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AN ACCELERATED PLAN TO DEVELOP
MAGNETIC FUSION ENERGY

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MASTER

1. INTRODUCTION

Though the government has slowed up its funding of fusion research, there may exist now or in the near future an economic incentive for the private sector to accelerate fusion development for its own reasons. The purpose of this paper is to lay out the cost and schedule for such an accelerated development plan based on a number of studies carried out over the last five years. In Sec. V, we also summarize the present state of knowledge of the capital cost of a commercial fusion power plant.

A complete assessment of the economic incentive to develop fusion is beyond the scope of this paper. However, the main point can be simply stated. Namely, whereas utilities now face a high risk of uncertain and escalating costs, fusion would cap the cost of energy production at roughly present levels. Relative to oil, coal, and gas, this follows from the fact that fusion fuel is cheap and abundant, and fusion does not pollute the atmosphere. Relative to conventional nuclear power from fission, fusion plants would have a similar capital cost but enjoy greater public acceptance and free utilities from future cost burdens such as waste disposal. Inherent differences between fusion and fission make fusion plants less hazardous, and fusion waste could be disposed of at the plant site with no long-term effects.

On the technical side, fusion is indeed ready for accelerated development. After many years of research, the scientific feasibility of fusion is now almost certain--a claim that could not have been made a decade ago--and the virtues of fusion energy have withstood the scrutiny of increasingly sophisticated engineering analysis. Fusion does indeed hold the promise of an essentially inexhaustible fuel supply with environmental and safety advantages responsive to public concerns about nuclear power.

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II. PREVIOUS PLANS

The fastest timetable to develop fusion was probably that represented by the Magnetic Fusion Energy Engineering Act of 1980.¹ This Act, never implemented, called for an engineering test facility by 1990 and a demonstration power plant by the year 2000.

When it became evident that the engineering test facility called for in the 1980 Act would be delayed, the fusion community set out to devise an alternative plan that would still meet the objectives of the Act. This culminated in a report by the DOE Magnetic Fusion Advisory Committee (MFAC) completed in 1983.² In addition to a continued broad R&D effort, the MFAC plan called for:

1. Initiation in FY 86 of the Tokamak Fusion Core Experiment (TFCX) designed to achieve ignition and long-pulse burn.
2. Potential utilization of an upgrade of the Mirror Fusion Test Facility (MFTF) to provide a cost-effective means for testing "blanket" and power-system components in steady-state.

This plan also was not implemented and the present DOE plan, issued in 1985, postpones engineering development into the next decade or beyond.³

III. AN ACCELERATED ENGINEERING DEVELOPMENT PLAN

In effect, the MFAC plan of 1983 accelerated the engineering test phase by dividing the job of the previously proposed engineering test facility between two smaller facilities, the TFCX and MFTF. As was noted in the MFAC report, this saved time and money by reusing equipment at existing sites and by exploiting technological innovations since the 1980 plan was formulated.

The plan we propose is similar to the 1983 MFAC plan, with further technological innovations. The key elements are TIBER⁴ (which replaces the TFCX above); MFTF-Upgrade⁵; and the Demonstration Reactor. The TIBER is the latest design for a tokamak of minimum size to ignite DT fuel using all of the technologies relevant to a fusion reactor (superconducting magnets,

shielding, etc.). In other words, TIBER would be the first demonstration that the fusion "fire" will burn reliably. The TIBER would also include sections of the thick-walled "blanket" that converts the fusion energy (mainly energetic neutrons) to heat and steam to run the electric power generators. However, it is the MFTF-Upgrade, a neutron source dedicated to blanket testing, that would provide data on blanket reliability under long-term exposure to neutrons. Finally, the Demonstration Reactor would put it all together in the world's first fusion electric power plant.

A time table is given in Fig. 1, which shows TIBER and MFTF-Upgrade carried forward in parallel. Together, the results from these facilities trigger a decision to proceed with the DEMO, and they continue to provide operating experience and data while the DEMO is under construction. Like the 1983 MFAC plan, the present plan calls for a continued, broad-base program to enrich the information base and stimulate further innovation. This base program includes a short-pulse ignition experiment (CIT) that will provide operating experience for TIBER, and continued development of reactor concepts alternative to the mainline tokamak and mirror. Also, in addition to their engineering functions, the TIBER and MFTF-Upgrade will advance our understanding of the tokamak and mirror reactor options.

IV. DEVELOPMENT COST

A budget to carry out the above plan is presented in Table I. The figures given are based on a number of planning exercises carried out by DOE and the fusion community over the past several years. Costs are in constant 1985 dollars.

The total integrated development cost including facilities is similar to that envisaged in the Magnetic Fusion Energy Engineering Act of 1980.¹ About half of this cost is in the Base Program and half in new engineering facilities.

The Base Program, at \$500M per year, is that recommended in the 1983 MFAC Plan² and is roughly the level at the peak year of funding in 1984 when the fusion budget was \$471M nationwide (see Table II). At that time, the

Figure 1. Accelerated fusion engineering development plan.

TABLE I. BUDGET FOR FUSION ENGINEERING DEVELOPMENT (millions of \$).

	87	88	89	90	91	92	93	94	95	96	97	98	99	Totals
TIBER														
Design	50													
Construc.		200	200	200	200	200								
Operations							150	150	150	150	150	150		
	<u>50</u>	<u>200</u>	<u>200</u>	<u>200</u>	<u>200</u>	<u>200</u>	<u>150</u>	<u>150</u>	<u>150</u>	<u>150</u>	<u>150</u>	<u>150</u>		1,950
MFTF-U														
Design			20											
Construc.				100	100	100	100							
Operations								100	50	50	50	50		
			<u>20</u>	<u>100</u>	<u>100</u>	<u>100</u>	<u>100</u>	<u>100</u>	<u>50</u>	<u>50</u>	<u>50</u>	<u>50</u>		720
DEMO														
Design							50	50						
Construc.									500	500	500	500	500	
Operations													200	
							<u>50</u>	<u>50</u>	<u>500</u>	<u>500</u>	<u>500</u>	<u>500</u>	<u>700</u>	2,800
Subtotal facilities	<u>50</u>	<u>200</u>	<u>220</u>	<u>300</u>	<u>300</u>	<u>300</u>	<u>300</u>	<u>300</u>	<u>700</u>	<u>700</u>	<u>700</u>	<u>700</u>	<u>700</u>	5,470
Base program	<u>400</u>	<u>500</u>	<u>500</u>	<u>500</u>	<u>500</u>	<u>500</u>	<u>500</u>	<u>500</u>	<u>500</u>	<u>500</u>	<u>500</u>	<u>500</u>	<u>500</u>	6,400
Total	450	700	720	800	800	800	800	800	1200	1200	1200	1200	1200	11,870

TABLE II. U.S. FUSION RESEARCH BUDGETS
(In millions of dollars)

<u>Fiscal Year</u>	<u>Magnetic Fusion</u>
51-53	1.00
54	1.74
55	4.72
56	6.73
57	10.74
58	29.32
59	30.73
60	33.60
61	30.00
62	24.77
63	25.50
64	22.48
65	23.10
66	23.10
67	23.90
68	34.99
69	29.16
70	29.28
71	30.27
72	32.70
73	38.90
74	56.80
75	89.00
76	219.10
77	316.30
78	332.40
79	355.90
80	350.20
81	394.10
82	451.00
83	447.00
84	471.00
85	429.60
86	365.50

program included the necessary R&D elements short of the major facilities needed to embark on engineering development. Budget decreases in 1985-86 have postponed technology development and forced stretching out the completion of major facilities (TFTR and MFTF-B). These program elements should be restored by ramping the Base Program budget back to the \$500M level as soon as possible.

The budgets given for the major engineering facilities are based on documented construction costs together with estimates for design and operation based on past experience. Typically, annual operating costs are comparable to annual construction outlays, since in a one-of-a-kind experimental operation the same array of technical skills is required in construction and operation. As shown in Table I, the construction costs are taken to be:

TIBER	\$1000 M
MFTF-Upgrade	400
DEMO	2500

The TIBER estimate is based on a current design and agrees with earlier estimates for machine designs of similar size (e.g., TFCX).⁴ These estimates are based on actual experience in constructing the TFTR (\$314M) and MFTF-B (\$242M). The track record of cost versus estimate has been very good for these devices. These costs do not include supporting R&D, which is included in the Base Program.

The MFTF-U estimate is based on costs given in Ref. 5.

The DEMO cost is more speculative but is in the right ballpark. Conceptual reactor designs in the 250-350 MW_e range suitable for a DEMO have been completed recently.⁶ The DEMO cost given here is based on a tokamak reactor producing 350 megawatts of net electrical output.⁷ This estimate (\$2500M) is comparable with other large first-of-a-kind tokamak design

studies (for example, the international INTOR design, presently estimated at \$2700M).⁸ A small tandem mirror reactor design, in progress, is yielding similar estimates.

Finally, we comment on the ability of the fusion research program to grow at the rate indicated in Table I. Again, the program has a good track record, having previously sustained a successful period of rapid growth in the mid-1970's, as shown in Table II. The present capability for growth is in fact greater than a decade ago because a large core of trained people now exists, both in universities and national laboratories and in the industries that were involved in constructing TFTR and MFTF-B. Indeed, without growth, this talent pool will soon be lost to other fields.

V. CAPITAL COST OF COMMERCIAL PLANTS

Our present understanding of fusion capital cost has been summarized in a recent paper by Logan.⁹ He finds a total cost of construction in the following range:

\$2000 to 4000/KW_e.

This includes the direct cost of hardware; indirect costs for insurance, temporary site facilities, etc.; and interest cost and inflation during construction. Having been derived from direct costs in current dollars, this would be the total cost of construction by the time the plant is completed if construction began today. Given the uncertainty in forecasting twenty years into the future when the first commercial plants might be initiated, this would appear to be an acceptable capital cost range, especially when the cost-stabilizing characteristics of fusion are taken into account. Indeed, the above cost range compares favorably with present utility experience.

In arriving at this cost range, we have assumed that the total cost is only twice the direct cost (a multiplier of 2) even though recent experience for conventional nuclear reactors has been far less favorable. We base the

more favorable outlook for fusion on the expectation that the environmental and safety advantages of fusion will persuade the public to accept expeditious construction schedules in contrast with the current prolonged construction periods for conventional nuclear plants (sometimes 10 years or more). Thus, we have assumed a 6-year construction time and an inflation rate of 6%. In his paper, Logan argues that even shorter construction times may be possible with modular construction techniques. The cost incentive for a shorter construction time is evident in the following table of the total-to-direct cost multiplier for 30% indirect charges and various construction times and inflation rates:

Construction time (years)	Multiplier at 6% inflation	Multiplier at 10% inflation
4	1.4	2.0
6	2.0	2.4
8	2.3	3.0
10	2.6	3.7

Finally, the range of direct costs reflected in the above range of total costs span present and future design options. The lower end of the range is based on a direct capital cost of \$1000/KW_e--equal to the present direct cost of fission reactors¹⁰--which Logan argues may be achievable by incorporating improvements discussed in his paper. The upper end of the range, based on a direct cost of \$2000/KW_e, is derived from the following recent studies of tokamak and mirror fusion reactors:

Design	Net electric power (MW _e)	Direct capital cost (millions of \$)*	Direct \$/KW _e	Year study completed
Starfire (tokamak)	1200	2225	1854	1980 ¹¹
MARS (mirror)	1200	2526	2105	1984 ¹²
TPSS (tokamak)	600	1360	2266	1985 ¹³
MINIMARS (mirror)	600	1240	2067	1986 ¹⁴

* 1985 dollars. Includes approximately 15% contingency.

VI. CONCLUSIONS

We have shown that, despite funding delays since the passage of the Magnetic Fusion Energy Engineering Act of 1980, fusion development could still be carried to the point of a demonstration plant by the year 2000 as called for in the Act if funding, now about \$365 million per year, were increased to the \$1 billion range over the next few years (see Table I). We have also suggested that there may be an economic incentive for the private sector to become involved in accelerating fusion development on account of the greater stability of energy production costs from fusion. Namely, whereas fossil fuel prices will surely escalate in the course of time, fusion fuel will always be abundantly available at low cost; and fusion technology poses less future risk to the public and the investor compared to conventional nuclear power. In short, once a fusion plant is built, the

cost of generating electricity--mainly the amortization of the plant capital cost--would be relatively fixed for the life of the plant. In Sec. V, we found that the projected capital cost of fusion plants (\$2000 to \$4000 per KW_e) would probably be acceptable if fusion plants were available today.

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