% of the beam.

A.2.2.2 Low-beta Linac Portion

A 500 keV heavy ion has a velocity of about .002 c. This is about a factor of 2.5 times lower than any existing heavy ion accelerator. (A Model Heavy Ion Linac with beta=0.003 has operated successfully at BNL.) Because the drift tubes become so small, it is necessary to go down in frequency as the velocity decreases. If one took the GSI Wideroe linac as an example, one might consider scaling that to 2.5 times lower frequency, i.e., 10MHz. However, space charge forces are another factor which must be taken into account.

Longitudinal space charge forces become more severe as the bunches become shorter. Therefore, the maximum transportable current is inversely proportional to the frequency. If one assumes that some ratio of longitudinal space charge force applied to rf focusing constitutes a longitudinal current limit, then it follows that i(max) is proportional to TE/(fA), where T is the kinetic energy of the ion, E is the average accelerating field, f is the frequency, and A the atomic number.

An estimate of what can be expected can be obtained empirically by examining the performance of an accelerator operating near its longitudinal space charge limit, of which the FNAL 200MeV proton linac is probably the best example. Using the FNAL peak current figures of 300-400mA, one obtains the following approximate relation for heavy ions; (f/E)=10 and i(max)=20mA. For this study E was about 0.2MV/m and f=2MHz. This choice is not completely arbitrary. For instance, as one increases E, and increases the frequency at the same time, the drift tubes become shorter, the aperture becomes smaller and the transverse focusing requirement becomes more severe. In the model described here, the longitudinal "synchrotron" oscillation frequency is below that of the transverse "betatron" oscillation frequency. This situation remains throughout the linac. A choice of high gradient and high frequency could lead to a situation where the longitudinal frequency is greater than the transverse. Sometime before the end of the linac, this relationship would have to be reversed. The coupling of transverse and longitudinal motion can give rise to emittance blow-up, and is to be avoided where possible.

Table 3 shows the sequence of events as one goes from the 2MHz, 20mA injector to the beginning of the 160mA, 192MHz linac section. The columns i(tr) and i(lo) are the ratios of the injected current to the space charge limited current in the transverse and longitudinal dimensions, respectively. Note that the current is taken as the limiting value at injection to the 2MHz section. The most severe problem occurs at the injection into the 48MHz Alvarez. If one was limited at injection into the 2MHz structure, then an emittance blow-up of about $(1.34)^{3/2}=1.55$ would be expected.

TABLE 3

Parameters at injection to each linac section.

E	q	v/c	f	i	i(tr)	i(lo)
0.5MeV	1	.002116	2MHz	20mA	1.	1.
2.0	1	.004232	4	40	.63	1.
6.4	2	.007570	4	40	.32	.704
12.8	2	.010706	8	80	.36	1.
30	2	.016390	48	160	1.1	1.34
120	2	.032781	96	160	.69	1.34
480	2	.065562	192	160	.43	1.34

If we assume an adiabatic damping of the longitudinal phase space, and further assume that the phase length of the beam at the entrance to each new linac system is the same, we then find the following relation:

$$(v/cf)(zE)^{1/3}=\text{const.}$$

This allows one to determine reasonable beta values at which to jump the frequency without losing beam. For different frequency linacs with the same average electric field, one sees that one must double the velocity if one wants to double the frequency. For this example, if one did not want a bunch of greater phase length than that at the beginning of the 2MHz structure, one obtains:

$$v > 6.2\cdot 10^{-4} fc(zE)^{1/3}$$

where f is in MHz, and E in MV/meter.

A.2.2.3 Low-beta Alvarez Portion

After a suitable length of 8MHz Wideroe linac one can jump to an Alvarez structure at 48MHz. The longitudinal acceptance is increased in the Alvarez because it has an average accelerating field in the neighborhood of 1MV/meter. The first set of Alvarez tanks are about 45 meters long. Then the frequency doubles, and after 135 meters of 96MHz structure we go to 192MHz. This is the frequency which will be kept for the remainder of the linac. About 80 meters of the 192MHz linac are included in the low-beta portion. This is the section of the system which would be replicated for redundancy to provide higher reliability and to permit maintanence on one low-beta linac while the rest of the system remains in operation. In the later portion this redundancy will not be necessary because individual rf stations can be serviced while the beam accelerator is operating.

Alvarez linacs in both this frequency range and velocity range have been built previously and present absolutely no new scientific or technical problems. However, the high current and the beam loading percentage are unprecedented. More than 50% of the rf power will be going into the beam. While the FNAL linac has accelerated much higher currents, the pulse length was rather short, and the acceleration depended on energy stored in the cavities. The highest long pulse currents are about 100mA at the BNL linac (pulse length about 200 usec). The 160mA assumed for this design is 60% higher than at BNL, but is not expected to present any serious problems.* The duty cycle assumed is 10% maximum., which is relatively modest compared to the 25-35% duty cycles used in existing heavy ion linacs.

A.2.2.4 Alvarez High-beta Section

The high-beta portion of the linac is not like any existing linac. Whereas the Alvarez structure obtains its best shunt impedance in the range between beta's of .1 to .4, the existing proton linacs in this velocity range are of necessity quite different. While a proton will go through this velocity range in about 50 meters, the heavy ion linac requires about 5km. The change in structure from one tank to another is almost negligible. At the beginning of this section of linac, a synchrotron oscillation is about 82 meters long. Tanks 6 meters long would add 20MeV to the beam. If a single 6 meter cavity was turned off, a 10% increase in the acceleration of 5 upstream and 5 downstream cavities could compensate for this loss. This fact makes the reliability of the high-beta portion very much greater than it would be otherwise.

Because heavy ion fusion power stations are likely to be larger than conventional single unit power sources, the reliability of the ignitor is of rather greater concern. At a conventional or nuclear energy center, single units are about 1GWe.

The cavity design for the approximately 1000 cavities required in the high-beta section is especially simple. Because the ions have an energy of about 1GeV at the input end, the ratio of voltge gain/gap to total kinetic energy is very small (about 200 times smaller than for protons). What this means is that the effect of gap-defocusing is very small, and can be ignored without effecting anything. Also, the transverse emittance is about ten times smaller than for a similar proton linac. The consequence of this is that the drift tubes do not require magnetic lenses placed in them. These two factors allow one to make substantial design simplifications. The focusing elements can be inserted in the inter-tank regions, where their outer diameter is not constrained, and they can be simply maintained. The drift tubes themselves need never be aligned, because there are no lenses in them. The tank becomes a simple welded steel structure, the inside of which is then copper plated.

The principal cost item for the high-beta section is the rf system. It consists of 1000 2.5-3.0MW rf drive systems capable of operating with a 10% duty cycle, and 6.6ms long pulses. A number of options are available for the rf and a more detailed design is required to chose between them. New 200MHz kylstrons are just beginning to enter the market and

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* Some design studies for high current linacs used to breed fissile material have considered currents as high as 300mA.

appear like an attractive solution. The rule of thumb, $10/watt for peak, $1/watt for average does not appear to be far off the mark.

An interesting consequence of the small longitudinal phase advance in each cavity is that it is not necessary to provide amplitude modulation (i.e., feedback) on all of the rf systems. Roughly speaking, it is sufficient for only one cavity in 10 to control its amplitude during the pulse to adjust for time dependent beam-current fluctuations or drive fluctuations in the different rf systems.

A.2.2.5 Multiplier Rings

These rings are a novel part of this linac/accumulator scenario. The current multiplication in the accumulator is a factor of 100 over the linac current. This is obtained by stacking in the horizontal and vertical phase space. In principal, this could be done by putting 100 turns into a ring in one single operation. However, in the spirit of this design study, it was decided to use a more conservative technical solution involving two multiplier rings; one with a circumference of 6.3 kilometers and another with a 630 meter circumference. The large ring is a race track shaped and encloses the entire rf linac. The linac injects ten turns into the horizontal phase space of the long multiplier ring. This multiturn injection process is straight-forward. The first multiturn injection into a strong focusing synchrotron was done at the BNL AGS, and since has been in use at many accelerator laboratories. The next step is to extract the beam from the long multiplier ring, and rotate the beam by 90 degrees, i.e., exchange horizontal for vertical phase space. This can be done either with a solenoid or with a series of skew quadrupoles (quadrupoles rotated 45 degrees from their normal configuration). This beam is now multi-turned into the small multiplier ring, where once again ten turn multiturn injection is performed. Upon completion of this multiturn process the resulting beam is adiabatically "bunched" by a small rf system on the 1st harmonic of the revolution frequency. Then the beam is extracted, without loss, and transferred to one of the eight accumulator rings.

There are several advantages to this process over that of injection directly into all the accumulators. First, we require only the two sets of simple multiturn hardware. Since the beam remains in the multiplier only about 1/8 as long as in an accumulator, the vacuum requirement is much less severe. Therefore the chance that beam losses may effect the vacuum are reduced. Furthermore, since multiturn injection is the only function done in the multiplier rings, it is possible to take special precautions with regards to beam losses which would be awkward in the accumulators.

A.2.2.6 Accumulator Rings

There are two clusters of accumulator rings. A group of four rings are located in the same tunnel, and placed one on top of another. This technique was used, on a smaller scale, for the booster synchrotron for the CERN Proton Synchrotron. That system consists of four 25 meter radius synchrotrons in a stack. The accumulator rings are somewhat larger in aperture than the CERN booster and have a radius of 100 meters. There are no especially novel features in such a system. The fields in the magnets (about 2T) could be produced by conventional coils, although a considerable power savings would result from using warm iron magnets with superconducting coils. Table 4 gives a parameter list for the rings.

TABLE 4

Accumulator Parameters

Radius	100 meters
Average Magnetic Field	1.6 Tesla
Beam Emittance	6.cm-mr
Revolution Period	5.275 sec
Average Circulating Current	16 amperes
Storage Time	< 6ms
Vacuum	10^{-10}Torr
Betatron Oscillations/Revolution	10
Vertical Semi-Aperture	5cm
Horizontal Semi-Aperture	6cm

If we take an initial phase space of 20cm-mr at the 500 keV input to the linac, and assume adiabatic damping throughout, then we wind up with 20GeV U^{+2} ions with emittance of 0.1cm-mr. If we did "perfect" multiturn injection (i.e., no dilution), the area would be increased to 1cm-mr. The beam in the accumulator is assumed to have a transverse emittance of 6cm-mr. This gives a "safety factor" of six. We expect a dilution factor of two for the multiturn injection and another factor of two in the low energy portion of the linac. These factors are based upon experience, and conceivably could be improved upon. In any event we are left with a residual safety factor of 1.5. This is not very large, and illustrates the importance of determining the performance of the low energy sections before designing the final portions.

Each accumulator acquires the longitudinal phase space area of a total of about 84 of the 2MHz bunches. Each 2MHz bunch has longitudinal emittance of about .008 volt-seconds. Therefore the entire accumulator has a longitudinal phase space corresponding to 1.3 volt-seconds, assuming a factor of two dilution in the linac. Now chromatic aberrations in the final focus restrict the momentum spread in the beam. Given the requirement to bunch the beam, in order to obtain the requisite "peak currents", this translates into a limitation on the longitudinal phase space. Taking a 1/2% value for dp/p, and 20ns for the half width of the bunch we obtain a requirement of 4 volt-seconds. This leaves a safety factor of three for the longitudinal emittance. It is worth noting that the safety factors for both the transverse and longitudinal phase spaces could be increased by adding more accumulator rings. If the number of accumulator rings were doubled it would only increase the system cost by 20%.

A novel feature of the accumulator rings is the rf system to compress the beam longitudinally. Experiments at BNL have demonstrated that a rapid bunching of the beam can produce beams of higher currents than the space charge limit would imply because of the transient nature of the bunching. Each of these accumulator rings contains 100 small, low impedance cavities. These cavities are driven by a spark-gap switched resonant circuit. A voltage of approximately 10MV/turn is applied for 20-40 turns at the frequency of the first harmonic, i.e., around 200 kHz. Because systems to do this have not yet been built, and design work is just beginning, it represents the greatest cost uncertainty. The system is clearly buildable, but engineering is necessary to pin down the costs and produce optimized designs.

The storage times in the accumulator rings vary from 6ms for the first one filled, to only a few hundred microseconds for the last one. Assuming that hydrogen is the principal background gas, then a vacuum of 10^{-10}Torr will result in a lifetime for stripping, i.e., U^{+2} to U^{+3}, etc. on the order of 400ms. Therefore, on average, less than 1% of the beam will be lost on this account. Nevertheless, this represents about 1MW of average beam energy lost in the accumulator. Special precautions will have to be taken to collect these particles on appropriately designed aperture stops. This care is important for two reasons; one is that careless handling of these lost particles could cause physical damage to the vacuum chambers and/or deterioration of the vacuum, and the other consideration is that of activation of the machine components. It is desirable to keep the machinery as free of residual radioactivity as possible. Fortunately, heavy nuclei with energies of 85MeV/nucleon tend to stop before having a nuclear interaction. An appropriate choice of material can further minimize the amount of residual activity produced.

It is a design option, of course, to improve the vacuum to bring it into the 10^{-11}Torr range. However, beam loss due to the ion-ion charge exchange from the collision of particles within the beam among themselves may become important. There is no direct experimental measurement of the charge changing cross sections, say $U^{+2} + U^{+2}$ to U^{+3} + etc. Plausible estimates of the cross sections put the lifetime in these accumulators at about 1 second. The lifetime could be increased by using a larger radius accumulator. Lifewise, a lower betatron frequency would also increase the lifetime. Since the lifetime increases as $R^{5/2}$, the loss rate could be halved by increasing the radius from 100 meters to 132 meters.

A.2.2.7 Transport and Final Focus

Before the longitudinal bunching process has terminated in the accumulator rings, the beams are extracted and transported for a distance of about 1 kilometer to the target chamber. During this time the bunch continues to shorten, until at the end of the transport the instantaneous current in each beam has risen to 2500 amperes, or a peak power of 25 TW/beam. The eight beams result in a total of 200TW for about 50 ns, corresponding to the total input energy of 10MJ. Pulse shaping can easily be done by shaping and timing of the eight separate bunches.

The beams are transported in tunnels containing four beams. The beams consists of series of quadrupoles whose strength increases somewhat as the beam gets closer to the boiler. The transport consists of 10cm diameter iron quadrupoles, employing superconducting coils as an energy conserving measure. Since this is a "once-through" system, the vacuum over most of the 1 kilometer can be in the 10^{-8}Torr range. In the last 100 meters, these will be a transition to a higher pressure, perhaps to 0.03 Torr at the boiler directly. The principal limit on the peak current in these transport lines is the beams' own space charge, which tends to defocus the beam. The currents assumed in this study are able to be transported without resorting to any neutralization schemes, although savings would result if space charge neutralization is shown to be a possible solution to the transport problem.

For the last few meters of beam transport, the beam is within the boiler, and must be focused to a suitable spot.

In this case, a spot size of about 0.5cm diameter is required. The magnetic quadrupoles would probably be 5-10 meters from the final focus. Because of the close integration of the final focusing elements with the boiler, no effort was made in this study to attempt a design or cost estimate for these lenses. These costs would be included as part of the boiler cost.

Each of the quadrupole focusing elements subtends a solid angle of about 0.015 steradians. All eight of them then intercept about 1% of the pellet energy. One important consequence of this is that one can quite readily afford to take special precautions to protect the front surface of these lenses, which one might not wish to consider for the entire boiler. Therefore, the radius of the boiler and the focal length of the lenses do not have to coincide. It is quite plausible to have the lenses "protrude" into the chamber.

There have been suggestions made that an intense beam of heavy ions might propagate in a self-focusing mode through the chamber if the pressure was in the 1Torr range. If this turns out to be the case it would be a considerable simplification. Lacking experimental confirmation, it seems prudent to assure that one can obtain satisfactory performance in a vacuum. The "gas" expected in the boiler is in fact predominantly metal vapor. This would come from either the pellet, the walls or a liquid heat transfer medium in the boiler. These metal vapors are easily condensed out by a spray of colder material. This same spray of cold liquid metal will also extinguish any plasma in the chamber, which may have been residue from the previous shot. The metal spray is the logical equivalent of the exhaust stroke of an internal combustion engine.

Appendix B

SINGLE PASS DRIVER WITH AN INDUCTION LINAC

B.1 1MJ DRIVER SYSTEM

The following description of a 1MJ Linear Induction Accelerator LIA, is taken from an LBL report (Keefe [1978]). The accelerator is designed to accelerate uranium in one bunch from a 1MeV source to a final energy of 19GeV. The source is assumed to be a large area contact ionization type similar to the one ampere cesium source under development at LBL. However, other high current heavy ion sources might be equally, or even more, suitable. The beam is initially accelerated by a three stage, pulsed drift tube linac DTL (Faltens [1977]). A stripping cell and charge separating analyzer are located between the second and third drift tubes. The beam is then accelerated by a series of low voltage induction acceleration modules in the $q=+4$ charge state to an energy of 200MeV. This completes the injector portion of the accelerator.

For the bulk of the acceleration, from 0.20GeV to 19GeV, the current level at any energy is continuously adjusted by bunch length control to be near the cost minimum. Near the end of the accelerator a modest energy tilt is applied in order to compress the bunch and increase the beam power to the desired 100TW level. The beam implodes somewhat like an elastic spring (Judd [1977]). The energy tilt and bunch shape are controlled so that at the time of the beam's passing through the final focusing magnets, the space charge forces of the bunch remove the previously applied energy tilt. At the end of the final acceleration/compression section, and before the final focusing lenses, the beam is split vertically and horizontally by thin septum magnets to facilitate focusing onto the target. In this type of system, since one bunch is split transversely, timing is determined by path lengths to the target and the final beamlets would be in perfect synchronism.

B.1.1 Detailed Description of the Accelerator

B.1.1.1 The Injector

This section describes one possible way of achieving the initial acceleration of a charge of more than 150uC to about 200MeV. Other conceptual designs have been and will be pursued for this energy interval. While this interval represents less than 1% of the particle energy required at the target, it presently accounts for several percent of the cost and a larger fraction of the technical problems. The alternative designs, such as the one presently being investigated by Herrmannsfeldt [1978], offer promise of very large cost reductions, but will require comparative evaluations and detailed designs. The system described here accelerates the entire charge in three large drift tubes which are followed by a low gradient induction accelerator section.

The accelerator begins with injection of 7.5A of U^{+1} from a large area, 1MV source into a 1MV drift tube about 27 meters long. The source may be of the contact ionization type (Hashmi [1975]) which would supply uranium ions of very low transverse energy and which would be of similar design to the LBL Cs ion source. Alternatively, it may be of an entirely different type and for some other heavy element of A > 200. However, the calculations are all based on a uranium source. The drift tubes are pulsed in a bipolar manner to provide 2MV potential difference each. At the end of the second drift tube, the particles are stripped in a helium gas cell and the $q=+4$ charge state selected. It is assumed that the loss in particle number is compensated by the increase of charge state in such a manner that the required charge of 210uC is obtained at the output. The beam is further accelerated in the third drift tube with ramped voltages in order to start decreasing the pulse duration. It is clear that the beam energy as a function of longitudinal position should be constant up to the analyzer. However, it is not yet certain what the maximum energy tilt limit is for the transport system and how rapidly the pulse duration can be decreased. In this scenario, the voltage at the input to the third drift tube is taken as a flat 1MV, and the voltage at the output as a linear ramp in time from 0 to 1MV.

The drift tubes are followed by a series of low voltage induction acceleration modules. The core cross section is determined by the time integral of core voltage. Therefore a tilt in voltage waveform may be superimposed on the average voltage of the pulse without any increase in core size. The rear particles of the bunch must have somewhat higher energy than the front particles in order to decrease both the physical bunch length and the pulse duration. At the beginning of the induction section, the acceleration rate has an average value of about 20kV/m, or 80 keV/m for the q=+4 charge state. At this average acceleration rate the bunch, which is initially about 70m long, at an average energy of 12MeV, should have a tilt of ± 2.8MeV just to maintain its length, and a somewhat larger tilt in order to start bunch length compression. Later in the acceleration process the required ramp is fractionally much smaller. The maximum energy tilt desired may be obtained in a distance shorter than the initial bunch length if the induction units are driven with triangular voltage pulses, while a longer distance is required with a less steep voltage ramp. For simplicity, we assume that the particles in the middle of the bunch are accelerated at the average rate permitted by the induction cores. The induction cores used at the beginning all have a constant cross section which is sufficient for 1 volt-second of acceleration. As the beam pulse is accelerated its duration is decreased as $V^{-5/6}$, and consequently the acceleration rate is increased.

Some of the above may be clarified by a sequence of energy profiles of the bunch as a function of z at constant t at several locations, and of the core voltage pulses at these location as a function t, shown in Fig. 18.

In addition to the linearly-rising voltage waveforms required for pulse shortening, it is necessary to counteract the average longitudinally defocusing electric field at the ends of the bunch, arising from the space charge. This may be accomplished by applying opposite polarity steep ramps or "ears" which form a sort of rf bucket for the particles. Because the beam generated electric field varies across the radius of the beam, there is no waveform which may be externally applied to compensate for the space charge forces on all of the particles. Instead, for a sufficiently strong applied field, there will be an equilibrium bunch shape. Individual particles will slowly oscillate longitudinally as in an approximately square potential well.

The transverse focusing within the drift tube section is provided by periodic electrostatic focusing. The focusing within the induction section is with internal quadrupoles.

In addition to the electrostatic focused DTL, other possible injection systems for the LIA that have been considered include:

1. drift tubes with very large, high field solenoids,

2. an rf linac plus a low energy accumulator ring (Godlove [1976]);

3. recirculating the beam through the low energy accelerator structure with rapid multiple pulsing (Faltens [1977]), and

4. a tree of linacs to build up to the requisite current level.

With any of these injection systems, the goal is to match the output current of the injector to the transportable current limit of the quadrupole focusing system of the accelerator. As examples, this limit is about 1A at 1MeV and 7A at 10MeV for U^{+1} in a 4T FODO lattice with a normalized beam emittance of 3cm-mrad. Because the acceleration cost per meter is a rapidly decreasing function of energy, it is desirable to inject at as high an energy as possible. Alternative designs are evaluated on the basis of their cost per unit of beam energy as a function of beam energy.

B.1.1.2 Accelerator Modules with Quadrupole Focusing

Several packaging configurations are possible for the induction accelerator modules and focusing quadrupoles. At low energies, the space needed for focusing magnets, and the core requirements, combine to provide very low average accelerating gradients. As acceleration proceeds, a smaller fraction of the accelerator length needs to be devoted to the magnets, and the accelerating modules themselves change in appearance. Peak voltage constraints become dominant as the particle energy is increased and the pulse duration decreased. The differential cost of acceleration is a monotonically decreasing function of particle energy. This results in a proportionately small increase in cost for a large increase in beam energy when the system is desired to be extended.

B.1.1.3 Modulator Requirements

The driver or modulator must supply current to the induction core and to the beam. The core current may have a variety of waveforms while the magnitude of the core current may be greater than or less than the beam current. The beam current has a magnitude which is determined by the transverse and longitudinal focusing requirements of the bunch, and is an increasing function of the particle kinetic energy--of the order of amperes at 1MeV for U^{+1} and kiloamperes atGeV energies. Near the end of the pulse the current to the core rises rapidly as saturation is approached.

At the low-energy end of the machine the beam current may be ignored, and a modulator-compensating network combination constructed to generate a voltage waveform which would be optimized for one voltage level and pulse duration. A suitable pulse generating circuit could be a tapered-impedance, lumped-element transmission line. The calculated energy required to drive the accelerating core has been doubled to arrive at total modulator energy requirements, thus accounting for uncertainties in core losses, and for energy put into compensating networks, dissipated in the circuitry, and left in the modulator after the pulse. The core requirements are easily measured, and part of the core evaluation program will be to select the best material and core geometry and to determine how far into saturation any core should be driven. The preliminary estimates are that most cores would dissipate less than one kilojoule.

At the high-energy end of the accelerator, the beam current becomes the major load for the modulator. To guard against damage in the event that the modulator is pulsed in the absence of beam, a resistive load may be placed in parallel with the core to help limit the open circuit voltage and to greatly increase the pulse damping rate. For initial estimating purposes, the energy required by the core plus the beam has again been doubled to arrive at total modulator requirements. In the high energy region, the energy required per unit is only about 100 joules, and several accelerating units may be driven in parallel with one modulator. In all cases enough damping will be provided between sections to prevent dumping most of the energy at any one location in the event of a fault. A suitable pulse generating circuit here would be a Blumlein pulse line and a spark gap switch. If a resistor placed in parallel with the core is chosen so that under normal operating conditions the current flowing into it is equal in magnitude to the beam current, then in the absence of the beam the accelerating gap voltage is less than 1/3 higher than the voltage in the presence of the beam, while the acceleration efficiency would be near 50% when normal beam current is present.

B.1.1.4 Final Bunching and Acceleration Section

The acceleration voltages are ramped steeply in the final section to provide simultaneous acceleration and tilting of the momentum ellipse. At the end of this section, the beam is split transversely into four beams, which are then brought separately to the target, with two beams incident from each side as shown in Fig. 19.

Assuming an average acceleration rate of 0.8MV/m, this section of modules will occupy a length of 1km, accelerating the q=+4 beam from 16GeV to 19GeV, while the beam splitters, final focus, and bending will require about 350m along the beam path. The applied voltage pulses in this final section consist of three major parts: the accelerating field; the bunching ramp; and the space charge field compensating "ears." The incident particles are assumed to have been previously slightly ramped in energy in order to compensate the bunch lengthening which would normally occur from acceleration. At subrelativistic velocities, the bunch length L is proportional to its velocity v with L=Li(v/vi)=1.09 Li over the course of the last kilometer, where Li and vi are the initial bunch length and velocity, respectively. This would correspond to a bunch lengthening of about 6 meters for the 70 meter long incident bunch. The energy tilting required to keep the bunch length constant is equal to the energy difference between the front and rear particles of the bunch - that is 56 q MeV for this example. This energy tilt of about 1.4% is assumed to have been applied previously for bunch length control.

To achieve the desired final bunching an additional ramp of 200 q MeV (i.e.,±100 q MeV) will be applied within the last kilometer. As the bunch leaves the accelerating structure, the rear end of the bunch will gain an additional 35 q MeV, because at that point the bunch will have already decreased to half of its initial length. Within the accelerator, the particles within the bunch all move in the rest frame of the center of the bunch as if in a force field whose magnitude varies linearly from the center. The collapse of the bunch is parabolic within the accelerator and linear outside. Space charge repulsive forces become dominant when the bunch is quite short, and determine the minimum length of the bunch. These repulsive forces are dependent on the current, bunch profile, beam radius and beam pipe radius. It is expected that, by proper design, most of the energy tilt which causes the bunch compression will be removed by the space charge repulsion at the end of the drift path.

B.1.1.5 Final Focus

Both geometric and chromatic aberrations place certain limitations on the nature of the final-focus lenses and indirectly therefore on the minimum number of beamlets that will be required to strike the focal spot. For the example of interest here, it appears that geometric aberrations are the limiting factor in determining the required number of beamlets. If we consider focusing with quadrupole doublets (a triplet allows a little relaxation in the conditions described below), then reference to Garren [1976] shows that his parameter b will probably be between 5 and 35, where

b=L/(rho*theta),
L=standoff distance (5-10m),
rho=magnetic radius of ion in a field equal to the pole-tip field of the lens, and
theta=Half angle of the beam at the target. Combining this result with those of Neuffer [1978] on the third-order aberrations we can derive a limit on the maximum permitted radial excursion X, of $X \leq (1 \text{ to } 2) r*rho$, where r=focal spot radius. In many cases examined, X turns out to be of order 15cm.

In addition, from Neuffer's results we can derive a limit on the normalized longitudinal emittance that can be tolerated in a beamlet in a final focus lens: ≤ 0.12*beta*gamma*$r^{4/3}$. For a typical case the emittance limit may be in the range 0.5 to 0.7cm-mr.

In doublet configurations discussed by Garren, the maximum radial excursion was in the x-plane and aberration problems are far worse in this plane than in the y-plane. This asymmetry arises because of assumptions of equal emittance in both the x- and y-planes. Recent results by Neuffer indicate that the emittance in the y-plane (and hence excursions in y) can be increased to about 1.5 the emittance in the x-plane before aberrations in each plane have comparable effects. Figure 20 shows a concept for transverse splitting of the beam into four beamlets just upstream of the final lenses by a four- way septum current-sheet magnet. (Similar schemes can be devised for 2-, 3-, 6- and 9-way splits, etc.) The septum edge is below the spall threshold, but could if needed be armored with tantulum, titanium or carbon. Apart from losses on the splitting septum, there should be very little dilution in the process despite the somewhat irregular beam envelopes emerging from the splitter.

We can define, for transverse splitting, the minimum number of final beams as:

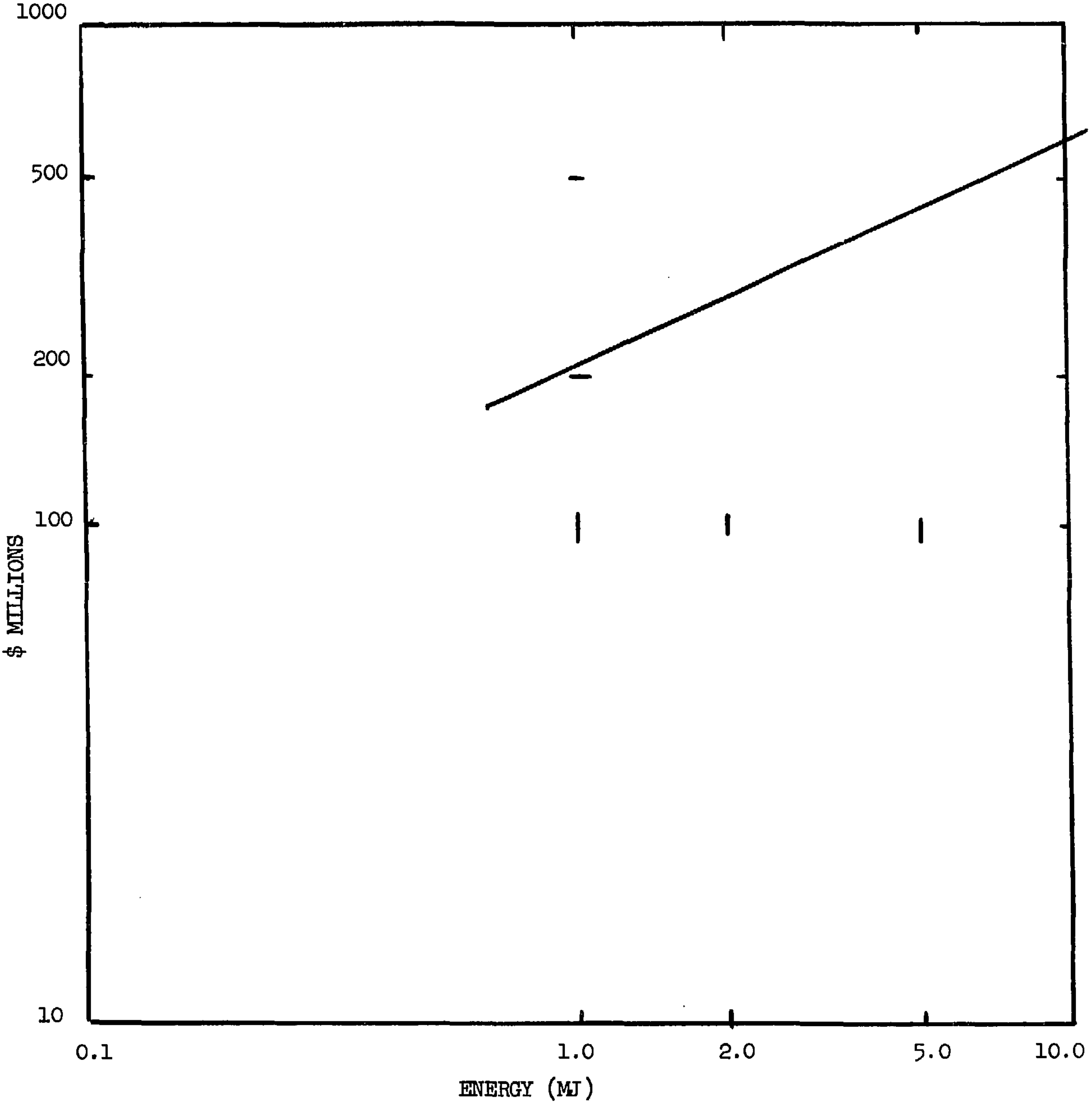
$$n = (2/3)(\text{transverse emittance/longitudinal emittance})^2.$$

For transverse and longitudinal emittance of 3cm-mr and 0.7cm-mr, respectively, twelve beamlets, arranged for example in two clusters of six, would meet the requirements.

B.2 10MJ DRIVER SYSTEM

The sample 1MJ design described above can be expanded to higher total energy be increasing either the length of the LIA or by increasing the charge being accelerated, or by some combination of both. The computer-optimized cost program has been used to find the trajectory of minimum costs as a function of energy which is plotted in Fig. 21. These costs do not include injection and final transport systems, and thus are usually considered to be about 80% of the completed cost estimate. They also, of course, do not include indirect construction costs.

FIGURE 21: Optimized Costs for LIA Driver
(without injection and final transport)



Appendix C

IMPLEMENTATION SCENARIOS

by W. B. Herrmannsfeldt

A large number of scenarios have been suggested for the implementation of HIF. A selection of such scenarios is presented in this appendix. Comments as to the relative merits and problems of each scenario are the personal opinion of the author unless otherwise identified.

C.1 THE 10MJ ICF RESEARCH CENTER

The most ambitious first step which has been suggested is probably that of a 10MJ facility by Al Maschke. The accelerator part of this proposal is contained in Appendix A.2. The thinking has gone beyond the accelerator system to include several target areas. These could be specially devoted to;

1. pellet R & D,
2. blast chamber testing,
3. accelerator beam tests.

As success is achieved in each of these, target areas would be adapted to testing disigns for;

1. tritium breeding,
2. steam generation,
3. fissile fuel breeding.

At even more advanced stages, target areas could devoted to;

1. advanced fuel pellets (i.e., with little or no tritium),

2. direct conversion of electromagnetic energy from the blast to electric power,

3. direct chemical conversion (e.g, production of "natural" gas).

The 10MJ accelerator system is intended to be large enough to allow such a wide range of experiments while recognizing that in the early stages, both the accelerator and the pellets may have to be downrated somewhat.

Comments: At $0.8B to $2.0B, depending on whose estimates one wishes to use, this facility is both the most expensive and the most economic route to fusion energy. In fact, no research tool in history has cost so much. Since the price does not include laboratories, pellet factory, target areas, offices, etc., the total could easily approach $3B. Paradoxically, it is also very probably the cheapest route to fusion since it would bypass years of piecemeal developments, currently costing $150M/year, but clearly underfunded at that rate. The $350M/year currently being spent by MFE is probably a better guide to what is realistically needed. By concentrating the entire ICF program on such a facility for a decade, one can virtually guarantee a definitive statement at the end about the feasibility of ICF.

The largest drawback to this plan is not the price, which as was pointed out above, is not so much more than is already being spent, but is in the political issues. The only possible way in which such a project could be promoted would be by a unified push by the scientific community including, especially, all parts of the fusion community. With the multitude of fusion schemes, both MFE and ICF, now being promoted, it will be very difficult to achieve such a unity in the immediate future.

C.2 STAGED APPROACH

This scenario, based essentially on the staged program described in Chapter 5, would devote 2 1/2 to four years on accelerator R & D along two parallel fronts:

1. rf linacs with current multiplying rings (possibly including synchrotron rings),

2. single pass linear induction accelerators.

At the end of this period, a decision would be made choosing one of these systems to be built on a suitable site.

C.3 INTER-LABORATORY ALLIANCES

Alliances between weapons laboratories and accelerator laboratories offer one of the most logical scenarios toward a HIF facility. Probably the most obvious alliance candidate is LBL-LLL because of their proximity. Other possibilities involve ANL and BNL as accelerator laboratories allied with LLL, Sandia or LASL, or possibly NRL, in any possible combination. Yet another possiblility is for LASL, which has a strong rf linac group, to pursue HIF by itself.

Comments: There is at least some precedent for a large-scale collaboration between DOE laboratories in the joint LBL-SLAC project to build PEP. For a collaborative effort to be joined, both laboratories must see the project as being to their advantage, even though the construction cannot be located at both centers. In the case of a large HIF facility, it is possible that it would not be located at any of the existing scientific labortories. Rather some of the production and test facilities, such as Savannah River, Arco, Idaho, and the Nevada Test Site are probably more appropriate locations.

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