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MHD Magnet Cost Analysis

Develop and Test
an Internally Cooled, Cabled Superconductor (ICCS)
for Large Scale MHD Magnets

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1.0 Introduction

The program to develop an advanced ICCS conductor to be incorporated into an advanced-design MHD magnet system for a retrofit MHD power generation topping cycle requires cost data to compare the costs projected for this device with costs for more conventional MHD magnet systems that have already been designed and/or constructed. To that end, the considerable component and magnet systems costs developed previously have been gathered and are presented here in a uniform fashion with costs scaled to 1984 dollars.

It is evident from reviewing the data presented that there is still a significant effort needed to develop commercial manufacturing technology for these sophisticated magnet systems that will bring cost per unit down significantly from those seen for one-of-a-kind devices. It is hoped that this report will provide both a basis of comparison for any system to be developed and will also spur creation and implementation of the programs necessary to bring MHD magnet system manufacture to commercializable reality.

Much of the data presented herein was obtained from a program to develop superconducting magnets for commercial magnetohydrodynamic (MHD) power generation plants, initiated in 1976 and continued through early 1984, that was conducted by the Massachusetts Institute of Technology (MIT) under sponsorship of the U.S. Department of Energy (DOE). The overall objective of the program was to prepare the technological and industrial base required for minimum time, cost and risk implementation of superconducting magnets for MHD. Work accomplished on this program in the period from 1976 through September 1982 is summarized in report, Reference 1 and work from October 1982 through April 1984 is summarized in Report, Reference 2. Those reports contained selected cost information relating to specific component developments and magnet system designs, but omitted a considerable body of information on cost analysis, cost documentation and cost estimation performed during the program.

The purpose of this report is to summarize cost analyses performed, cost data developed and results achieved during the period 1976 to 1984 under the MHD Magnet Technology Development Program. Both cost work already reported and cost work not previously reported are covered in this report.

Because magnet system capital cost represents one of the largest single component costs in the MHD topping system, it is very important that magnets be designed to have the minimum material and manufacturing cost consistent with achievement of predicted performance and required reliability in service. Accordingly, cost analysis work was carried out at MIT in parallel with magnet design and technology development with the following objectives:

- To generate progressively more reliable magnet cost estimates and cost scaling information as needed by DOE and other investigators for comparing and evaluating overall MHD power generating systems and for budgetary planning. (System sizes up to 2000 MWe)
- To identify, break down and analyze the various elements of magnet cost as a basis for improving the cost-effectiveness of overall magnet systems by improved design, better material selection, component and manufacturing development and careful interfacing with other system components.

This report records for reference purposes the results of cost estimates made on a number of MHD magnet designs, ranging from large commercial size to experimental test facility size. It outlines estimating methods used, describes the results of studies made for the purpose of improving the cost effectiveness of magnet systems and lists actual costs of MHD magnets constructed during the report period.

While the bulk of the cost analysis work dealt with linear MHD magnets, cost estimates of conceptual design disk-type MHD magnets were made and are included in this report.

Estimated and actual costs of a few large fusion and physics experiment magnets are also listed for comparison with MHD magnet costs.

The report deals primarily with superconducting magnets, but information is also included on room temperature and cryogenic magnets used for MHD experiments.

Information used for estimating costs for future magnet designs is presented, including curves of magnet costs vs size parameters, lists of component cost algorithms and descriptions of estimating and scaling procedures. Cost escalation is discussed and a list of escalation factors applicable to magnet systems in the period 1975 to 1995 is included.

Nearly all of the cost data presented is for "first unit" (one of a kind) magnets. The effects of multiple unit production and manufacturing learning curves on magnet costs are discussed in Section 4.1.7.

It should be noted that in many of the data presented in this report, magnets of similar bore size and field strength have widely different estimated (or actual) costs, even when adjusted for escalation. Investigations have shown that while a small part of these discrepancies may be due to design factors, the major part is due to differing degrees of thoroughness, conservatism, and accounting methods used in estimating and to differences in manufacturing, management and business practices, as well as to many other factors which can affect first unit costs during construction.

The MHD magnet technology development program is not yet completed, and the associated cost analysis work is also not completed. In line with recommendations in Section 3.0 of Reference 1, it is urged that planning of future steps toward commercialization of MHD include continuation of cost analysis effort as a part of the overall technology development program.

2.0 Overall Results

Overall results of cost-related work accomplished during the magnet technology development program include the following:

- An improved capability was developed to make reliable predictions of future magnet system costs.
- A greater appreciation was gained of the influence of source of design and manufacture on magnet system costs. (It became clear that magnets designed and manufactured by industry tend to be substantially more expensive than those designed and built by government laboratories.)
- Substantial progress was made in identifying design features which result in lower magnet system cost while maintaining adequate performance and reliability.

3.0 Approach

The cost analysis and related cost work associated with the magnet technology development program was conducted in four major areas, namely:

- Total magnet system cost studies
- Magnet component cost studies
- Special cost studies
- Cost estimating and scaling procedures

The summary of work accomplished (Section 4.0) presents information in these same categories and sequence.

In the first category, total costs of typical magnet systems are presented in tables, the variation of total cost with magnet size is shown on curve sheets, the relationship of total magnet system costs to other equipment costs is identified and cost escalation is discussed. (These data are useful in making budgetary predictions for future total magnet system costs.)

In the second category, a breakdown of magnet system costs into component costs, other direct costs and indirect costs is presented. Tables of typical component costs and component cost algorithms are presented. (These data are useful in making detailed cost estimates for future magnet components and systems.)

In the third category, results of special studies are summarized. The objective of most of the studies was to analyze the effect of magnet design variations and alternatives on magnet system cost. (These results are useful in improving the cost-effectiveness of future magnet designs.)

In the fourth category, estimating and scaling procedures are described, ranging from quick procedures for making preliminary estimates on new magnet concepts to more lengthy procedures for making estimates on completed designs with drawings. (These procedures will serve as guides in future magnet cost estimation.)

4.0 Summary of Work Accomplished

4.1 Total Magnet System Cost Analysis

4.1.1 Definition of Total Magnet System Cost

The term "total magnet system cost" as used here refers to the total cost (direct and indirect) of the magnet system installed and ready to operate in a power plant or test facility. Generally included are costs of the following items:

Direct cost items

1. Magnet components, including shop assembly and shop tests
2. Shop engineering, tooling, quality assurance, etc.
3. Packing and shipping to site
4. Assembly and installation on site
5. Accessory systems, including shipping and installation
6. Shakedown test

Indirect cost items

7. Design and analysis
8. Supporting development
9. Program management
10. Site special costs
11. Profits and fees
12. Contingency allowance

Not included in "total magnet system cost" are cost of foundations and cost of buildings to house the magnet and its accessories.

Also not included in the above list are preliminary (conceptual) design studies and preliminary development that usually represent a separate phase of an overall magnet program and are done prior to the start of the design and build phase.

The estimates for total magnet system cost presented in this report, except where otherwise noted, assume that preliminary design studies and preliminary development have been accomplished under separate funding and that design concept, conductor configuration and manufacturing approach have already been selected and developed to the point where magnet layout drawings, engineering calculations and detailing can proceed.

The term "direct cost" as used here refers to the cost of the equipment (hardware) items including shipping, site assembly, site installation and testing of these items. Also included as direct cost are shop engineering, quality assurance and similar costs in support of manufacture of components. Material, manufacturing labor, testing labor, manufacturers' overhead, G and A and profit are included in these "direct cost" items.

The term "indirect cost" as used here refers to overall program engineering and administrative costs and other costs not directly associated with individual hardware items.

Design and analysis, Item 7 (under "Indirect cost items"), is the cost of designing the magnet system and components and the cost of the analysis done in support of the design. Usually included are layouts, assembly and detail drawings and materials lists for the magnet itself; specifications for purchased parts, accessories and instruments and controls; system diagrams; and assembly and operating instructions.

Supporting development, Item 8, refers to special development work and laboratory testing conducted in parallel with design and analysis, as distinct from preliminary (conceptual) design and preliminary development carried out prior to the start of actual magnet design.

Program management, Item 9, is the cost of managing the overall program, including design and analysis, equipment procurement, component manufacture, installation and shakedown testing.

Site special costs, Item 10, are charges made by the site general contractor for on-site services, insurance, etc. (usually applied as a percentage of equipment and installation costs).

Profits and fees, Item 11, are charges applied by the magnet system contractor responsible for the overall program (as distinct from manufacturers' profits included in cost of components).

Contingency allowance, Item 12, is an allowance to cover unforeseen extra costs, inaccuracies in estimating, etc.

Where a magnet program involves design and construction of a single unit, all cost items apply in full to the single unit. Where multiple units of the same design are involved, some of the cost items may be in part nonrecurring, and the nonrecurring portions may be prorated over the multiple units.

4.1.2 Estimate of Total Cost of a Retrofit MHD Magnet System

The estimate presented below ($50,000,000 for a 4.5 T retrofit MHD magnet system) is an example of a magnet system budgetary cost estimate broken down into the major elements that determine the total overall cost. In this case, the cost of an initial preliminary design and development effort (Phase I) is included,[a] this effort being applied in the first year and one-half of a total five and one-half year program.

The budgetary estimate, one of several supplied by MIT to PETC early in 1984, covers a magnet system for a retrofit MHD power plant in the range of 200 to 500 MW_t input. It was prepared in connection with a PETC investigation of retrofitting a coal-fired central station power plant (specifically, an older plant in need of renovation) with an MHD topping unit. Such an arrangement is being considered as a practical and cost-effective means of obtaining early experience with commercial-scale MHD power generation.

The magnet design incorporates an ICCS winding and other features representing the latest state of the art. The design characteristics of the system on which the estimate was based are listed below:

Channel type	Linear, supersonic
Channel power output	35 MWe
Peak-on-axis field	4.5 T
Channel active length	9.5 m
Warm bore aperture at start of active length	0.9 × 0.9 m
Warm bore aperture at end of active length	1.6 × 1.6 m

A five and one-half year program for the design, development, construction and installation of the magnet system was estimated. The program schedule is shown in Fig. 4.1.

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[a] Note that in the next sections (Sections 4.1.3 and 4.1.4) total magnet system costs shown in tables and curves <u>do not</u> include preliminary design studies and preliminary development costs.

The total cost of the magnet system installed was estimated to be \$50,000,000 in 1984 dollars (rounded off). A breakdown of the cost estimate is given in Table 4-I.

Indirect costs, including overhead, G & A and profit are included in the items listed, where appropriate.

The cost of \$6,000,000 for the preliminary design studies, preliminary development and verification tests (Phase I of the program) is an engineering estimate taking into account the size of the magnet and the present status of development work on design features such as the ICCS winding. In considering magnets larger than the 4.5 T retrofit MHD magnet described here, it is expected that Phase I costs will increase with magnet size, but at a rate slower than the increase in total magnet system cost shown on the curves of cost versus size parameter presented in Section 4.1.4. For example, it is expected that the Phase I costs for a magnet designed for a 1000 MWe MHD channel would be about \$ 10,000,000 (slope of cost curve vs size parameter $VB^2 \cong 0.2$).

Table 4-I

Cost Estimate Breakdown
Design,Development and Construction of 4.5 T Retrofit MHD Magnet System[a]

	Phase I Conceptual Design and Development	Phase II Detail Design and Mfg Plan	Phase III Component Mfg and Installation
Conceptual design and analysis	2000	–	–
Prelim. dev't and verification tests	2500	–	–
Detail design and analysis	–	2900	–
Mfg planning and tool design	–	1000	–
Tool mfg and assy[b]			1000
Component mfg and assy[b,c]			18,000
Total, components on site			19,000
Site Ass'y, installation, shakedown			5400
Support engineering			2000
Total, magnet system installed			26,400
Program Management	300	500	2000
Total before contingency	4800	4400	28400
Contingency Allowance (25%)	1200	1100	7100
Total, incl. contingency	6000	5500	35,500
TOTAL, design & constr. Phases II & III			41,000
Total incl. prelim. des. studies and prelim. dev't Phases I,II, & III			47,000
			(50,000, rounded)

[a] 1984 k$

[b] includes cost of shipment to site

[c] includes cost of accessories

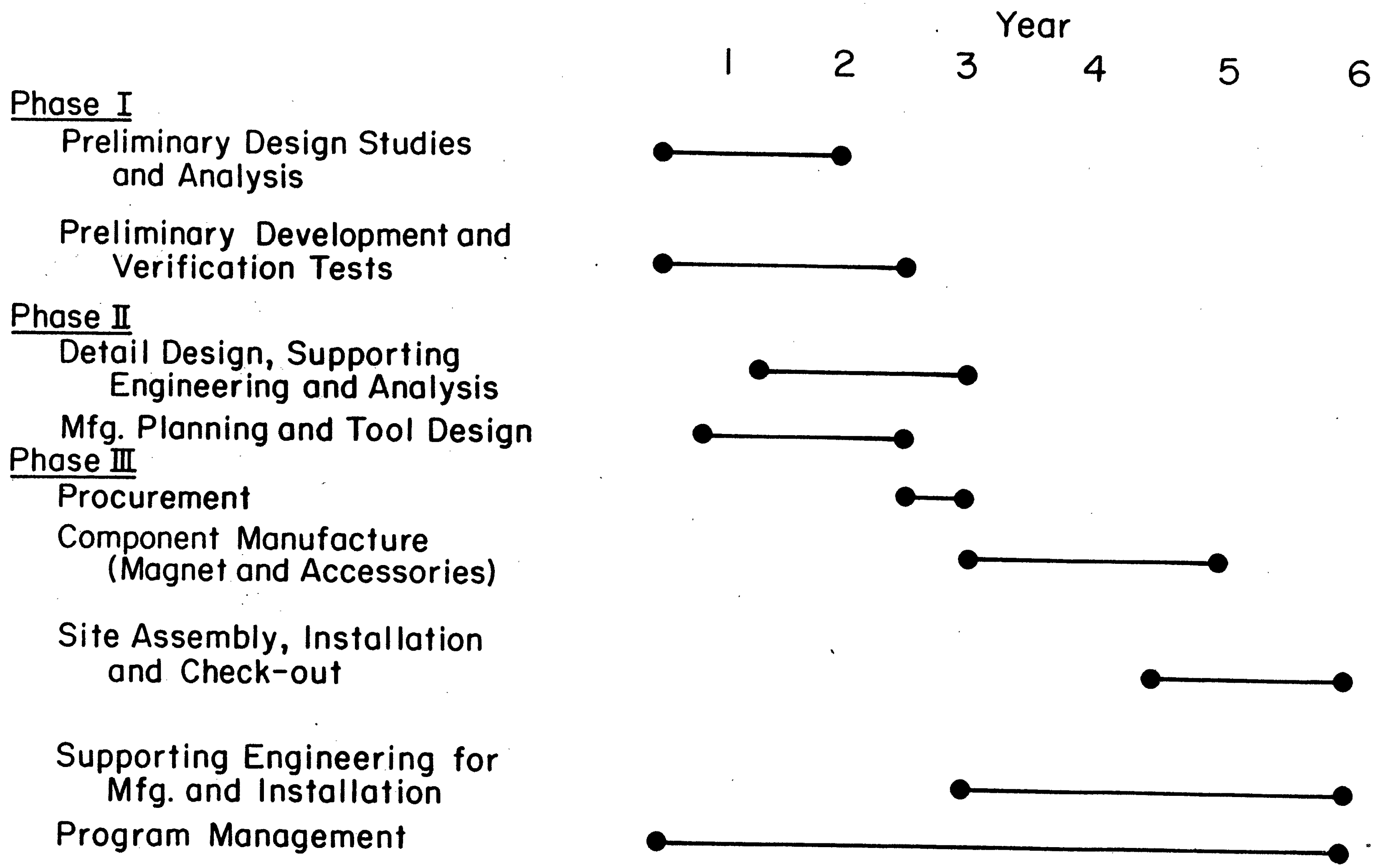


Figure 4.1
Schedule: Desgin, Development and Construction of 4.5 T Retrofit MHD Magnet System

4.1.3 Estimated and Actual Total Costs of Various MHD Magnet Systems and the Relationship of Cost to Magnet Size, Stored Magnetic Energy and Channel Power

During the report period, cost estimates and actual costs where available, were documented for more than 20 superconducting MHD magnet systems ranging from commercial sizes (1400 MWe to 200 MWe channel output) down to retrofit and test facility sizes (100 MWe to 5 MWe channel output). Most of the estimates were made as a part of the MIT program, while a few were made by other organizations in the MHD community.

Several of the alternative MHD magnet designs generated under the MIT program were specifically for purposes of evaluation and comparison in an effort to determine which designs were most promising for future development, cost effectiveness being a major criterion.

Major characteristics and total costs of representative magnet systems are listed in the following tables:

Table 4-II	Commercial-Size MHD Magnet Systems
Table 4-III	Engineering Test Facility (ETF) and Retrofit MHD Magnet Systems
Table 4-IV	Component Test Facility Magnet Systems
Table 4-V	Commercial-Size Disk-Type MHD Magnet Systems

The tables list original costs and costs adjusted to 1984 dollars to facilitate comparison (see Section 4.1.8 for escalation factors used).

The total costs listed do not include costs of preliminary (conceptual) design work, preliminary development and verification testing because those activities are assumed to be accomplished under the Magnet Technology Development Program or other separately-funded program.

The method and thoroughness of the estimating procedure used to arrive at the magnet system estimated costs listed in Tables 4-II through 4-V varied considerably from case to case. In the cases of the CASK commercial-size magnet (Table 4-II) and the ETF 6 T

Table 4-II

Major Design Characteristics and Estimated Costs of Commercial Size MHD Magnet Systems

Magnet designation		BL6-MCA	BL6-P1	CASK	CSM-1A	PSPEC	ECAS
Designer		MCA	AVCO	GD	MIT	GE	GE
Date of design		1977	1977	1979	1980	1978	1976
Magnet type		Rect.sad. +race tr.	Circ.sad. con. shell	Circ.sad. con. stave	Rect.sad.	[e]	[e]
Peak on-axis field,B	(T)	6	6	6	6	6	6
Active field length[a]	(m)	17.4	17.43	14.5	14.5	24	24
Aperture, start of active length[b]	(m)	1.57 sq.	2.69 dia.	3.28 dia.	2.2x2.8	2.45 dia.	2.87 dia.
Aperture, end of active length[b]	(m)	3.36 sq.	4.84 dia.	4.5 dia.	4.0x4.2	5.4 dia.	6.5 dia.
Design current	(kA)	20	14.5	50	52.2	[e]	[e]
Winding current density, average	$(10^7 A/m^2)$	1.78	1.3	1.28	1.15	[e]	[e]
Ampere turns	(10^6)	38	37	34.4	37.6	[e]	[e]
Stored energy	(MJ)	6710	6100	6300	7200	11,500	15,200
Total weight	(tonnes)	2664	3483	2644	1850	7320	4110
Size parameter, VB^2	$(m^3T^2))$	1544	3560 (2491)[d]	4411 (2522)[d]	2526	4071	5820
Total magnet system cost, original[f]	(k-dollars)	75,300[c]	56,876[c]	87,151[c]	75,590	116,100	43,000
Total magnet system cost, 1984 dollars[f]	(k-dollars)	119,100[c]	90,000[c]	117,800[c]	102,800	157,900	72,300

[a] Length from 0.8 B to 0.6 B

[b] Without warm bore liner

[c] Includes MIT estimate of cost of accessories and miscellaneous

[d] Based on bore inlet size, which is smaller than bore at start of active length

[e] Data not available

[f] Total cost including design and analysis but not including preliminary design studies and preliminary development.

Table 4-III

Major Design Characteristics and Estimated Costs of Engineering Test Facility (ETF) and Retrofit MHD Magnet Systems

Magnet designation		ETF-MCA	ETF6-P1	ETF6-GE	ETF6-West	ETF-Alt.	ETF-MIT	RETRO 4.5
Designer		MCA	AVCO	GD	West.	AVCO	MIT	MIT
Date of design		1977	1977	1978	1978	1978	1980	1984
Peak on-axis field	(T)	6	6	6	6	6	6	4.5
Active field length[a]	(m)	8	8	8	12	9	11.7	9.3
Aperture, start of active length[b]	(m)	0.64 sq.	0.9 dia.	0.9 dia.	2.6 dia.	1.5 sq.	1.53x1.93	0.98 sq.
Aperture, end of active length[b]	(m)	1.24 sq.	1.75	1.75 dia.	2.6 dia.	2.28 sq.	2.19x2.82	1.68 sq.
Design current	(kA)	20	5.5	9.0	10	13	25	25
Winding current density, average	$(10^7 A/m^2)$	2.39	1.5	1.5	2.0 est.	1.44	1.42	1.63
Ampere turns	$(10^6 A)$	16	19.2	19.2	35.8	[e]	27.9	15.6
Stored energy	(MJ)	1160	820	820	3400	1888	2900	700
Total weight	(tonnes)	376	535	535	380	1420	1000	370
Size parameter, VB^2	(m^3T^2)	118	254 (183)[d]	254 (183)[d]	2290	729	986	179
Total magnet system cost,original[f]	(k-dollars)	16,600[c]	15,100	42,100	36,000[c]	21,100	55,580	41,000
Total magnet system cost, 1984 dollars[f]	(k-dollars)	26,400[c]	23,900	62,100	57,200[c]	31100	68,600	41,000

[a] Length from 0.8 B to 0.6 B

[b] Without warm bore liner

[c] Includes MIT esitimate of cost of accessories

[d] Based on bore inlet size, which is smaller than bore at start of active length

[e] Data not available

[f] Total cost including design and analysis but not including preliminary design studies and preliminary development

Table 4-IV

Major Design Characteristics and Estimated Costs of Component Test Facility MHD Magnet Systems

Magnet designation		USSCMS	Stanford	CFFF	CDIF/SM
Designer		ANL	GD	ANL	MIT/GE
Date of design		1976	1978	1978	1978
Peak on-axis field, B	(T)	5	7.3	6	6
Active field length	(m)	2.6	2.3	3.35	3.4
Aperture, start of active length[b]	(m)	0.4 dia.	0.55 dia.	o.85 dia.	0.85x1.05
Aperture, end of acive length[b]	(m)	0.6 dia.	0.55 dia.	1.00 dia.	1.05x1.05
Winding current density	(10^7A/m^2)	2.82	2.08	2.0	1.83
Ampere turns	(10^6A)	6.7	11.5	13.7	14.22
Stored energy	(MJ)	34	80	210	240
Total weight	(tonnes)	37.9	70	172	144
Size parameter, VB^2	(m^3T^2)	8	27	61	88
Total cost, original estimate[f]	(k-dollars)	3900	5500		8100
Revised cost	(k-dollars)	-	-	10,370[d]	22,300[e]
Total cost, 1984-dollars[f]	(k-dollars)	6600[c]	8100	14000	24300

[a] Length from 0.8 B to 0.6 B

[b] Without warm bore liner

[c] Manufactured and assembled 1977

[d] Manufactured and assembled, 1979

[e] Partially manufactured,1981 (work terminated)

[f] Total cost including design and analysis, but not including preliminary design studies and preliminary development

Table 4-V

Major Design Characteristics and Estimated Costs of Commercial Size Disk-Type MHD Magnet Systems

System description[a]		Single solenoid with 1 disk channel	Single solenoid with 2 disk channels	Split pair solenoid with 1 disk channel	Saddle magnet with linear channel (for comparison)
Magnet designer		MIT	MIT	MIT	MIT
Date of design		1980	1980	1980	1980
Peak field at channel centerline	(T)	7	7	7	6
Outer radius of channel	(m)	5.2	3.75	4.32	-
Outer radius of magnet	(m)	7.65	6.00	4.00	-
Active length of channel	(m)	-	-	-	24+
Size parameter, VB^2	(m^3T^2)	980	980	980	5200
Design current	(kA)	50	50	50	50
Winding current density	($10^7 A/m^2$)	2.5	2.5	2.5	1.0
Superconductor		Nb3Sn	Nb3Sn	Nb3Sn	NbTi
Weight	(tonnes)	1352			
Magnet system cost, original[b]	(k-dollars)	60,000	45,600	60,000	150,000
Magnet system cost, 1984 dollars[b]	(k-dollars)	74,000	56,000	74,000	185,000

[a] All systems sized for 1000MWe channel output. Estimates prepared for Westinghouse study, Reference 6.

[b] Total cost includes design and analysis, but does not include preliminary design studies and preliminary development

magnet for the 200 MWe power plant (Table 4-III), major components were designed in some detail, drawings were made and manufacturing studies were carried out. Cost estimates were then prepared by personnel experienced in manufacturing and estimating procedures.[3,4] In the case of the ETF 6 T magnet design developed by AVCO from 1977 to 1979 (Table 4-III), a special manufacturing and cost study[5] was conducted by AVCO to substantiate magnet costs contained in their plant conceptual design study of 1977.

In most other cases, the cost estimates were proposal or budgetary estimates, made without the benefit of component drawings and/or manufacturing studies.

The cases of the CFFF and CDIF/SM magnets (Table 4-IV) were special because manufacturing took place subsequent to the proposal estimates and actual magnet costs became available for comparison with proposal estimates, as noted in Table 4-IV. (See Section 4.3.6 for further discussion.)

A discussion of procedures used in estimating costs of MHD magnet systems is contained in Section 4.4.

The cost estimates for disk-type generator magnets (Table 4-V) were made by MIT in connection with a Westinghouse investigation of disk-type MHD power generators.[6]

Inspection of Tables 4-II through 4-V reveals that estimated costs of magnet systems of similar size often differ widely. This wide variation is shown graphically on curves of magnet cost vs size parameter presented in Section 4.1.3. Reasons for the variation are discussed in Section 4.1.3.

Detailed lists of characteristics and costs for more than fifty magnets (MHD, fusion, physics experiment) are listed in Appendix A for reference purposes.

The trends in total magnet system cost with magnet size parameter, VB^2, and with stored magnetic energy are shown in curves, Figures 4.2 and 4.3. The size parameter VB^2, used as the abscissa in the curves, is a parameter reflecting the magnet warm bore volume and the square of the magnetic field. It is an appropriate parameter to use in cost vs size plots, since it is an approximate indication of the MHD power-generating capacity in the active volume of the magnet. The parameter is defined in Appendix B. Since this parameter requires only that the peak on-axis field, active length and magnet bore inlet dimensions be known, it is particularly convenient for preliminary studies where magnet characteristics such as total weight and stored energy have not yet been determined.

The curves are average curves for superconducting saddle-coil magnets based on a number of data points having a relatively wide spread (see Appendix C). Most of the data points are estimated costs; a few are actual costs. Selected points from Tables 4-II, 4-III and 4-IV are plotted in Figures 4.2 and 4.3 to illustrate this spread. The curves may be used for making preliminary cost estimates for new magnet systems, keeping in mind the need to allow contingencies for the wide variations that are possible.

It should be noted that the slope of the curves toward the upper end is about 0.65.

This is consistent with an estimating relationship used in the electric power industry as shown below:

Equipment cost $\simeq$ (equivalent power rating)$^{2/3}$.

This relationship is known as the "Lang Factor."

It would be more convenient when making preliminary estimates of magnet costs for MHD power plants, if curves of magnet cost plotted directly vs MHD channel output in MWe were available (instead of curves of cost vs magnet stored energy or size parameter VB^2). However, a single curve of magnet cost vs channel power is not practical because channel power output depends not only on the field and bore volume (stored energy) available within the magnet, but also on the design of the channel (mach number, etc.) and the packaging of the channel within the magnet bore (bore volume utilization), both of which may vary substantially from system to system. The best we can do toward greater convenience is to provide a family of curves of magnet cost vs channel power as shown in Figure 4.4, with curves drawn for various channel power densities (P_d) and various bore utilization factors (F_v). These curves are derived from the same average cost data as that used for Figure 4.2.

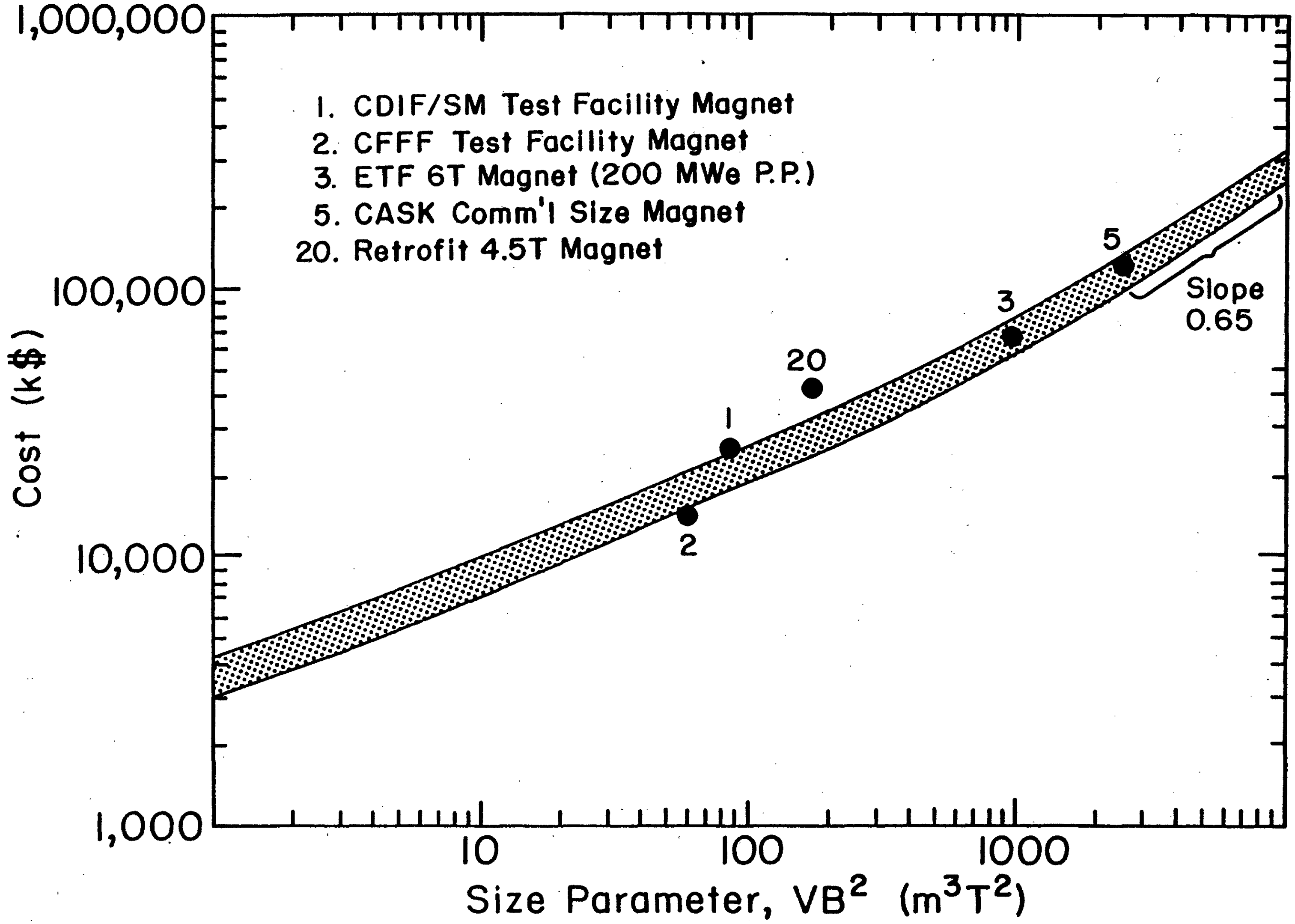


Figure 4.2

Curve of Estimated MHD Magnet System Cost (1984$) vs Size Parameter VB^2

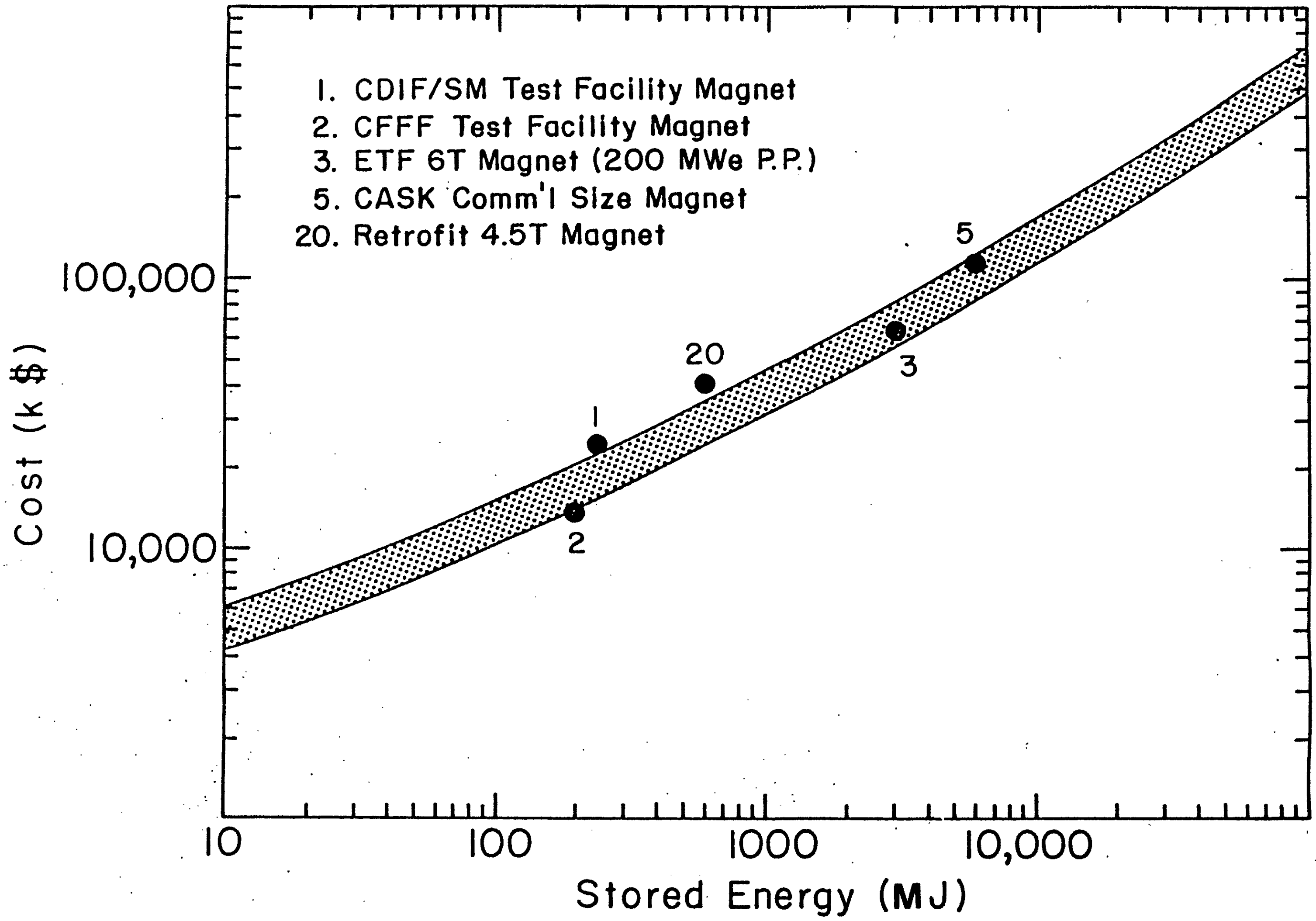


Figure 4.3
Curve of Estimated MHD Magnet System Cost (1984$) vs Stored Magnetic Energy

4.1.4 Relationship of Magnet System Cost to Overall Power Plant Costs

The relationship of magnet cost to overall MHD topping system cost is shown in Table 4-VI, listing estimated costs of major components of a hypothetical 500 MWe MHD topping system with high temperature preheater. The magnet, at 22 % of the total, is the largest single item except for the preheater system which is 36 % of the total. Since magnet cost is significant in the overall system, it is important that effort be applied to magnet cost reduction. The total estimated cost for the complete power plant, including bottoming system, was over \$ 975 × 10^6, of which the magnet system represented about 14 %. Costs are in 1984 dollars.

4.1.5 Cost Algorithms (Unit Costs) for Complete Magnet Systems

Cost algorithms (cost per unit of stored energy, cost per unit of weight) are useful in comparing magnet systems and in scaling magnet costs from a known baseline design.

Table 4-VII lists cost algorithms for the 15 magnet systems whose characteristics and costs are listed in Tables 4-II through 4-V. The trends of magnet system cost algorithms with magnet size (size parameter VB^2) are shown in curves, Figures 4.5 and 4.6. These curves are average curves based on a large number of data points from the same sources as used for the curves of Figures 4.2 and 4.3 (see Appendix C). The curve of \$/kJ vs VB^2 (Figure 4.6) shows that this algorithm decreases fairly steeply with increase in magnet size as measured by VB^2 (from \$ 250/kJ average for small magnets to \$ 15/kJ average for large magnets). The curve of \$/kg vs VB^2 (Figure 4.5) shows this algorithm decreasing less steeply than \$/kJ with increasing VB^2, \$ 200/kg for small magnets to \$ 50/kg for large magnets. It is obvious from these plots that magnet cost algorithms are very size dependent. Particular magnet cost algorithms are applicable to particular size magnets only.

Table 4-VI

Estimated Costs of Major Components of a 500 MWe Topping System

	Estimated cost[a]	Percent of total
	k-dollars	percent
Combustion Equipment	39,600	6.3
MHD Generator	14,000	2.2
Magnet system	140,000	22.4
Inverters	102,600	16.4
Preheater system	222,900	35.7
Seed system	43,700	7.0
Other	62,300	10.0
	625,100	100.0

[a] 1984-dollars

Table 4-VII

Cost Algorithms for Complete MHD Magnet Systems[a]

Magnet system	Stored energy	Total weight	Size parameter VB^2	Total cost	Algorithm, energy basis	Algorithm, weight basis
	MJ	tonnes	m^3T^2	1984k$	$/kJ	$/kg
Commercial size						
BL6-MCA	6710	2664	1544	119,100	17.7	44.7
BL6-P1	6100	3483	2491[b]	90,000	14.8	25.8
CASK	6300	2644	2522[b]	117,800	18.7	44.6
CSM 1A	7200	1850	2526	102,800	14.3	55.6
PSPEC	10,500	7320	4071	157,900	13.7	21.6
ETF and retrofit size						
ETF-MCA	1160	376	118	26,400	22.8	70.2
ETF6-P1	820	535	254	23,900	29.1	44.7
ETF-Alt.	1888	1420	729	31,100	16.5	21.9
ETF-MIT	2900	909	986	68,600	23.7	75.5
Retro-4.5	700	370	179	41,000	58.6	110.8
Component Test facility size						
USSCMS	34	37.9	8	6600	194	174
Stanford	80	91	27	8100	101	89
CFFF	210	172	61	14,000	66.7	81.4
CDIF/SM	240	144	88	24,300	101.3	168.8
Commercial size disk gen. magnets						
Single solenoid, single channel	6000	1352	980	74,000	12.3	54.7

[a] 1984 dollars

[b] Based on bore inlet size, which is smaller than bore at start of active length.

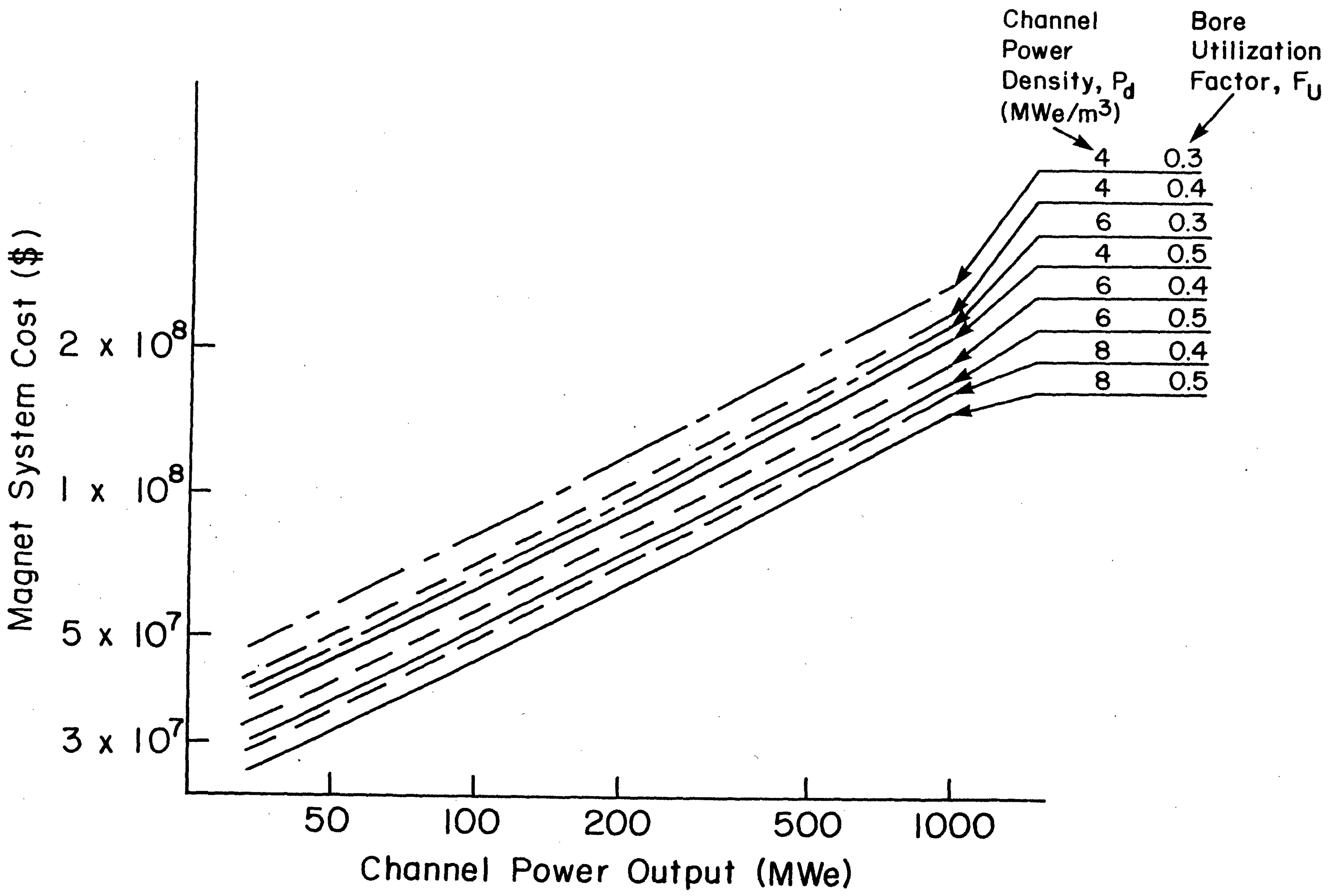


Figure 4.4
Curves of Estimated Magnet System Costs (1984$) vs MHD Channel Output with Various Power Densities and Bore Utilization Factors

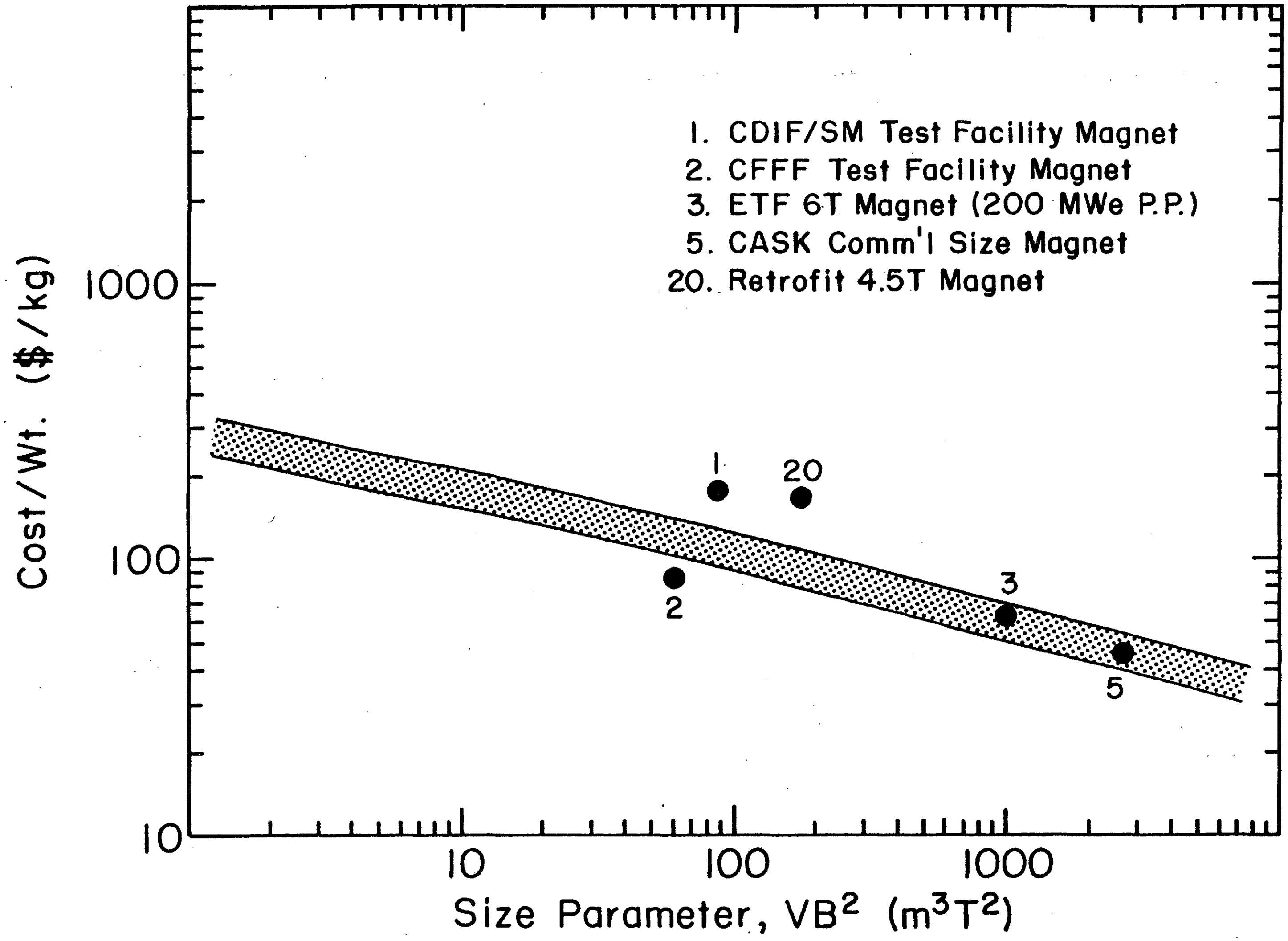


Figure 4.5
Curve of MHD Magnet System Cost Algorithm, $/kg, vs Magnet Size Parameter VB^2

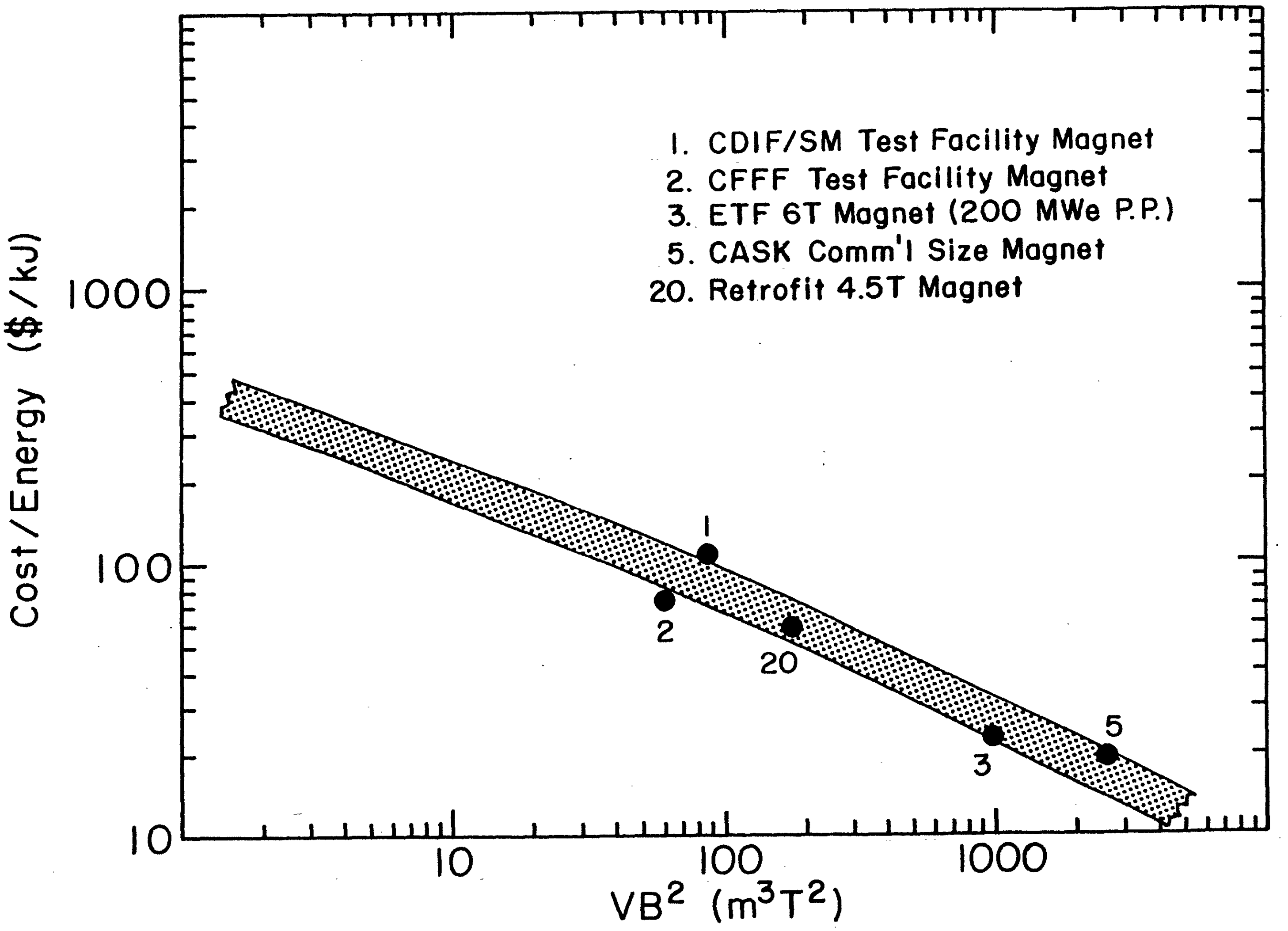


Figure 4.6
Curve of MHD Magnet System Cost Algorithm, $/kJ, vs Magnet Size Parameter, VB^2

4.1.6 Comparison of Cost Algorithms ($/kg) of MHD Magnets with Those of Other Types of Heavy Industrial Equipment

It is of interest to compare magnet cost with cost of other commercial equipment on a per unit weight basis. Figure 4.7 shows graphically the relative size and cost per kilogram of a baseload MHD magnet compared to a large LNG tanker (combining large structure and cryogenics), a commercial motor and an industrial gas turbine. Only the gas turbine is more expensive than the magnet on a per unit weight basis. The other items are substantially cheaper.

4.1.7 Estimate of Lowered Magnet System Cost with Multiple Unit Production

Substantially all of the cost data contained elsewhere in this report pertains to "one-of-a-kind" or "first unit" costs. Total magnet costs therefore include the full cost of design and analysis, supporting development, tooling and project management in addition to the cost of material and manufacture of the single magnet.

If a particular MHD magnet design were to be produced in the future in lots larger than one, the costs of design and analysis and similar "one-time" costs could be prorated over multiple units, thus reducing unit cost. Also, manufacturing should become more efficient with increased quantity production (the "learning curve" effect). A preliminary estimate of cost saving through multiple unit production was made at MIT and presented in the 1979 and 1980 Workshops[7,8]. This estimate is summarized below.

For one commercial-scale conceptual design, cost estimates were made for a single unit and also for 10 units. Unit costs were found to be about 25 % lower for the lot of 10 than for the first unit. The estimated cost reduction factors applied to a breakdown of major cost elements of the magnet system, which resulted in the above-mentioned lower cost on a 10 unit basis are listed in Table 4-VIII. From these data, a representative curve of unit cost vs VB^2 was plotted for a first unit and a lot of 10 of the same design. This is shown in Figure 4.8.

An example of lowered cost is as follows: A magnet system sized for use with a 500 MWe channel (MVU[a] = 0.35) would have an estimated "single unit" cost of 140 million dollars. According to the curve, a magnet of the same design would have an estimated cost of 105 million dollars (average) per unit as one of a lot of 10 similar units. Costs are adjusted to 1984 dollars.

---

[a] MVU, magnetic volume utilization, is the ratio of actual plasma volume in the MHD channel to the volume of the warm bore.

Table 4-VIII

Table of Factors Used in Estimating Magnet Cost in a Lot of Ten vs. Cost of First Magnet Built

Item	Cost Reduction Factor[a] (Estimated)
Conductor	0.90
Substructure	0.85
Main Structure	0.85
Helium vessel	0.85
Thermal radiation shield	0.85
Vacuum vessel	0.85
Coil winding	0.70
Assembly, installation and test	0.70
Accessories	0.90
Tooling	0.20
Project management	0.70
Design and analysis	0.15

[a] Cost reduction factor = cost per magnet, lot of 10 / cost of first magnet built.

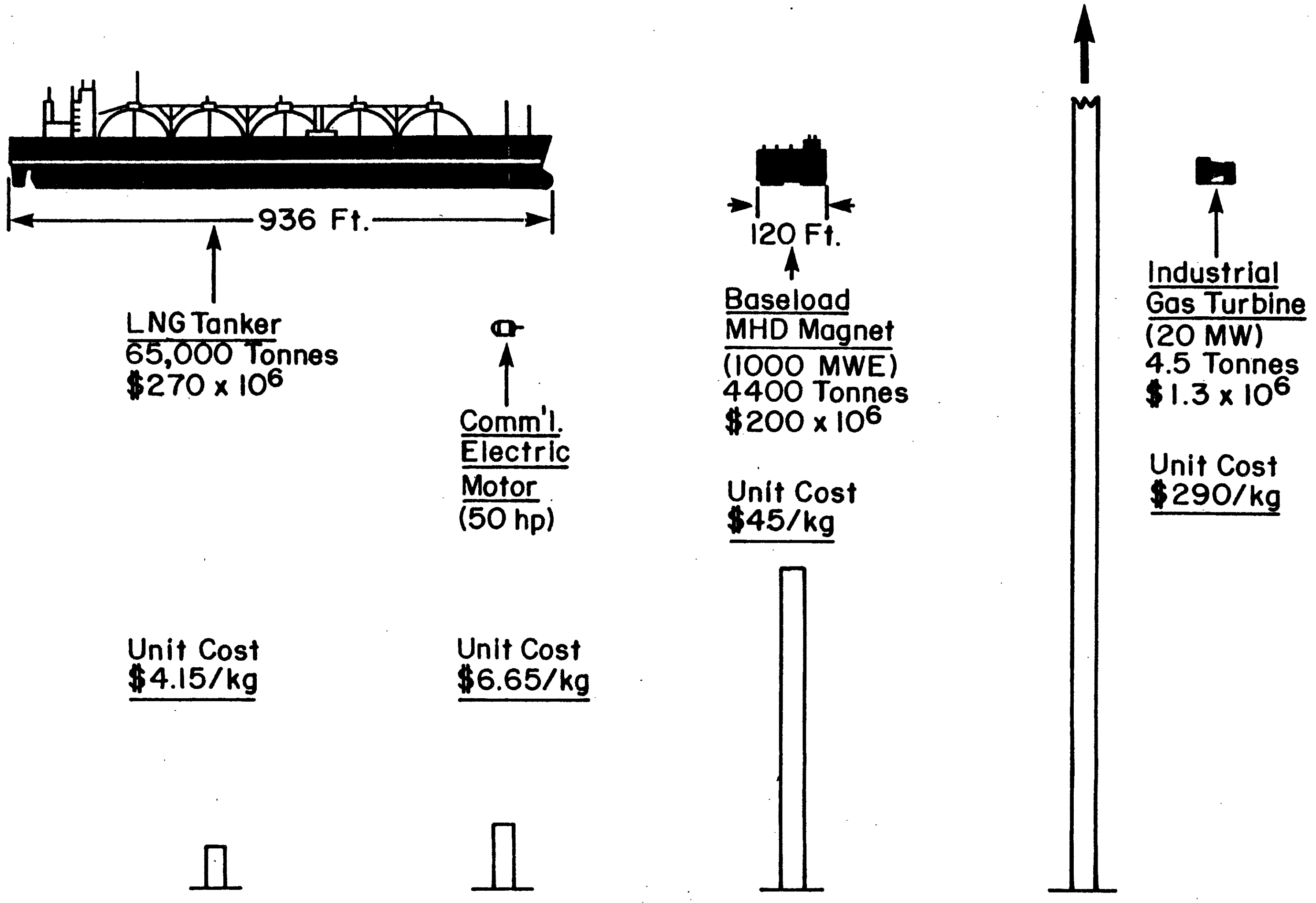


Figure 4.7
Chart Showing Comparative Costs of MHD Magnet and Other Commercial Equipment on a "Per Unit Weight" Basis (1984$)

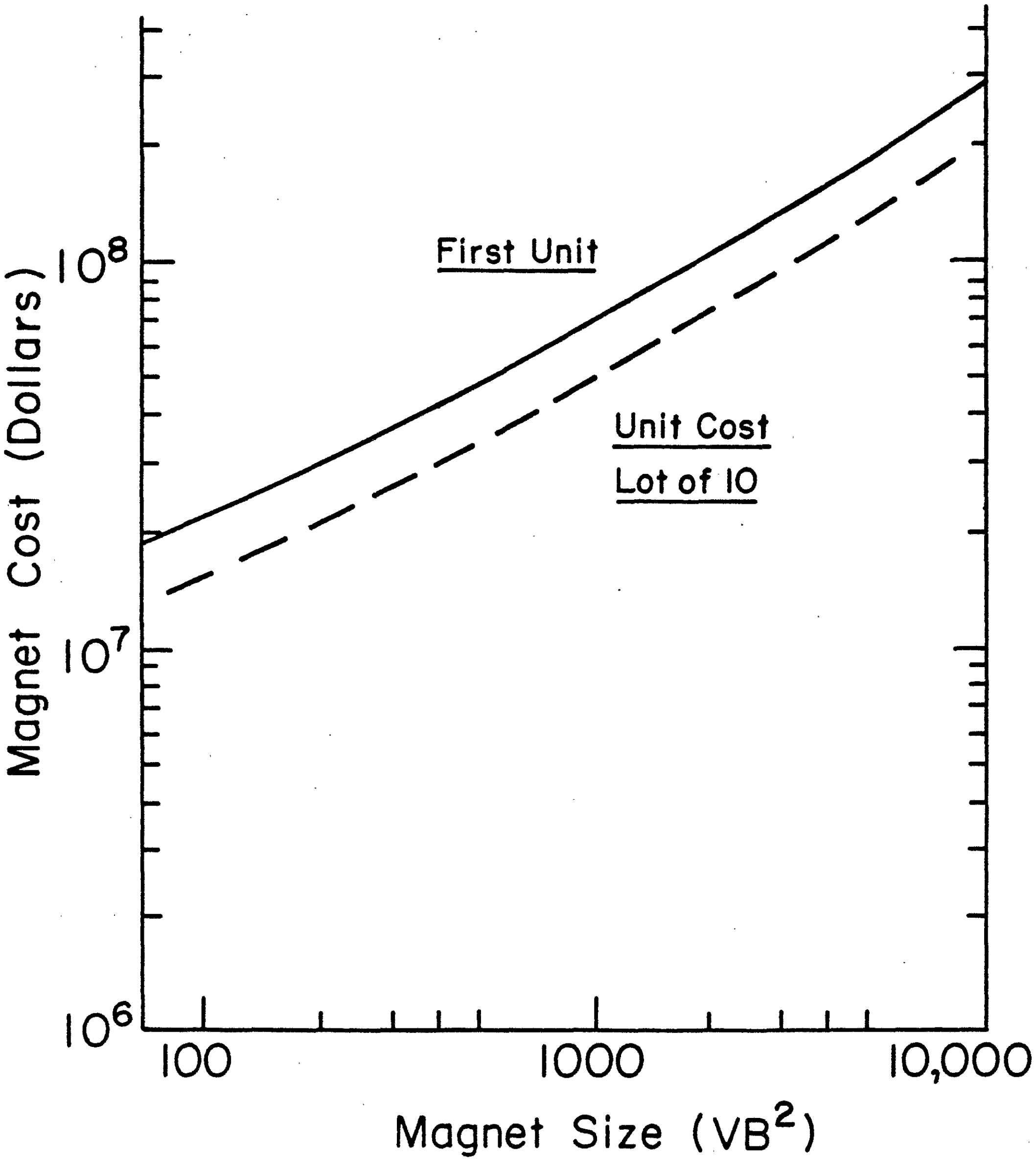


Figure 4.8
Curve of Unit Cost of First Unit and of a Lot of Ten
of Same Design (Commercial Size MHD Magnet Systems)

4.1.8 Cost Escalation

In the period covered by this report, 1976 to 1984, inflation was severe and the cost of conventional (nonnuclear) power plant equipment is estimated to have risen by a factor greater than 1.6. In order to extrapolate past cost estimates to current dollars and/or to make a meaningful comparison of magnet cost estimates made at different times, it is necessary to know approximately the yearly inflation factors which apply to the MHD magnet system. In this report, the factors listed in Table 4-IX have been used.

Table 4-IX is based on the Plant Cost Index listed in "Chemical Engineering" (CE) published monthly by McGraw Hill. Additional information on cost escalation, together with the basis for selection of the CE index for use in magnet system estimating is continued in Appendix E.

The escalation factors listed in Table 4-IX do not necessarily apply to individual components of the magnet system. For example, the cost of superconductor is strongly influenced by raw material costs (Nb, Ti, etc.) which may not vary with time in the same way as other power plant machinery.

4.2 Magnet System Cost Breakdowns (Component Costs, Indirect Costs, etc.)

4.2.1 Typical Magnet System Cost Breakdown (ETF - MIT 6 T Magnet)

A typical MHD magnet system cost breakdown is presented in Tables 4-X and 4-XI, using the 6 T magnet for the MHD ETF 200 MWe power plant as an example. The first table contains estimated component costs, assembly costs, etc. (direct costs) with algorithms calculated on a cost/weight basis ($/kg) for most items. The second table contains estimated program indirect cost items such as design and analysis, program management, fee and contingency allowance, together with magnet system total installed cost. Algorithms are calculated as percentages of appropriate subtotal costs for most indirect items (design and analysis, program management, etc.).

The purpose of the tables is to identify the various component, assembly operation and program (indirect) cost items which are responsible for the total installed capital cost of an MHD magnet system, and to show relative magnitudes of the various items in a near-commercial-size magnet system.

The component costs listed in Table 4-X are the costs of the fabricated components f.o.b. the component manufacturer's plant, including cost of materials, labor, burden, shop engineering, G & A and profit markup applied by the component manufacturer.

It is of interest to note that the conductor, the superstructure and coil containment assembly (including the liquid helium vessel) and the cryostat (thermal shield and vacuum vessel) are clearly the three major components in terms of cost, and their costs are of the same magnitude. This is significant because it shows that no one component dominates magnet cost and cost reduction efforts must give careful consideration to all three components mentioned.

It is also of interest to note that program (indirect) cost items as listed in Table 4-XI, including design and analysis, engineering, program management, site special costs, etc., when added together make a very significant part of the total magnet system cost, about 40 % in the example shown. Program cost items referred to above are described as follows:

Special site costs are site contractor costs such as site engineering, site insurance, etc. which are prorated over the costs of the equipment being installed. (These are applicable mainly in estimates for commercial-scale MHD magnets installed at power plants.)

Design and analysis costs are costs incurred in preparing the magnet design and detail drawings, including costs of electromagnetic, stress and thermal analysis, preliminary manufacturing planning and preparation of specifications and standards.

Supporting development costs are costs of special testing, research and development required in support of the design and analysis effort.

Program management costs are costs of managing the entire program starting with design and analysis, covering component manufacture and magnet assembly, and extending through final installation and shakedown testing. Quality assurance may be included in this item.

Fee is the program management contractor's fee or profit, usually a percentage of the total cost of the program.

Contingency allowance is an allowance added to the estimated total cost of the program to provide for errors in estimation and for unforseen cost extras.

It should be noted that G & A expense in most cases is assumed to be included in the costs of components and other program cost items. Also, the fee or profit on individual manufactured components is assumed to be included in the cost of the component.

Drafting costs (the costs of making layout, assembly and detail drawings) are assumed to be included in design and analysis. Cost estimating information on drafting is contained in Appendix H.

Table 4-IX

Cost Index and Escalation Factor used for Magnet System Costs 1975 to 1984

Year	Cost index	Escalation factor (Reference 1984)
1975	100	1.769
1976	105.3	1.680
1977	111.9	1.581
1978	120.0	1.474
1979	130.9	1.351
1980	143.2	1.235
1981	162.8	1.087
1982	172.1	1.028
1983	173.7	1.018
1984	176.9	1.000

Table 4-X
Sheet 1

Typical MHD Magnet System Cost Breakdown
Component Costs, Assembly Costs, etc.
(Estimate for 6 T Magnet System, 200 MWe ETF Powerplant)

Item No.	Item	Weight or capacity	Cost[a] (1980k$)	Cost[b] (1984k$)	Cost algorithm[c]	Reference
	<u>Magnet without accessories</u>					
1	Conductor (weight basis)	102 tonnes	6164	7643	74.39 $/kg	Wt. conductor (1)
1a	Conductor (capacity basis)	6.69x10^9 AmT	-	-	1.14 $/kAmT	AmT conductor (1a)
2	Insulation	in 3	in 3	in 3	-	-
3	Substructure	90 tonnes	1278	1585	17.61$/kg	Wt. substructure (3)
4	Coil fabrication[d]	-	1479	1834	17.98$/kg	Wt. conductor (1)
5	Helium vessel	227 tonnes	3729	4624	20.37$/kg	Wt. He vessel (5)
6	Superstructure	273 tonnes	4180	5183	18.99$/kg	Wt. superstructure (6)
7	Structure, total 3, 5, 6,	590 tonnes	9184	11,392	19.31$/kg	Wt. structure, total (7)
8	Coil, vessel, structure assembly[e]	-	2600	3224	4.66$/kg	Wt. cold mass (9)
9	Cold mass, total 1, 2, 4, 7, 8	692 tonnes	19,430	24,093	34.82$/kg	Wt. cold mass (9)
10	Cold mass support system	in 11	in 11	in 11	-	-
11	Thermal shield	39 tonnes	1705	2114	54.21$/kg	Wt. thermal shield (11)
12	Vacuum vessel	178 tonnes	2420	3001	16.86$/kg	Wt. vacuum vessel (12)
13	Cryostat, total 10, 11, 12	217 tonnes	4125	5115	23.57$/kg	Wt. cryostat (13)
14	Total, all components assembled 9, 13	909 tonnes	23,555	29,208	32.16$/kg	Wt. total, components (14)
15	Mfg. engineering, tooling	-	1650	2046	2.25$/kg	Wt. total components (14)
16	Pack and ship components	-	619	764	0.84$/kg	Wt. total components (14)
17	Total components on site	-	25,824	32,018	35.23$/kg	Wt. total components (14)
18	Final assem. and install on site	-	3368	4176	4.59$/kg	Wt. total components (14)
19	Total, magnet installed on site	-	29,192	36,194	39.82$/kg	Wt. total components (14)
20	Shakedown test	-	380	471	0.52$/kg	Wt. total components (14)
21	Total, magnet installed and tested	-	29,572	36,665	40.34$/kg	Wt. total components (14)

(Direct costs only. See Table 4-XI for indirect and total costs.)

[a] Includes manufacturer's G&A and profit

[b] Escalation factor = 1.24, 1980 to 1984

[c] Algorithms are 1984$

[d] Includes installation of coil in He vessel (including shop labor, shop eng'g. and burden)

[e] Includes site labor and burden

Table 4-X
Sheet 2

Typical MHD Magnet System Cost Breakdown
Component Costs, Assembly Costs, etc.
(Estimate for 6T Magnet System, 200MWe ETF Powerplant)

Item No.	Item	Weight or capacity	Cost[a] (1980$)	Cost[b] (1984$)	Cost algorithm[c]	Reference
	Accessories					
22	Cryogenic and vacuum system	688W at 4.5K	1400	1736	2520$/W	Cap. of cryo. sys. (22)
23	Power supply system	2.63MW	900	1116	424$/kW	Cap. of power supply (23)
24	Warm bore liner	14 tonnes	495	614	43.86$/kg	Wt. liner (24)
25	Instruments and controls	-	in 22, 23	-	-	-
26	Total access., fob factory	-	2795	3466	-	-
27	Pack and ship accessories	-	82	102	2.9%	Cost, total access. (26)
28	Total access. on site	-	2877	3567	9.9%	Mag. components on site (17)
29	Install access. on site	-	550	682	19.1%	Cost total access. (28)
30	Total access. installed	-	3427	4249	11.7%	Cost magnet installed (19)
	Magnet and accessories					
31	Total mag. and access, inst. on site	-	32,999	40,919	45.02	Wt.total mag. comp. (14)

(Direct costs only. See Table 4-XI for indirect and total costs.)

[a] Cost includes manufacturer's G&A and profit

[b] Escalation factor = 1.24, 1980 to 1984

[c] Algorithms are 1984$

It was assumed in preparing Tables 4-X and 4-XI that the magnet system was a "first unit" and that all costs, including costs such as tooling that might otherwise be prorated over a number of units, were allocated to the single unit.

4.2.2 Estimated Component Costs for Representative MHD Magnet Systems

Costs of major components, operations and indirect items for three representative MHD magnet systems, ranging from commercial-size down to test facility size, are listed in Table 4-XII. The purpose of the table is to show the relative magnitude of the component costs and how relationships vary with magnet size.

4.2.3 Cost Algorithms for Components, Operations and Indirect Items for MHD Magnets and Fusion Magnets

Table 4-XIII lists cost algorithms for representative MHD and fusion magnet components, operations and indirect items.

Figure 4.9 contains a series of bar charts showing graphically the range of values of component cost algorithms for MHD magnets based on cost data available for approximately 20 magnets of various sizes and types (see Appendix D). Figure 4.10 contains a series of bar charts showing the range of cost algorithms for manufacturing operations, accessories and other cost items for the same 20 magnets. Figures 4.11 and 4.12 contain bar charts comparing MHD and fusion magnet component cost algorithms.

Table 4-XIV lists cost algorithms for fabricated parts, accessories, manufacturing operations, shipping and other items. For each item the application, the source of the data and the data are given. These data are presented for reference purposes.

Appendix F lists cost data for raw materials and partially fabricated items (cable, etc.) used in connection with MHD magnet construction. These data are also presented for reference purposes.

Lists of cost algorithms for components and other program cost items for several magnets covering a range of sizes are contained in Appendix D. These data may be useful for obtaining appropriate (average) cost algorithms for estimating future MHD magnet costs.

Table 4-XI

Typical MHD Magnet System Cost Breakdown
Program (Indirect) Costs and Total Cost
(Estimate for 6 T Magnet System, 200 MWe ETF Powerplant)

Item No.	Item	Cost (1980k$)	Cost (1984k$)	Cost Algorithm	Reference
	<u>Magnet without accessories</u>				
1	Magnet direct cost, total, installed and tested	29,572	36,665	40.34$/kg	Line 21, Table 4-IX
2	Design and analysis	3021	3746	10.2%	Magnet direct cost (1)
3	Program management	2266	2810	7.7%	Magnet direct cost (1)
4	Magnet total incl. d&a and proj. mgt.	34,859	43,221	-	-
5	Site special costs	3765	4669	10.8%	Cost, magnet total (4)
6	Magnet total before contingency allow.	38,624	47,890	-	-
7	Contingency allowance	11,587	14,368	30.0%	Magnet total before c.a. (6)
8	Magnet total incl. indir. costs and c. a. (without accessories)	50,211	62,258	68.49$/kg	Wt. total components Line 14, Table 4-IX
	<u>Accessories</u>				
9	Access. dir. cost, total, installed	3427	4249	11.6%	Magnet direct cost,total (1)
10	Des. and anal., prog. mgt., etc.	604	749	17.6%	Cost, access. dir. total (9)
11	Access. total, incl. d&a, prog. mgt., etc.	4031	4990	-	-
12	Site special costs	444	551	11.0%	Cost, access. total (11)
13	Access. total before conting. allow	4475	5541	-	-
14	Contingency allowance	892	1114	20.0%	Cost access., total (13)
15	Access. total incl. conting. allow.	5367	6655	10.7%	Cost magnet, total (6)
	<u>Magnet and accessories</u>				
16	Magnet system total, direct and indirect	55,575	68,913	75.81$/kg	Wt. magnet total (Line 14, Table 4-X

Table 4-XII

Costs of Major Components, Operations and Indirect Cost Items in Representative MHD Magnet Systems

Magnet designation	CFFF		ETF-MIT		CASK	
	Cost 1979$	%Total[a]	Cost 1980$	%Total[a]	Cost 1979$	%Total[a]
Conductor	856	8.3	6164	14.3	15,383	21.7
Structure (incl.substructure)	1827	17.6	9180	21.3	12,716	18.0
Cryostat	816	7.9	4125	9.6	10,875	15.4
Coil fabrication	442	4.2	1479	3.4	9645	13.6
Assem., install, test	1338	12.9	6348	14.7	4235	6.0
Mfg. eng'g., tooling, misc.	1211	11.9	2269	5.3	3961	5.6
Accessories	1306	12.6	3427	7.9	4525	6.4
Total direct cost	7796	75.2	32,999	76.5	61,340	86.7
D&A, support. dev't	2421	23.3	3625	8.4	4275	6.0
Program mgt.	153	1.5	2266	5.3	5170	7.3
Other indirect costs	0	0	4209	9.8	0	0
Total, direct and indirect	10,370	100.0	43,099	100.0	70,785	100.0
Contingency allowance	0	0	12,479	29.0	16,366	23.1
Total, incl. conting. allow	10,370	-	55,578	-	87,151	-

[a] Total direct and indirect cost, before contingency allowance.

Table 4-XIII
Cost Algorithms for Representative MHD and Fusion Magnet Components

Item	Units	Reference	Algorithms[a]						
			MHD				Fusion[b]		
Magnet Identification			CFFF	CDIF/SM	ETF	CASK	MFTF B sol.	MFTF YY	LCP GD
Magnet Characteristics									
Field Strength	T		6	6	6	6	3	7.7	8
Stored Energy	MJ		216	240	2900	6300		409	145
Size Parameter	m^3T^2		60	74	1006	2520			
Weight,total	tonnes		172	144	909	2644	–	341	
Cost Algorithms									
Conductor	$/kAmT	AmT cond	1.12	2.48	1.14	2.41	2.55	2.49	2.96
	$/kg	Wt. cond.	20	78	75	38	38	106	125
Coil fab.	$/kg	Wt. cond.	12	34	18	24	36	98	87
Shop eng'g & tooling	$/kg	Wt. cond.	14	45			31	16	40
Total, fab. & eng'g	$/kg	Wt. cond.	26	89	18	24	–	–	–
Total, wind pack[d]	$/kg	Wt. cond.	46	167	93	64	105	220	252
Struct., substruct., LHe ves	$/kg	Wt., struct substr., LHe ves	24	18	19	9	34	24	85
Assem. cold mass	$/kg	"	7	4	5			6	40
Total cold mass	$/kg	"	39	75	35	24			
Cryostat[e]	$/kg	Wt cryo.	35	52	24	32			
Total mag. comp.	$/kg	Wt. mag. comp.							
Pack & Ship	$/kg	Wt. mag. comp.	1.62	1.53	0.84	0.50			
Final Assem & Install	$/kg	Wt. mag, comp.	4.30	3.90	4.59	2.20			
Shakedown Test	$/kg	Wt. mag. comp.	1.12	2.11	0.52	0.26			
Total, mag. inst.[f]	$/kg	Wt. mag. comp.	45	78	40	28			
Program indir. costs[g]	Percent	Cost Mag. Install	58%	92%	73%	21%			
Total mag cost incl. indirect	$/kg	Wt. mag. comp.	71	190	75	43		70	2

[a] 1984 dollars

[b] Cost algorithms from TFCX SC Options Costing Workshop, PPPL, Apr. 10, 1984.

[c] 2nd coil (estimate)

[d] Total, conductor, coil fabrication, engineering total

[e] Thermal shield, cold mass supports, vacuum vessel

[f] Before indirect costs

[g] Indirect costs include design and analysis, site tools, program management, fee, contingency

Table 4-XIV

Cost Algorithms for Fabricated Parts, Manufacturing Operations, Accessories and Shipping[a]

Item	Application	Source	Date	Cost Algorithm		
				$/lb	$/kg	Other
Al alloy tanks	TARA	MIT	1982	17.50		
SS vacuum vessel	MHD ETF	MIT/CE est.	1980	–	13.60	
Coil Fab. (cryogenic)	MHD HDPE	AEDC/ARO	1977	–	11.94	
Cabling Copper Wire (not incl. mat'l costs)	MHD ETF	Phelps Dodge	1980			
Warm Bore Liner (5600lbs;$120,000	MHD CDIF/SM	MEPPSCO (John Hill)	1980	21.43		
Coil Winding, water-cooled hollow conductor	MHD CDIF/CM (60,000 lbs)	Everson	1980	5.00		
	MHD AVCO	Everson	1980	6.67		
	MHD Reynolds	Everson	1980	6.50		
Refrig. Syst.(666 W 4.5 K)	MHD ETF	MIT est.	1980			$1800/W
Barge Shipment 3100 tonnes; 979 mi	MHD magnet	MCA/Belding	1980		0.033	
Land Shipment 250 tons, 5 mi	Transformer	MCA/Belding	1980		0.12	
Power Supply:						
25 kA,2650 kW	MHD magnet	Kusko	1980			$290/kW
50 kA, 2560 kW	MHD magnet	Kusko	1980			$410/kW
892 A, 10.7 kW	USSCM(U25B)	ANL	1979			$1030/kW

[a] 1980 dollars

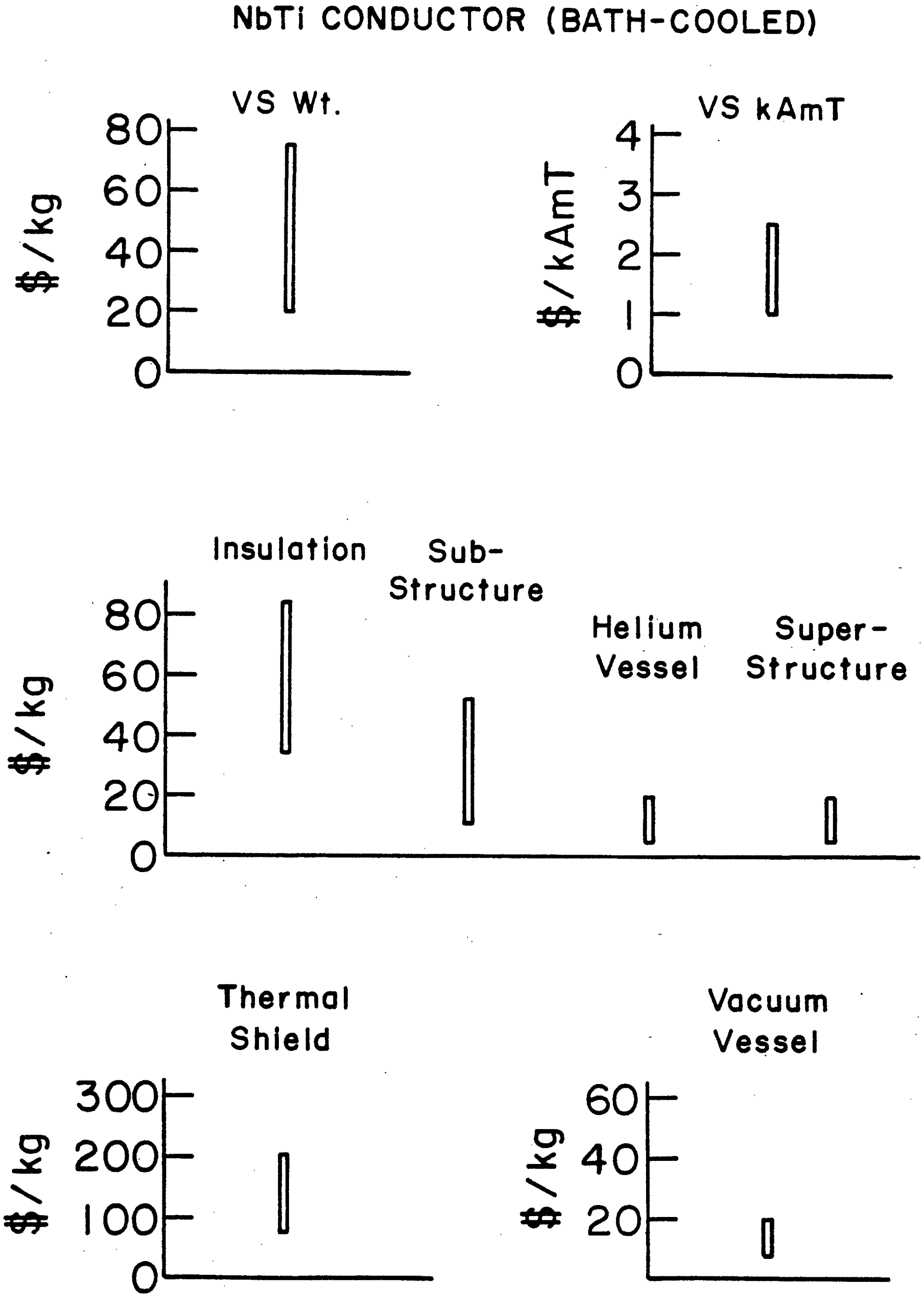


Figure 4.9
Cost Algorithm for Components of MHD Magnets (1984$)

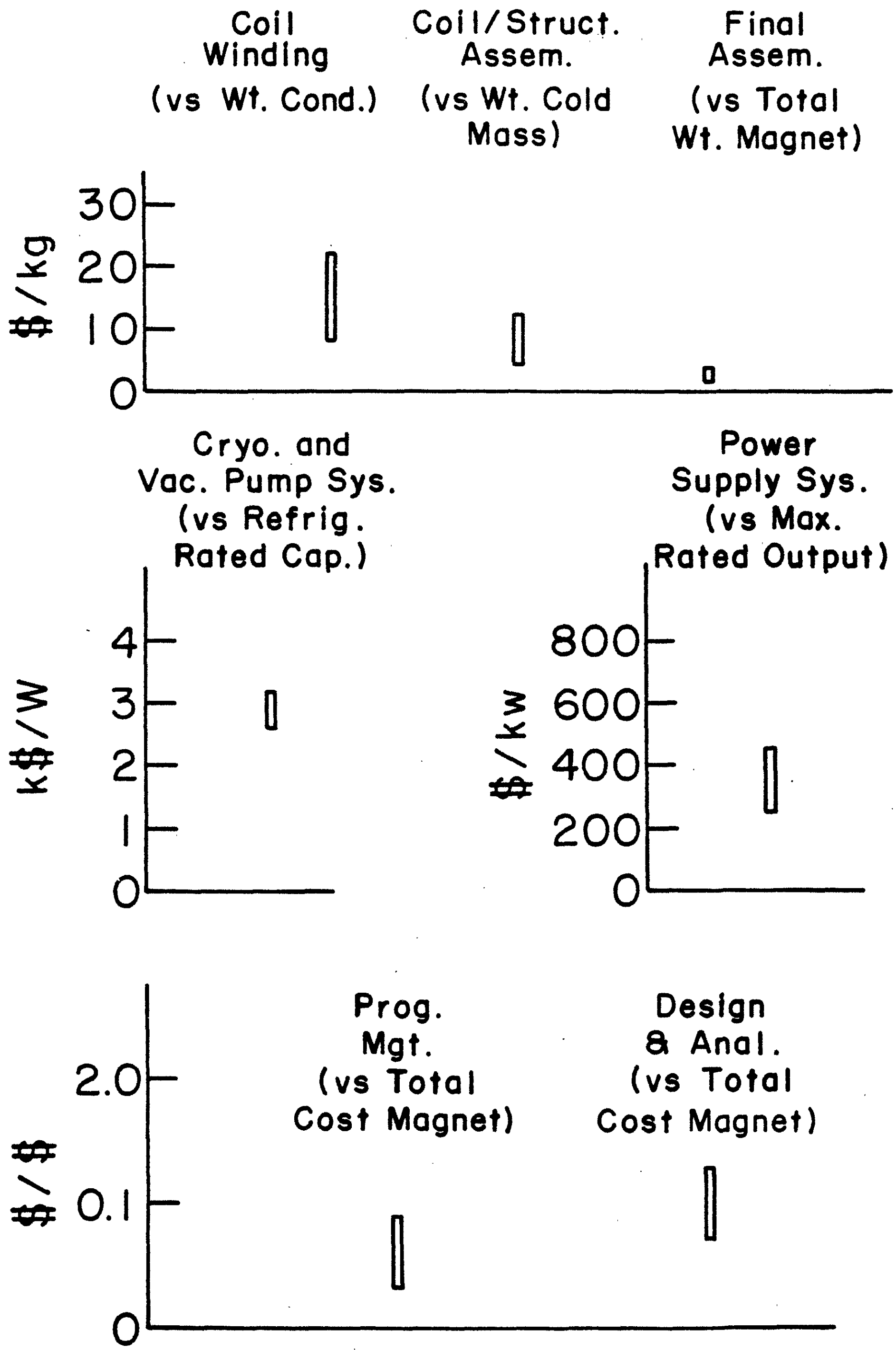


Figure 4.10
Bar Chart of Cost Algorithms for Manufacturing Operations, Accessories and Program Indirect Costs for MHD Magnets (1984$)

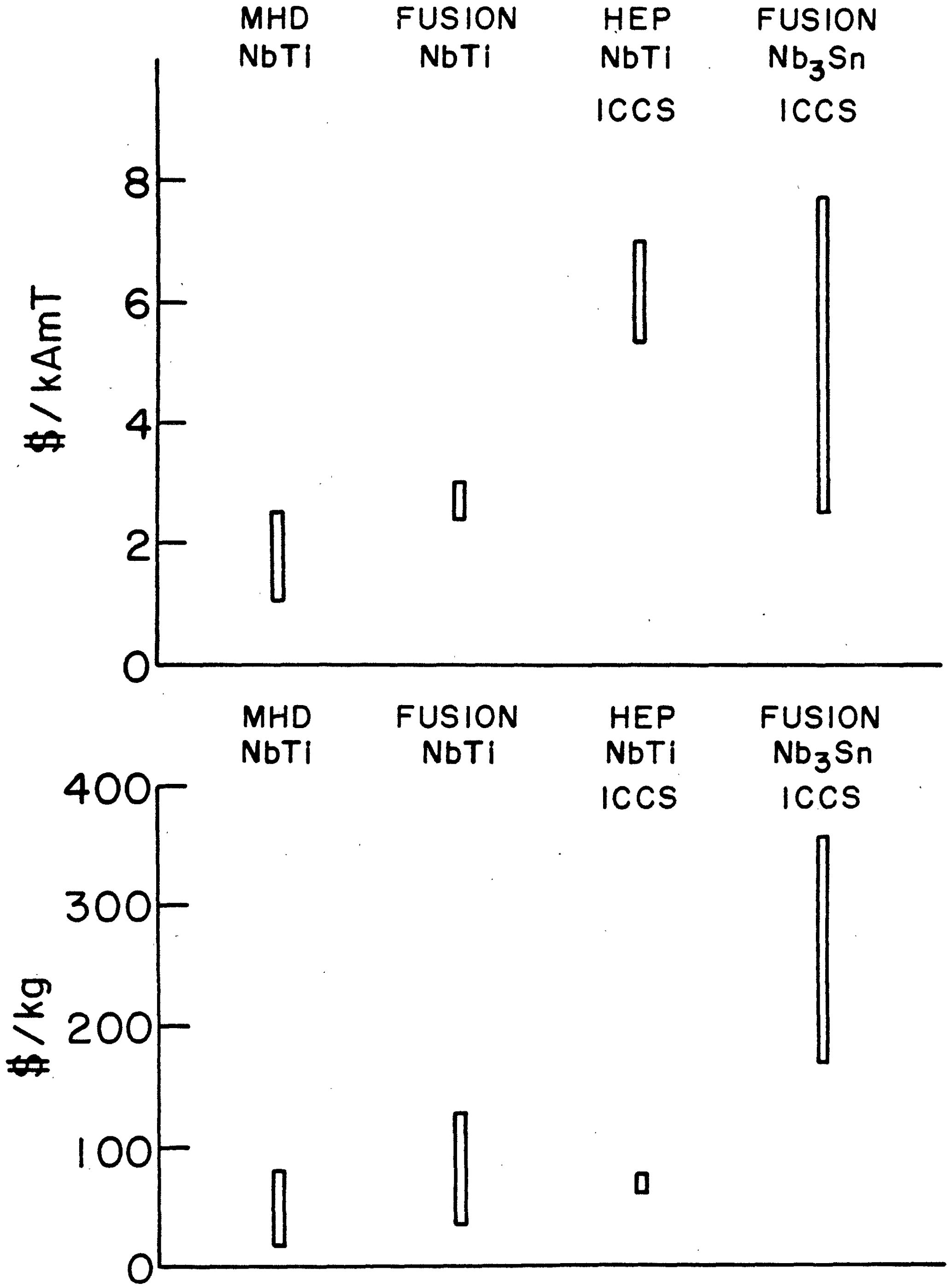


Figure 4.11
Bar Charts Comparing Conductor Cost Algorithms for MHD and Fusion Magnets
(1984$)

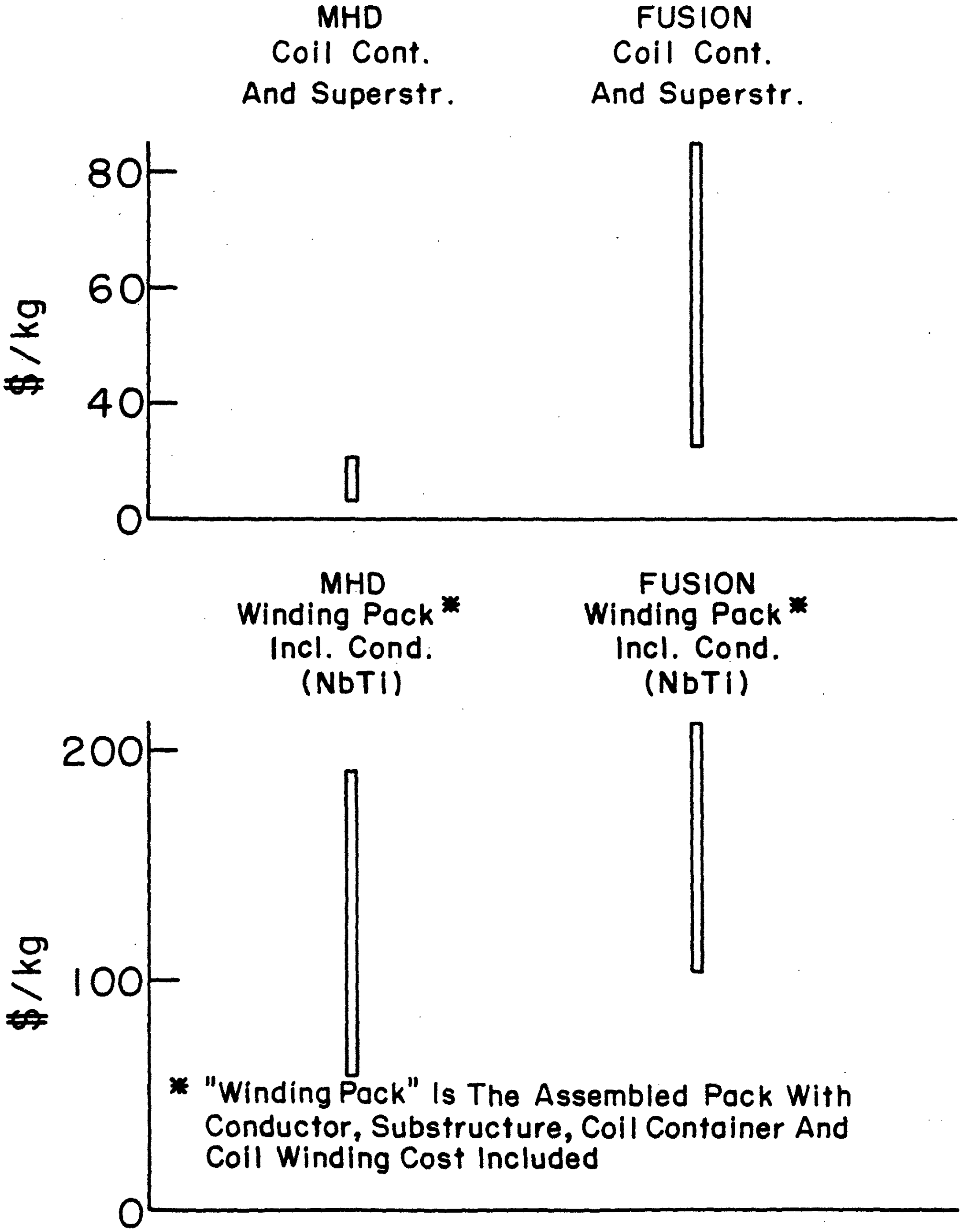


Figure 4.12
Bar Chart Comparing Component Cost Algorithms for Fusion and MHD Magnets
(1984$)

4.3 Special Cost Studies

A number of analyses and special studies were conducted in the period from 1976 to 1984, aimed at improving our understanding of magnet system costs and identifying approaches to cost reduction. This work is summarized in the following subsections.

4.3.1 Identification of Major Cost Drivers in an MHD Magnet System

Analysis of commercial-scale magnet system costs showed that the components of the magnet itself represented only about one-half of the total cost of the installed system. The balance of the total cost is made up of items such as design and analysis, project management, accessories, shipping and installation at plant site. A typical distribution of costs is shown in Fig. 4.13.

Within the magnet itself, the three major components, conductor, structure and cryostat, each represent roughly 1/3 of the total cost of components. However, scaling characteristics are such that with increasing magnet size the amount of conductor does not increase as rapidly as the amount of structure. For very large magnets, structure tends to predominate. This is shown in Figure 4.14, a bar chart of component costs for magnets for various MHD power outputs.

It is evident from the above that no one item is the predominant cost driver in an MHD magnet. Cost reduction requires a systems approach, with attention to a number of interrelated items.

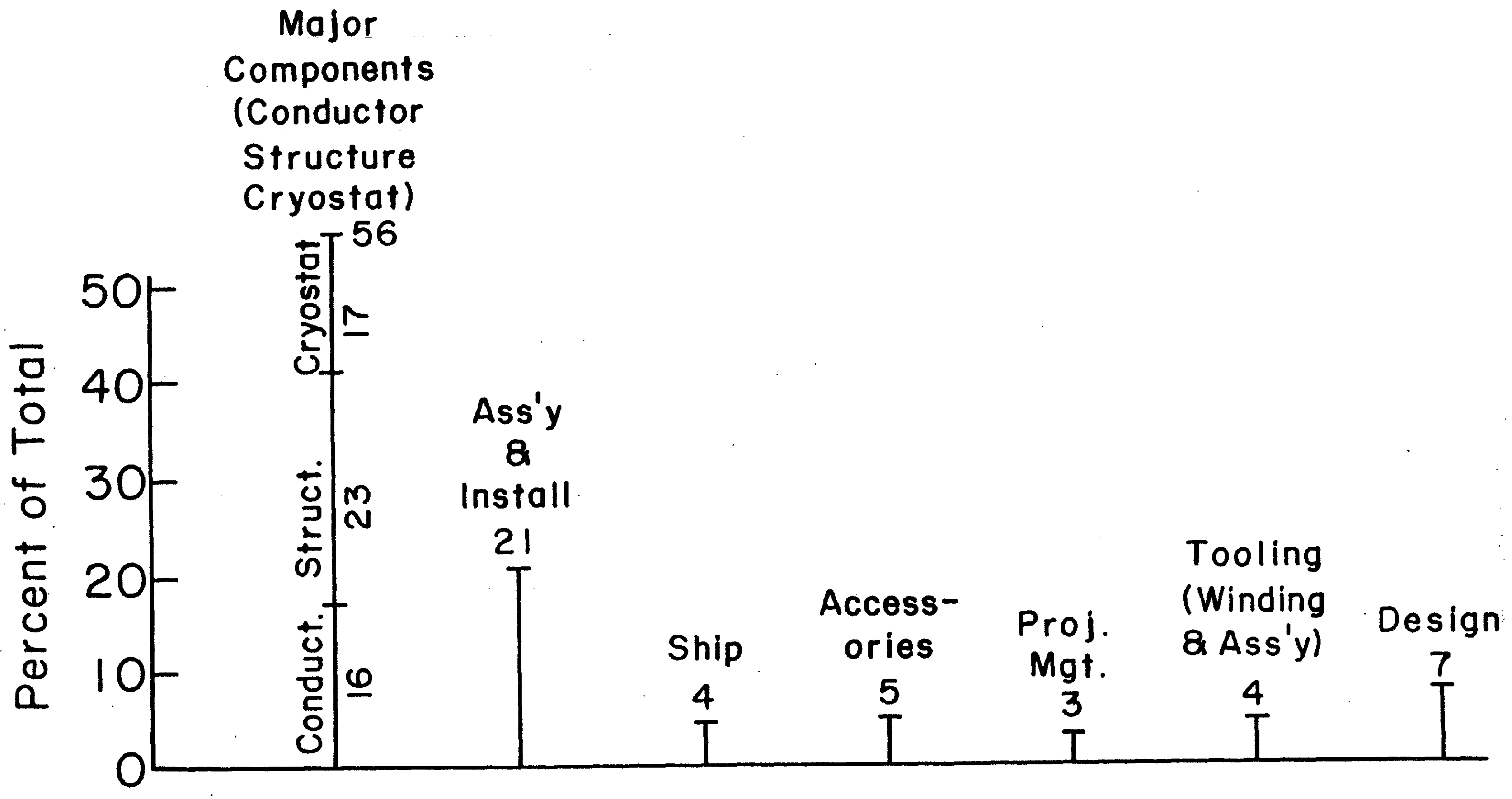


Figure 4.13

Bar Chart Showing Relationship Among Magnet Cost Elements

First Unit, Baseload Size

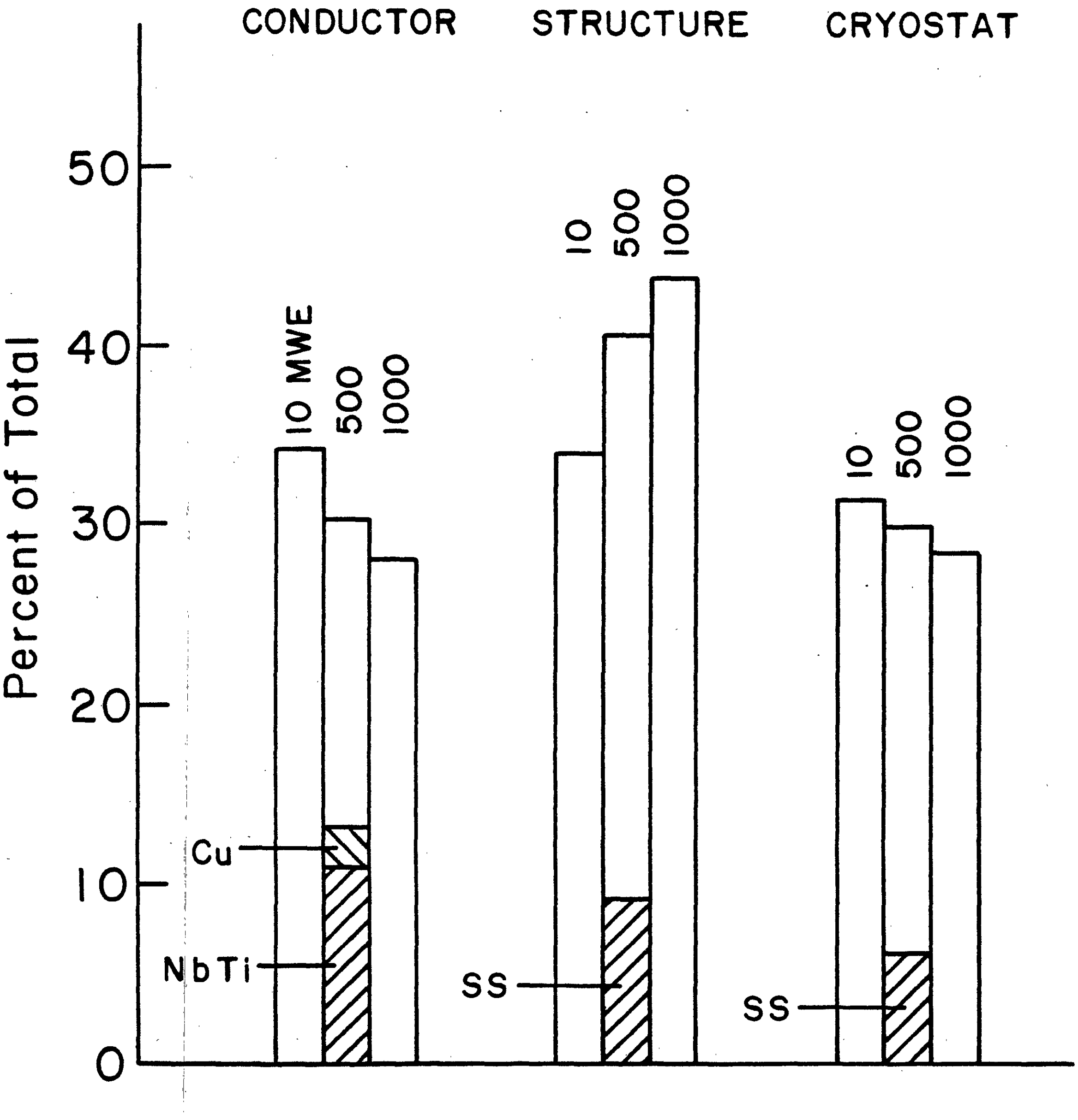


Figure 4.14
Bar Chart Showing Comparative Cost of MHD Magnet Major Components
(Magnets from 10MWe Test Facility to 1000 MWe Baseload Size)

4.3.2 Impact of High Current Operation on Magnet System Cost

The cost of many of the components, the cost of some of the steps in fabrication and the operating cost of a superconducting MHD magnet are all dependent on design operating current. A question naturally arises, therefore, as to what is the optimum current level from the cost standpoint. To investigate this question, a study of the impact of design operating current on magnet system cost was conducted by MCA under a series of subcontracts.

The approach taken was to develop a set of cost factors in the general areas of system components, fabrication and operation. Components considered included conductor, substructure, superstructure, Dewar, power supply subsystem and refrigerator/liquefier subsystem. Fabrication operations, including coil winding, magnet assembly and system installation were considered. Fabrication and quality control development were taken into account, as well as system operating expenses over a 10 year period. Three conductor configurations were selected and three values of surface heat flux were considered for the baseline conductor. The alternative conductor configurations were the fluted substrate, the semifluted substrate and the tricable type, as described in Section 4.1.8.2 of Reference 1. The studies covered operating currents from 10 kA to 250 kA and involved two magnet design concepts, the first incorporating a stainless steel channel and plate substructure as described in Section 4.2.2, Reference 1 and the second an aluminum alloy, nested shell substructure, as described in Section 4.2.3, Reference 1.

Results indicated that overall cost for the channel and plate substructure concept was minimum in the vicinity of 100 kA and for the nested substructure concept, in the vicinity of 50 kA. The curves of cost vs current were relatively flat in the region of the minimum.

Table 4-XV shows the estimated magnet system capital cost breakdown for the channel and plate concept with semifluted conductor and heat flux of 0.6 W/cm^2 for the current range of 10 kA to 250 kA. Table 4-XVI shows the magnet system estimated total cost, including ten year power cost, for the channel and plate concept with three types of conductor and three heat fluxes. Table 4-XVII shows the estimated magnet system cost breakdown and total cost for the nested shell concept with semifluted conductor and heat flux of 0.6 W/cm^2. Figure 4.15 shows curves of estimated component costs and total cost vs magnet current for the nested shell concept with semifluted conductor and 0.6 W/cm^2 heat flux.

Detailed information on the study is contained in References 9, 10 and 11.

Table 4-XV

Estimated Magnet System Capital Cost Breakdown And Integration ($\$10^6$)

(based on channel and plate concept using semifluted conductor at $\mathring{q} = 0.6$ W/cm^2)

Current (kA)	10	25	50	100	150	200	250
Conductor	8.24	8.39	8.51	8.73	8.97	9.21	9.38
Substructure	0.403	0.613	0.895	1.63	2.40	3.17	4.09
Power Supply Subsystem	0.213	0.240	0.268	0.348	0.428	0.507	0.586
Refrigerator/Liquefier Subsystem	0.464	0.547	0.653	0.883	1.08	1.32	1.53
Superstructure	15.2	15.2	15.2	15.2	15.2	15.2	15.2
Dewar	2.51	2.51	2.51	2.51	2.51	2.51	2.51
Miscellaneous Components & Shipping[1]	4.05	4.13	4.21	4.39	4.59	4.79	4.99
Windings & Substructure Fabrication	18.8	12.6	9.56	6.76	5.64	5.24	5.36
Fabrication & Quality Control Development	0.675	0.738	0.800	1.05	1.34	1.69	2.00
Assembly to Superstructure, Dewar & Support Systems	5.92	5.92	5.92	5.92	5.92	5.92	5.92
Subtotal	56.5	50.9	48.5	47.4	48.1	49.6	51.6
Administrative Expenses[2]	16.9	15.3	14.6	14.2	14.4	14.9	15.4
TOTAL COST[3]	73.4	66.1	63.1	61.6	62.5	64.5	67.0

1 Fifteen percent of total of previous six items

2 Thirty percent of Subtotal

3 Does not include design system quality assurance estimated at $\$2.93 \times 10^6$; does not include design support development

Table 4-XVI
Estimated Cost for Magnet System Based on Ten-Year Operation
(magnet incorporating channel and plate concept)

	Annual	10-Year			Total Cost		
	Power Cost	Power	Semifluted	Fully Fluted	Tricable	Semifluted	Semifluted
	at 0.04	Cost	$\dot{q}=0.6$	$\dot{q}=0.6$	$\dot{q}=0.6$	$\dot{q}=0.3$	$\dot{q}=0.9$
I	$/kWh		W/cm^2	W/cm^2	W/cm^2	W/cm^2	W/cm^2
(kA)	$\$10^3$	$\$10^6$	$\$10^6$	$\$10^6$	$\$10^6$	$\$10^6$	$\$10^6$
10	86	0.86	74.3	74.1	74.2	74.5	74.1
25	115	1.15	67.3	67.2	67.7	68.4	66.9
50	158	1.58	64.7	64.3	66.5	67.0	64.0
100	255	2.55	64.2	63.7	67.0	66.2	63.4
150	349	3.49	66.0	65.1	70.6	68.8	64.8
200	464	4.64	69.1	68.0	75.3	72.7	67.5
250	574	5.74	72.7	71.0	80.1	77.7	70.9

Notes:

- Semifluted and fully-fluted conductors are both separate-substrate conductors with final assembly required at the winding facility.
- Tricable is a complex integral-substrate conductor; final assembly not required at winding facility.
- Cost difference between separate and integral-substrate conductors primarily due to complexity of the latter geometry and not the fact that it is integral in nature.

Table 4-XVII

Magnet System Estimated Costs

(Based on nested shell concept using semifluted conductor)

Current, kA	10	25	50	100	150	200	250
Costs, 10^6 $:							
Conductor	8.73	8.87	9.00	9.23	9.67	9.74	9.92
Substructure	1.04	1.21	1.30	1.62	2.99	2.41	3.21
Superstructure	12.14	12.31	12.37	13.59	14.73	14.02	15.26
Vacuum Vessel	1.21	1.23	1.23	1.36	1.48	1.41	1.54
Power Supply	.21	.24	.27	.35	.43	.51	.59
Refrig. System	.47	.55	.65	.89	1.08	1.32	1.54
Total Components	23.83	24.40	24.82	27.04	30.39	29.41	32.06
Misc. & Shipping, 15%	3.57	3.66	3.72	4.06	4.56	4.41	4.81
Winding Fab.	17.15	11.27	9.08	6.90	6.75	6.61	6.56
Process Develop.	.68	.74	.80	1.05	1.34	1.69	2.00
Structural Assembly	5.50	5.50	5.50	5.50	5.50	5.50	5.50
Total Cost	50.72	45.57	43.93	44.55	48.53	47.62	50.92
Admin. Expenses, 30%	15.22	13.67	13.18	13.36	14.56	14.29	15.28
Total Installed Cost	54.94	59.24	57.10	57.91	63.09	61.90	66.20
Power Cost	.82	1.09	1.49	2.41	3.30	4.39	5.45
GRAND TOTAL	66.76	60.32	58.60	60.32	66.39	66.29	71.65

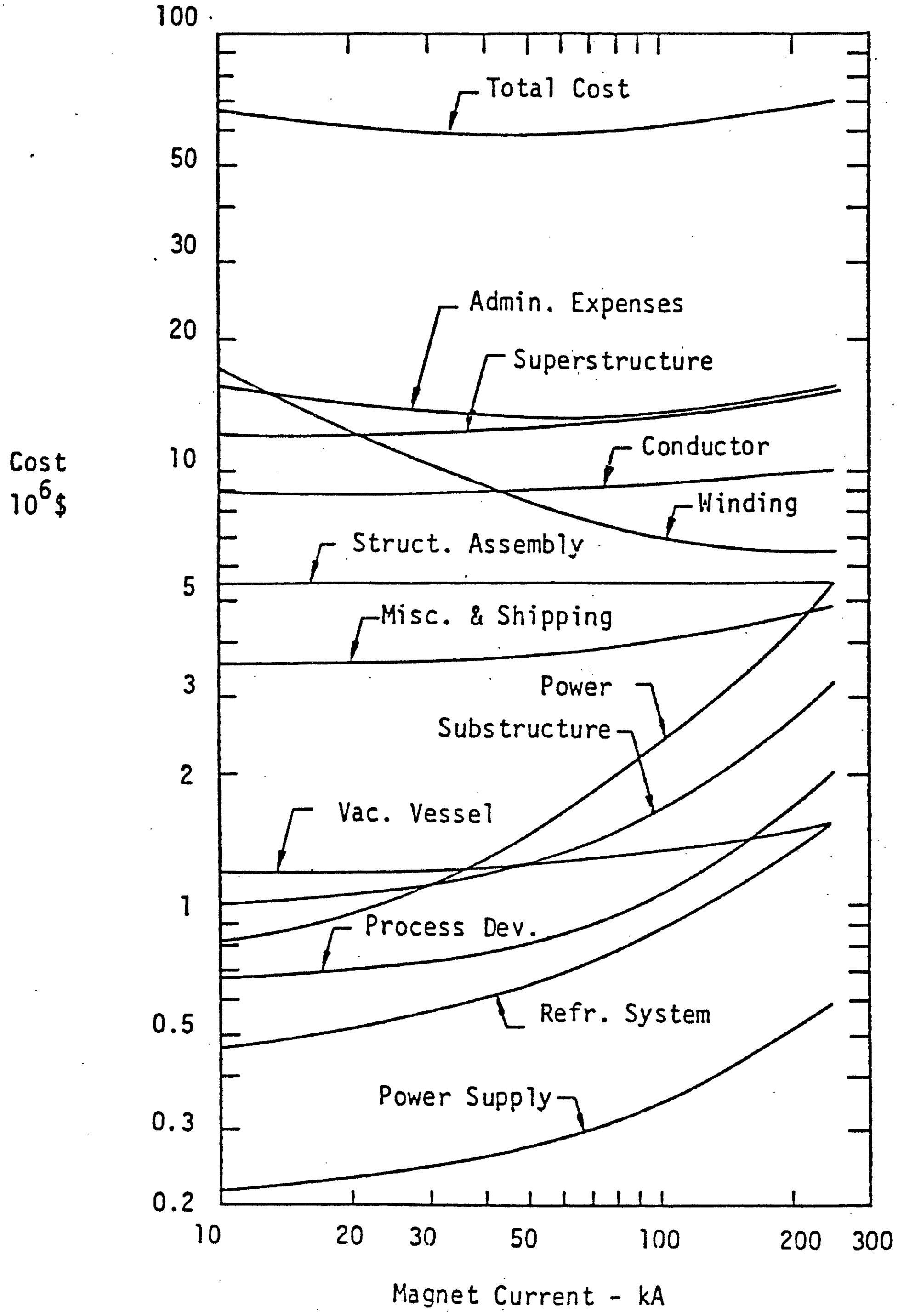


Figure 4.15
Component Costs and Total Cost vs Magnet Current for Nested Shell Concept (Semifluted Conductor)

4.3.3 Impact of Design Current Density [a] on Cost and Reliability of MHD Magnets

It has been generally recognized that the cost of an MHD magnet tends to become lower as design current density is increased, although the magnitude of the effect was not identified. It has been understood also that when high design current densities are selected in the interest of cost reduction, magnet protection becomes more difficult and the overall design may become less conservative from the safety and reliability standpoints.

Therefore, selecting design current density for commercial-size MHD magnets clearly requires careful cost/risk assessment. It was evident that to accomplish this, quantitative data were needed on the effect of design current density on magnet system cost, together with information on the effects on reliability criteria such as conductor heat flux, emergency discharge voltage and winding temperature rise under quench conditions.

A computer-aided study (Appendix A of Reference 2) was made at MIT in 1983 to determine analytically the effect of design current density on magnet system cost and on safety and reliability criteria. The study made use of computer codes described in Section 4.4.4. Major emphasis was placed on magnet systems of the size required for linear MHD generators in the channel power output range of 100 to 1100 MWe. Copper-stabilized NbTi windings with average current densities from 0.75×10^7 A/m^2 to 2.5×10^7 A/m^2 were considered.

A relatively simple analytical approach was used in the study which sought to identify general trends only. The results, tempered by engineering judgment to reflect the influence of factors not taken into account in the analysis, indicate that a saving of roughly 20 % may be realized on magnet systems at the large end of the size range by increasing current density from 1×10^7 A/m^2 to 2×10^7 A/m^2. The equivalent savings for magnet systems at the small end of the size range would be 25 % or more.

Figure 4.16 contains curves of magnet weight vs design current density and Figure 4.17 contains curves of magnet system cost vs design current density. Figures 4.18, 4.19 and 4.20 contain curves of heat flux, initial discharge voltage and final conductor temperature, respectively, as functions of design current density. In Fig. 4.19, for each case shown, the initial current is constant over the full range of current density.

The basis for the above curves was a series of magnet reference designs of different bore sizes, representing magnets for power plants in the 100 to 1100 MWe range, and all embodying the same design concepts. For each magnet size, at least three current densities between 0.75×10^7 A/m^2 and 2.5×10^7 A/m^2 were considered. With the aid of computer programs and using scaling techniques, the characteristics and estimated costs of magnets of each bore size and current density were calculated.

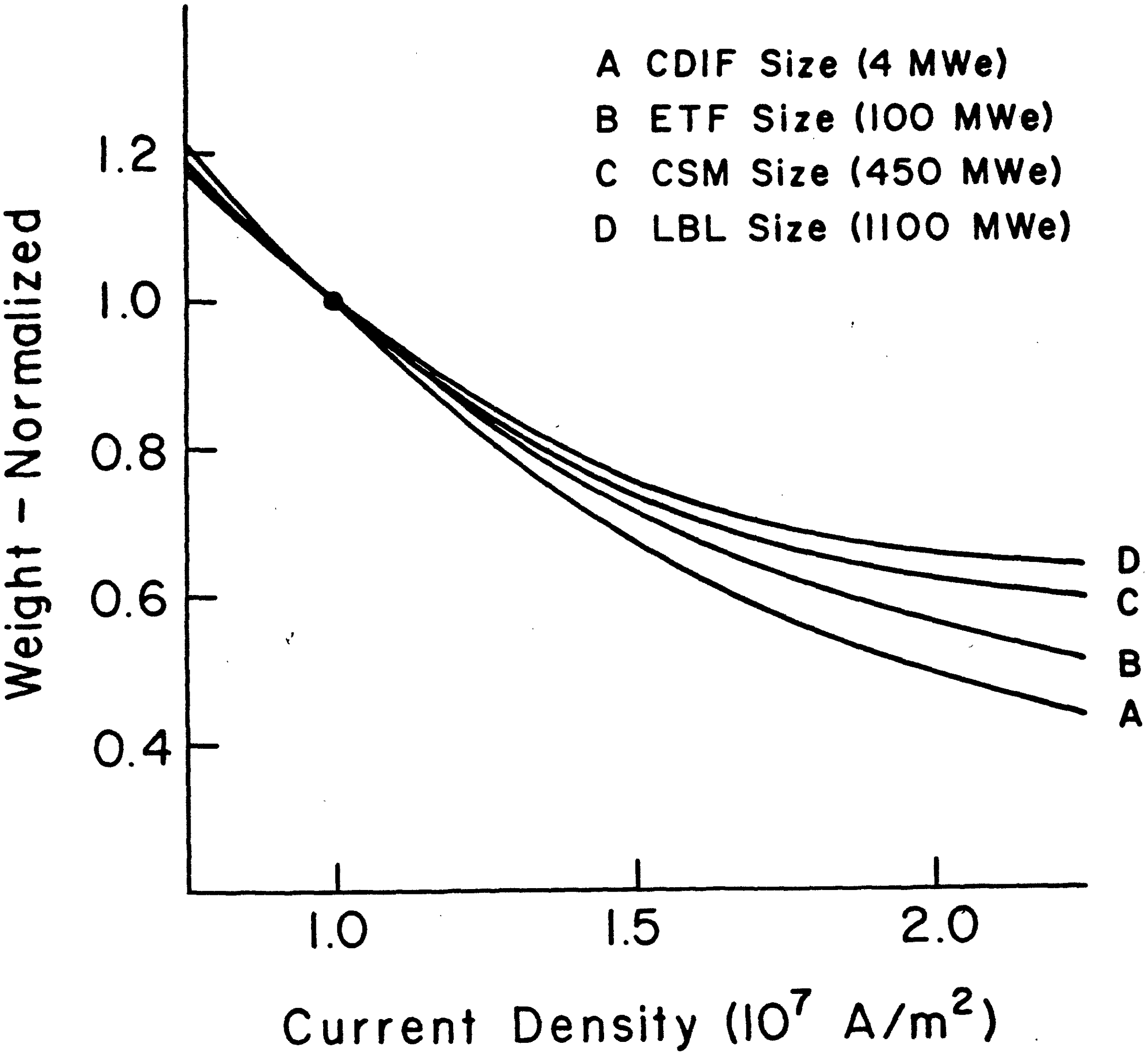


Figure 4.16
Curves of Normalized Magnet Weight vs Design Current Density

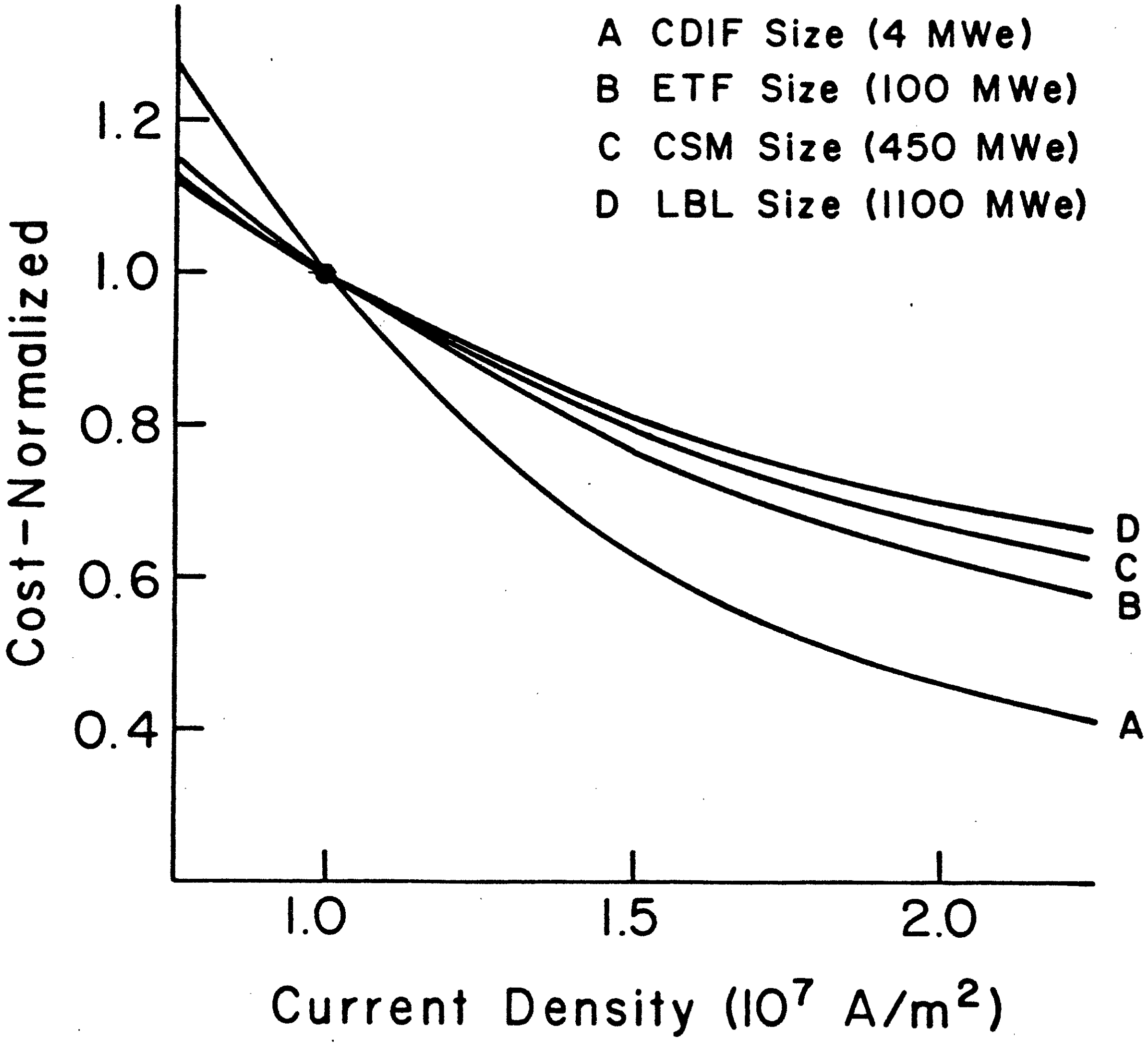


Figure 4.17
Curves of Normalized Magnet System Cost vs Design Current Density

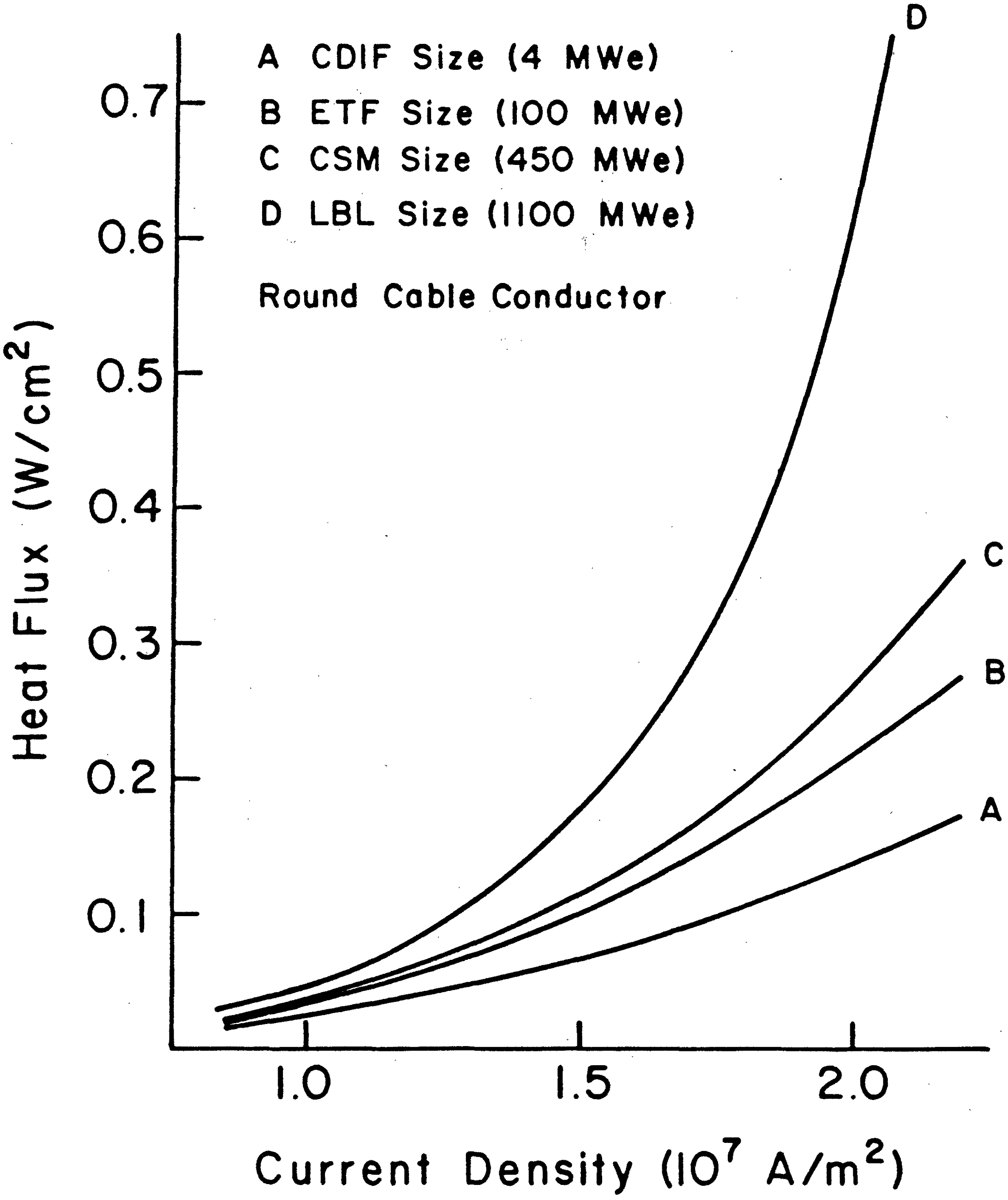


Figure 4.18
Curves of Heat Flux vs Design Current Density

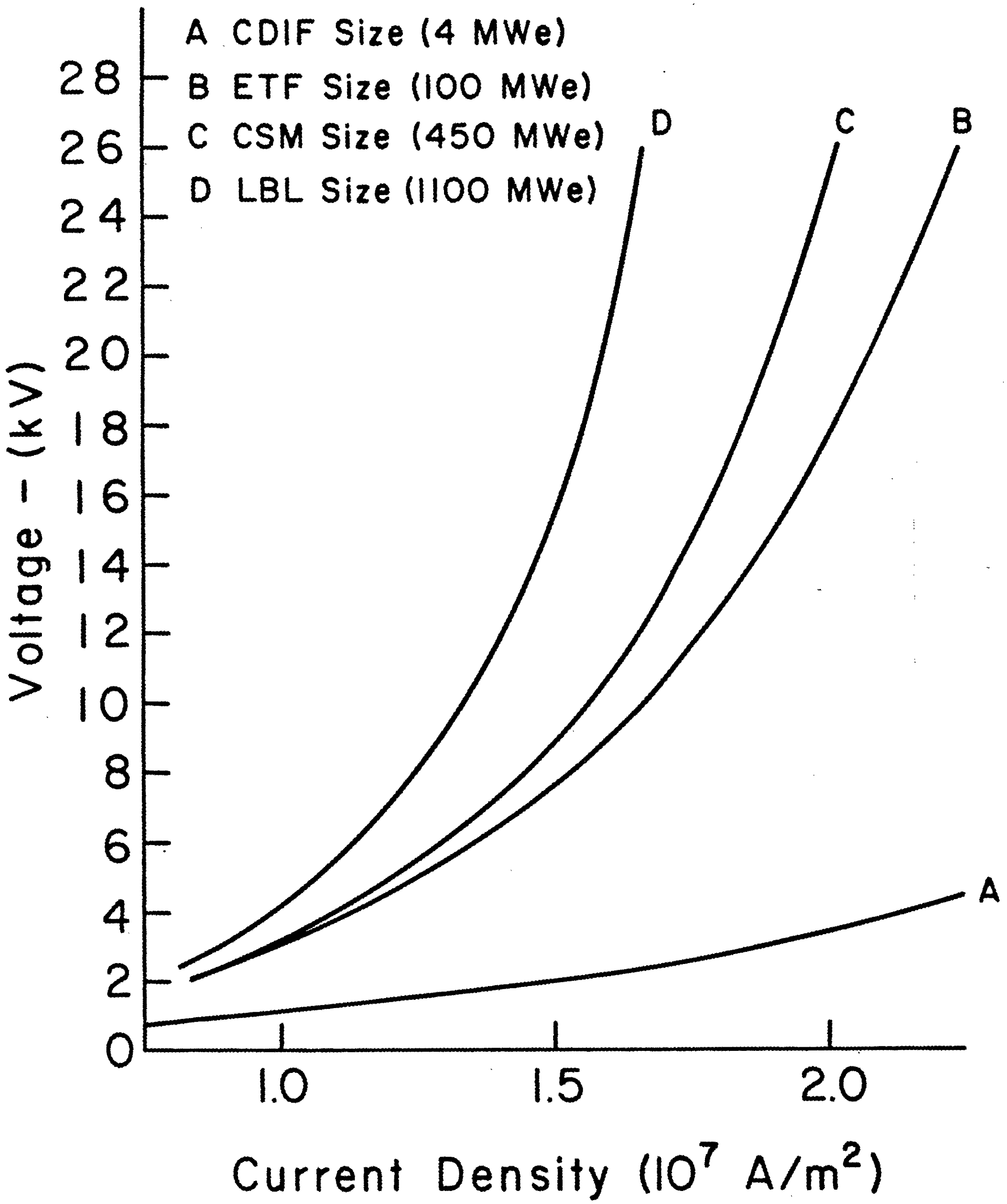


Figure 4.19
Curves of Emergency Discharge Voltage (Initial) vs Design Current Density

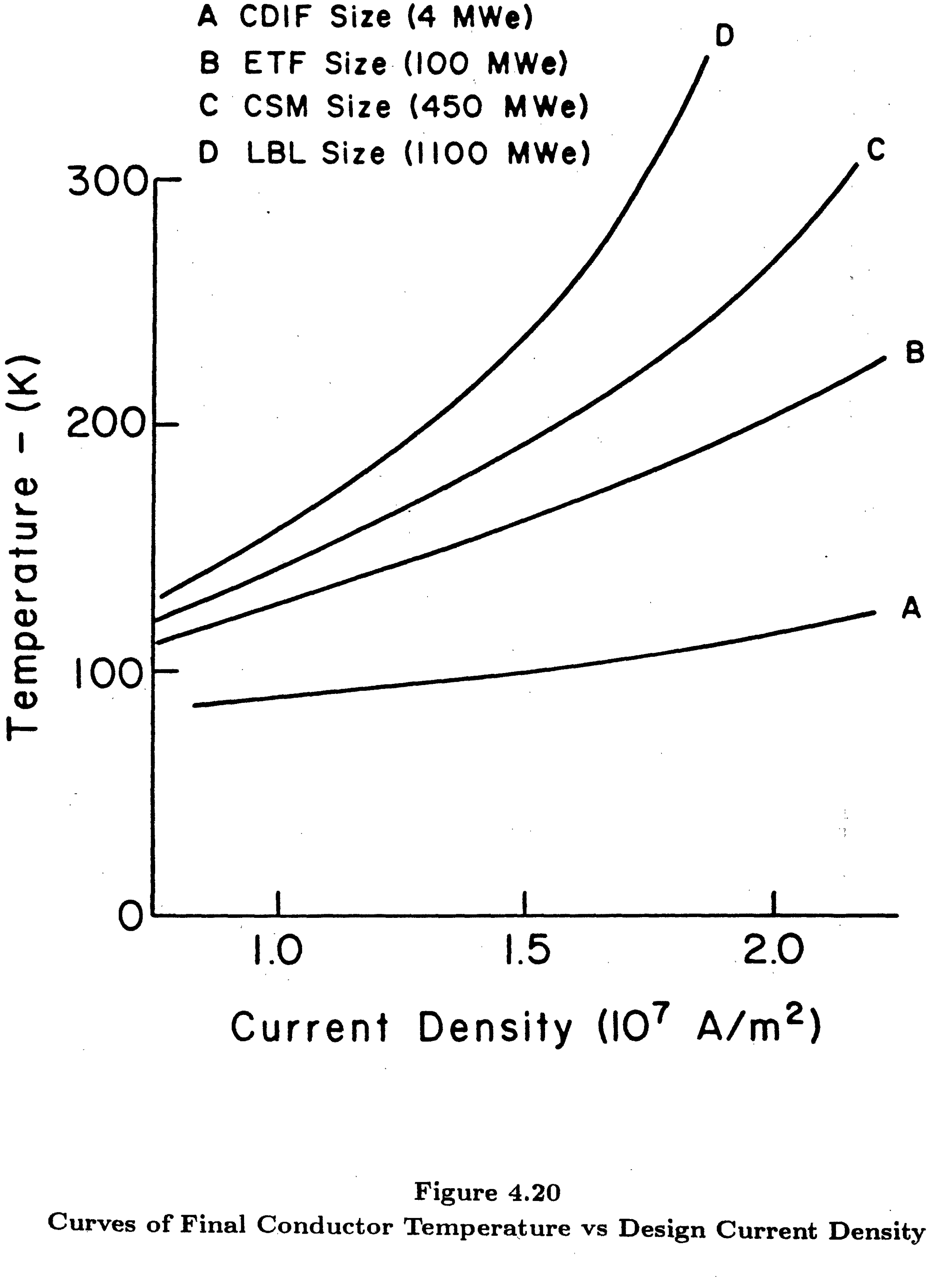


Figure 4.20
Curves of Final Conductor Temperature vs Design Current Density

For the limited number of computer-generated designs covered in this study, characteristics at the extremes of the parametric range, although indicative, do not necessarily represent good design practice. Values of heat flux, discharge voltage and conductor temperature shown on the curves were determined by scaling from reference magnet designs created with median conditions in mind, and therefore not optimized for the extreme conditions. (For example, high heat fluxes could be reduced by changing the detail design of the conductor; high discharge voltages could be lowered by increasing design current and/or by using parallel power supplies). In considering future magnet designs, the data in this study should be regarded as indicative of trends only.

It is of interest to note the range of design current densities used in past MHD magnet designs, as listed in Table 4-XVIII. Here a definite trend toward lower design current density with increasing magnet size is observed. Values range from 2.82×10^7 A/m^2 for the relatively small U25 Bypass magnet to 1.15×10^7 A/m^2 for the commercial-size CSM magnet. (However, current density in the conductor itself does not show the same trend, but varies erratically).

The observed trend to lower design current density with increased size is believed due in part to the instinctive desire of the designer to be generally more conservative as he enters the "unknown territory" of very large magnets, and in part to more specific influences such as the need for more conductor support material (substructure) in large windings and the tendency to provide extra copper and/or complicated extended surfaces to ensure that conductor surface heat flux is within acceptable limits. All of these factors make the winding pack bulkier and hence lower the average current density.

4.3.4 Relationships of Magnet Structure Weights, Stored Energies and Costs

In developing a cost-effective MHD magnet, the design of the force containment structure is important because it represents one of the larger components from both weight and cost standpoints.

Theoretically, the weight of the force containment structure should vary directly as stored magnetic energy, regardless of magnet size or field strength (assuming similar magnet proportions, current densities, materials and design stresses). The ratio of structure weight to stored energy in an actual magnet design is therefore a measurement of the efficiency of the structural design. A more efficient structural design would require less material and would be expected to result in cost saving.

It is consequently of interest to examine a series of MHD magnet designs (some built, some designed and cost estimated only) to determine the actual relationship between

Table 4-XVIII
Design Characteristics of Representative MHD Magnet Designs of Various Sizes

Magnet Identification		U25 Bypass	CDIF/SM	CFFF	ETF MIT	CASK	CSM-1A
Field	T	5	6	6	6	6	6
Warm bore inlet aperture	m	0.4 dia.	0.78× 0.97	0.8 dia.	1.5× 1.9	2.48 dia.	2.2× 2.8
Active length[a]	m	2.5	3.4	3.2	11.7	14.5	14.5
Stored energy	MJ	34	240	216	2900	6300	7200
Build	m	0.364	0.622	0.53	0.95	0.74	1.08
Design current	kA	0.89	6.13	3.675	24.4	50.0	52.2
Design current density, winding	10^7 A/m^2	2.82	1.87	2.0	1.42	1.28	1.15
Current density, conductor	10^7 A/m^2	5.0	6.28	2.63	8.16	2.2	5.7
Type of conductor		Rect. Built-up	Square Built-up	Rect. Built-up	Round Cable	Rect. Built-up	Round Cable
Substructure material		Fiber-glass & St. Steel[b]	Fiber-glass	Fiber-glass[b]	Fiber-glass	St. Steel	Fiber-glass

Notes:

[a] Active length for all magnets is distance between on-axis field points of 0.8 B_{peak} at inlet and 0.6 B_{peak} at exit.

[b] Banding between winding layers is used in place of a rigid substructure.

structure weight, stored energy and cost.

Table 4-XIX contains data for four MHD magnet designs covering a considerable size range (CFFF, CDIF, Retrofit 4.5 T and ETF 6 T). The table lists magnet characteristics including weights and costs used as a basis for the investigation, and then lists relationships derived from these data, including ratios of structure weight to stored energy (for straight region, ends and overall) and ratios of structure cost to stored energy.

Observations concerning the relationships given in the table, together with discussions including probable reasons for the rather wide variation in weight to energy ratios are presented below:

1. The ratios of transverse structure weight to stored energy in the straight region of the magnet winding (Table 4-XIX, Line 16) show a wide variation. The greatest spread is between the CFFF and CDIF, where the ratio in the former design is more than 100 % higher than the ratio in the latter design.

   Discussion

   The relatively high weight of the CFFF structure is due at least in part to three factors:

   1) the lower design stress in the CFFF structure

   2) the incorporation of a mechanical girder to tie plate joint in the CFFF (the CDIF joint is welded) and

   3) the inherently greater girder span in the CFFF circular saddle design as compared to the CDIF rectangular saddle.

   It should be noted, however, that mechanical joints, although heavier, may be preferable for large magnets because they facilitate field assembly and field inspection[a]. It should be noted also that ratio of cost to energy for structure overall (Table 4-XIX, Line 27) is only about 20 % higher in the CFFF design compared to that in the CDIF design, reflecting relatively good manufacturability in the CFFF structure design.

2. The ratios of straight region total structure weight (including transverse structure, longitudinal structure, substructure, etc.) to energy (Table 4-XIX, Line 17) show a wide variation, similar to that for transverse structure only, although slightly lower.

---

[a] Note that the retrofit 4.5 T and the ETF 6 T magnets have mechanical joints in their main structure.

The CFFF ratio is again highest and the CDIF lowest.

Discussion

Contributing to the high weight of the CFFF total structure is the cast coil-form, which is relatively low stressed.

3. The ratios of end-turn region total structure weight to energy (Table 4-XIX, Line 19) are considerably higher than corresponding ratios for the straight region. As in previous observations, the CFFF ratio is highest and the CDIF lowest.

   Discussion

   The above indicates that the designs for end-turn structures are generally less efficient than the designs for straight region structures. Since the end-turn regions represent a sizable portion of total structure weight (36 % to 57 % according to Table 4-XIX, Line 22) it is apparent that in future magnet designs, special attention should be given to end-turn regions to improve structural efficiency.

4. The ratios of total structure cost to total stored energy (Table 4-XIX, Line 27) show a variation of roughly 200 %, with the CFFF design having the highest ratio and the ETF design the lowest. The ratios become uniformly lower as magnet size increases.

   Discussion

   A major factor which accounts for the lowering of structure cost to energy ratio as magnet size increases is that the larger magnets have more of their structure located in the straight region, where structural efficiency is considerably greater (in the design considered).

The information contained in Table 4-XIX and the above discussions should be useful in future MHD magnet design work. The results tend to show which magnet designs are better from the structural efficiency standpoint. They also indicate that extra design effort on end-turn structure should result in lower overall structure weight and cost.

Table 4-XIX, (Sheet 1)

Relationships of Magnet Weights, Stored Energies and Cost

1.	Magnet identification		CFFF	CDIF	Retro	ETF
2.	Magnet characteristics					
3.	Peak on-axis field	T	6	6	4.5	6
4.	Size parameter, VB^2	m^3T^2	61	88	141	986
5.	Wt, magnet system	kg	172,000	144,000	320,000	909,000
6.	Wt, tot. (cold) struct.[a]	kg	85,700	53,600	147,000	590,000
7.	Length, winding overall	m	4.88	5.7	11.15	15.4
8.	Length, straight region	m	2.76	2.88	8.07	10.44
9.	Current density, avg.	$10^7 A/m^2$	2.0	1.8	3.2	1.4
10.	Energy, stored, total	MJ	216	240	487	2900
11.	Material, cold struct.		SS cast[b]	SS wrot.	SS wrot	SS wrot
12.	Des. stress, cold struct.	MPa	234	460	372	414
13.	Cost[c], cold struct. & misc.	k$	2385	2167	3650	10,430
14.	Cost[c], magnet system	k$	12,900	24,300	41,000	68,600
15.	Relationships, <u>str. region:</u>					
16.	Wt./energy, transverse struct. only[d]	kg/MJ	191	83	125	107
17.	Wt./energy, total struct.[a] in str. region	kg/MJ	289	142	252	145
18.	Relationships, <u>end regions:</u>					
19.	Wt./energy, tot. struct., ends	kg/MJ	668	396	471	417
20.	Relationships, <u>overall:</u>					
21.	% of total struct. wt. in straight region	%	52	43	64	56

Table 4-XIX, Sheet 2

Relationships of Magnet Weights, Stored Energies and Cost

	Magnet identification		CFFF	CDIF	Retro	ETF
22.	% of total struct. wt. in end regions	%	48	57	36	44
23.	Wt./energy, total struct.[a]	kg/MJ	397	223	302	203
24.	Wt./energy, total magnet	kg/MJ	796	600	657	213
25.	Cost/wt., total struct.[a]	$/kg	27.82	40.43	24.8	17.7
26.	Cost/wt., total magnet	$/kg	75	169	128	76
27.	Cost/energy, total struct.[a]	$/kJ	11.04	9.03	7.49	3.60
28.	Cost/energy, total magnet	$/kJ	60	101	84	24

a Includes transverse structure (girders, tie plates), coil form, other longitudinal structure, substructure and helium vessel if latter is part of load-bearing structure.

b Girders and coil form are cast stainless steel; tie plates are aluminum alloy; He vessel is wrought stainless steel.

c 1984 $

d Girders and tie plates only

4.3.5 Impact of MHD Channel/Magnet Interfacing on Magnet System Cost

In commercial-scale MHD generators the channel should be packaged inside the magnet bore with the most efficient space use practicable, in order to minimize the required bore size and thereby reduce the cost of the magnet, which is a major item in overall plant capital cost. To accomplish this successfully, the channel designer and magnet designer must work in close cooperation.

In addition to channel/magnet packaging, there are other important interfacing considerations that require careful attention. One example is that of supporting the power train (combustor, channel, diffuser) in relation to the magnet and the question of what forces the magnet must withstand as a result of thermal expansion of the power train. Another example is the provision for channel changeout, and the question of whether a movable magnet (roll-aside, turntable-mounted or roll-apart design) has overall advantages compared to the fixed magnet with movable diffuser.

A study was initiated in January 1980 to investigate channel/magnet packaging and to determine tentatively what packaging efficiencies may be expected in future commercial-scale MHD magnets. To provide channel technology input to the study, a contract was placed with MEPPSCO, Inc. for their engineering assistance, and help was also obtained from Avco Everett Research Laboratory, Inc. (AVCO).

The study showed that by careful packaging, the utilization factor (plasma volume/warm bore volume) could be increased from a value of about 0.25, associated with early reference designs, to 0.5 or higher. This means that the MHD power generated in a particular size magnet could be doubled, or for a given power, the size and cost of the magnet could be substantially decreased. Alternative channel/magnet bore configurations considered included those shown in Figure 4.21.

Other conclusions derived from the study were: 1) a square bore cross section is generally preferred over a round bore cross section, from the channel packaging standpoint, 2) a rectangular bore with the long dimension parallel to the field lines is the most advantageous bore geometry for types of channels which require many power leads (because lead bundles can be located in the ends of the rectangle, allowing maximum use of the central high field region for power generation) and 3) power generated in a given magnet bore volume can be nearly as high with a supersonic channel and 4 T peak-on-axis field as with a subsonic channel at a 6 T peak-on-axis field. (This leads to the conclusion that for a given MHD power output, the magnet cost would be substantially lower with a supersonic channel than with a subsonic channel).

The results of the study are reported in References 12, 13 and 14.

4.3.6 Comparative Analysis of Costs of CDIF/SM and CFFF Magnets

A study was made at MIT in 1982 to compare and analyze the costs of two MHD magnets of nearly the same size (CDIF/SM and CFFF) whose total design and construction cost differed by more than a factor of two. The purpose of the study was to determine what elements in design, construction and project management were most responsible for the difference in cost.

The major characteristics of the two magnets are listed in Table 4-XX.

The CDIF magnet was designed and partially constructed (work was stopped before magnet assembly) by the General Electric Co. (GE) based on a conceptual design provided by MIT. The CFFF magnet was designed, built and tested by Argonne National Laboratory (ANL).

The total costs (rounded off) as identified at the time of the study were as follows:

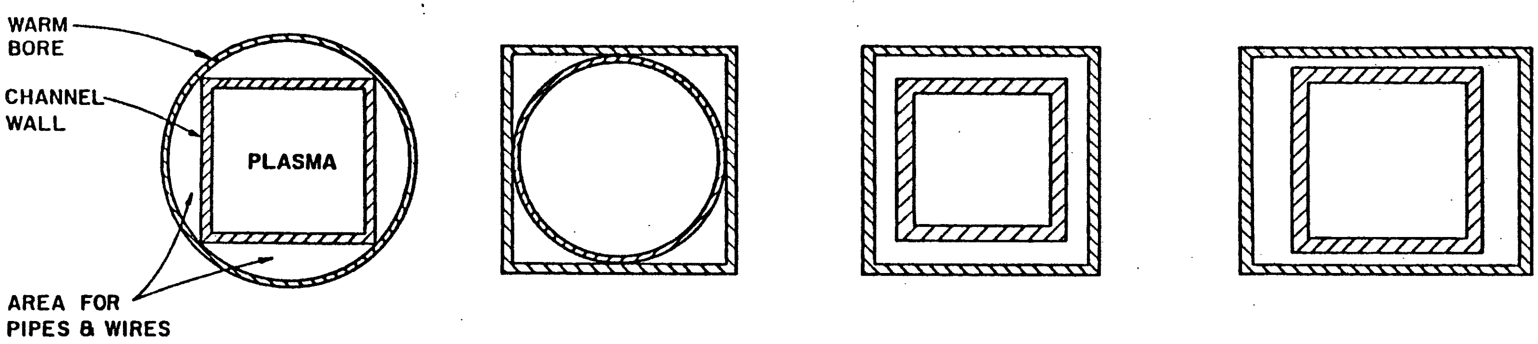
	k$
CDIF/SM (including MIT management and support) Data of 7/22/81	22,000
CFFF - Data of 7/16/80	10,000
Difference	12,000

Table 4-XX

Major Characteristics, CDIF/SM and CFFF Magnets

		CDIF/SM	CFFF
Peak on-axis field, B	(T)	6	6
Warm bore size at channel inlet[a]	(m)	0.85 x 1.05	0.8 dia.
Active length, 0.8 B to 0.6 B	(m)	3.2	3.35
Stored energy	(MJ)	240	210
Size parameter, VB^2	(m^3T^2)	88	61
Total weight	(tonnes)	144	172

[a] without bore liner



	SQUARE WINDOW-FRAME CHANNEL IN ROUND BORE (MEPPSCO)	CIRCULAR WINDOW-FRAME CHANNEL IN SQUARE BORE (MEPPSCO)	INSULATING-WALL CHANNEL IN SQUARE BORE (AVCO)	INSULATING-WALL CHANNEL IN RECTANGULAR BORE (AVCO)
PLASMA AREA (m^2)	7.9	9.6	6.8	10.0
WARM BORE AREA[a] (m^2)	15.9	16.0	16.0	20.0
MVU[b]	0.50	0.60	0.42	0.50

[a] Warm bore areas are typical for early commercial scale magnets, exit end.

[b] MVU = magnetic volume utilization factor.

Figure 4.21
Alternative Channel/Bore Configurations Considered to Achieve Maximum Bore Utilization

Conclusions reached were:

1. The elements most responsible for the total cost difference were the business and financial practices incident to performance of the work by a large industrial organization and the learning necessary because of limited prior experience by the GE team in design and construction of a large MHD magnet. These accounted for more than 5000 k$ of the 12,000 k$ difference, based on preliminary evaluations.

2. The differences in costs of magnet components (mostly subcontracted by both GE and ANL) and in costs of magnet assembly combine to give the CDIF/SM assembled hardware a cost roughly 2000 k$ more than that of the CFFF, or about 40% more. However, the CDIF/SM is about 20% larger in size (volume at high field), so correcting for size, the difference becomes considerably less. It is therefore concluded that the differences in conceptual design and manufacturability between the two magnets are relatively minor factors in the overall program differences.

3. The greater component cost of the CDIF/SM magnet, as presented in Conclusion 2, is largely due to cost of the CDIF/SM conductor, which is almost 1500 k$ more than that of the CFFF conductor. The CDIF/SM conductor differs somewhat in configuration from the CFFF conductor and represents 30% more quantity (in terms of ampere meters), but these differences alone cannot account for the very large difference which exists. It is concluded, therefore, that the conductor cost differential reflects mainly differences in procurement procedures (CPFF for the CDIF/SM; fixed price for the CFFF) and in source manufacturing efficiencies.

The study is described more fully in Appendix G.

4.4 Cost Estimating Procedures

Three general procedures have been used in making cost estimates for MHD magnet systems, namely:

- Preliminary estimation of overall magnet system cost using empirical curves (based on past experience)

- Estimation of magnet system cost using cost algorithms for components, program indirect costs and other cost items

- More detailed estimation, using estimated material, labor and overhead costs for each item in the system

In addition, scaling techniques and computer programs were developed to generate cost estimates and other data for families of magnets of similar design. The main purpose of that approach was to facilitate studies of effects of certain design variations on cost.

The estimating procedures and scaling techniques are described in the following sections:

4.4.1 Estimating Magnet System Cost Using Empirical Curves

This procedure is useful in preliminary MHD system studies, where a rough approximation of magnet system cost is needed before a particular magnet system design has been developed. It is necessary to establish only the size of the magnet bore (as required to accommodate the MHD channel), the desired peak-on-axis field and the length of the high field region (active length) to use this procedure.

The magnet size parameter (VB^2) is calculated as indicated in Appendix B, and magnet system cost determined from an empirical curve such as that in Figure 4.22 in which magnet system cost is plotted vs the size parameter, VB^2.

The curve in Figure 4.22 is the same as the curve in Figure 4.2, presented in Section 4.1.3, and is based on historical data including past estimates for a number of MHD magnets of various sizes. It should be noted that the curve represents data on superconducting saddle-coil magnets for ground-based linear MHD power generators with fields ranging from 4 to 6 T. The curve should not be used for other types of magnets or for magnets with fields much different from the range mentioned.

4.4.2 Estimating Magnet System Cost Using Cost Algorithms for Component and Other Costs

This procedure is useful when an estimate better than the rough approximation of the Section 4.4.1 procedure is wanted, and when a magnet design has been developed to the point where component weights have been estimated (but detail drawings and manufacturing planning are not necessarily yet available).

Component costs, assembly costs and other direct and indirect costs can then be determined using component cost algorithms as discussed in Section 4.2.3. Table 4-XXI is an example of the use of this estimating procedure.

Table 4 - XXI

Magnet Cost Estimate Using Component Cost Algorithms

Example – 4.5 T Retrofit Size MHD Magnet

		Weight (or Capacity)	Algorithm	Ref.	Cost k$ (1984)
1	Conductor	70 tonnes	133 $/kg	1	9310
1a	Conductor	(4.65 × 10^8 Am)	2.00/$kAmT	1a	(9300)
2	Insulation	in 3	–	–	in 3
3	Substructure	50 tonnes	13.50$/kg	3	675
4	Coil Fabrication	–	9.00$/kg	1	630
5	Helium Vessel	70 tonnes	21.00$/kg	5	1470
6	Superstructure	80 tonnes	21.00$/kg	6	1680
7	Coil,Vessel,Structure Ass'y	–	5.00$/kg	8	350
8	**Cold Mass, Total**	270 tonnes	–	–	14,115
9	Cold Mass Supports	in 10	–	–	in 10
10	Thermal Shield	20 tonnes	64.00$/kg	10	1280
11	Vacuum Vessel	80 tonnes	18.00 $/kg	11	1440
12	**Cryostat, total**	100 tonnes	–	–	2720
13	**TOTAL, All Components**	370 tonnes	–	–	16,835
14	Mfg eng'g, tooling	–	3.00$/kg	13	1110
15	Pack & Ship Components	–	1.00 $/kg	13	370
16	**Total, Components on site**	–	–	–	18315
17	Final ass'y,Install. on site	–	6.00$/kg	13	2220
18	**Total, Magnet installed on site**	–	–	–	20,535
19	Shakedown tests	–	1.00$/kg	13	370
20	**Total, Magnet installed and tested**	-	–	–	20.905
21	Accessories, incl. install.	–	20%	20	4180
22	Other costs	–	10%	20	2090
23	**Total Magnet and access. install.**	–	–	–	27,175
24	Design & Analysis, support dev.	–	11%	23	2990
25	Program Management	–	10%	23	2720
26	**Magnet Syst. Total** incl. d&a, prog. manag.	–	–	–	32,885
27	Contingency Allowance	–	25%	26	8,220
28	**MAGNET SYSTEM TOTAL COST**	–	–	–	41,105 (rounded 41,000)

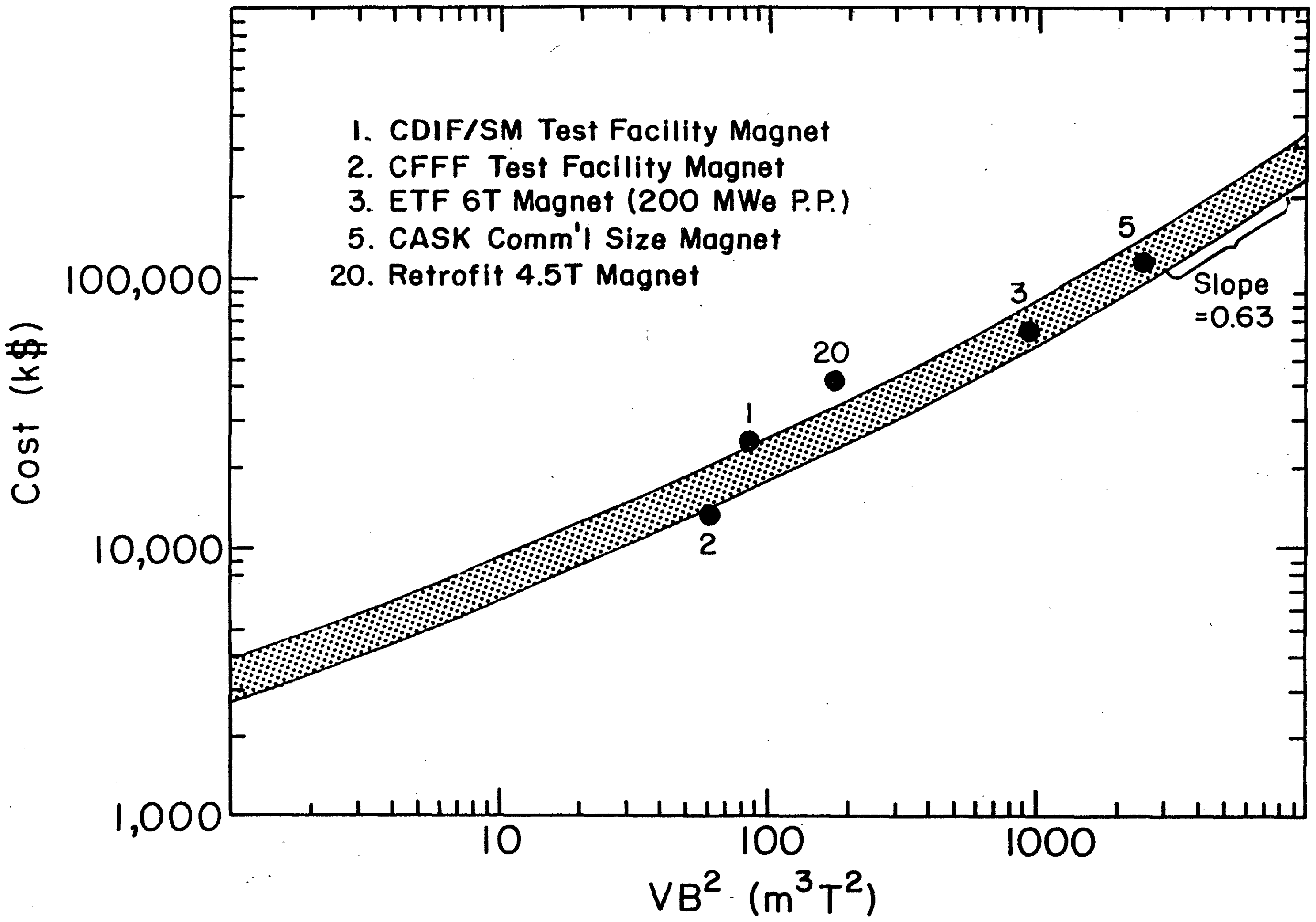


Figure 4.22
Curve of Estimates MHD Magnet System Cost (1984$) vs Size Parameter, VB^2

4.4.3 Estimating Magnet System Cost Using Estimated Material, Labor and Overhead Cost for Each System Item

This procedure, a detailed estimate starting with material, labor and overhead costs, is appropriate where adequate design information has been developed and where well-substantiated estimates are needed. Generally, it is necessary that a set of drawings and a manufacturing plan and associated flow charts be available.

Raw material costs must be based on quantities including allowances for scrap, test samples, design error, etc. Raw material costs must include cost of shipping, special handling, vendor certification or testing, etc. Limited information on raw material costs is contained in Appendix F.

Direct labor hours must be estimated for all direct manufacturing operations. Labor rates and overhead, as applicable for the particular manufacturing facility and operations, are then applied.

Costs of special tools, shop engineering, inspection, quality assurance, supplies, etc. must be added.

Indirect costs, G & A and profit are then applied to complete the price at the manufacturing facility.

Packing and shipping must be estimated for each item, including costs of special transportation means for shipping very large items to the plant site.

Plant site costs must include price of special tools required at the site, equipment contractor direct labor and overhead required for assembly and testing of equipment items, engineering supervision, indirect costs, G & A and profit. Also included in some cases are special site charges as established by the plant prime contractor.

A contingency allowance may be added on top of all other costs, according to manufacturer and/or plant prime contractor practice. (In the case of the MHD ETF/NASA plant estimate, the allowance was 30% on developmental items and 20% on well-proven commercially available major equipment items).

To illustrate how a detailed cost estimate is made up, portions of a typical detailed estimate are represented by the estimate sheets shown in figures listed below:

Fig. 4-23 Summary Sheet - Magnet Cost Estimate (Phases I - V) CASK

Fig. 4-24 Summary Sheet - Manufacturing Cost Estimate (Phase III) CASK

Fig. 4-25 Cost Breakdown - Substructure, Sheet 1 (Phase III) CASK

Fig. 4-26 Cost Breakdown - Substructure, Sheet 2 (Phase III) CASK

These sheets appeared in a cost estimate[3] prepared by General Dynamics for the CASK MHD magnet design. The estimate was for a first unit (1979 $) including conceptual design, detail design, construction and testing, but without accessories. Plant site special costs (charged by prime contractor) are not included in this estimate. The phase-by-phase work breakdown used and the costs for each major item (before fee and contingency) were as follows:

		WBS	Cost (1979 $)
Phase I	Conceptual Design	1000	990,472
Phase II	Detail Design	2000	3,285,150
Phase III	Manufacturing	3000	25,450,012
Phase IV	Site Final Assembly - Installation	4000	35,727,034
Phase V	Acceptance Test	5000	436,243
			65,888,911

Program management, quality assurance, etc. are included in each of the above items, but manufacturer's fees, plant site special costs and contingency allowances are not included here; they are included only on the Summary, Figure 4.23.

CONTRACT DATA

SALES ORDER NO:	6092-1-1
TYPE OF ESTIMATE:	BUDGETARY & PLANNING
PERIOD OF PERFORMANCE:	4 1/2 YRS. - UNIT #1

	UNIT #1
ESTIMATED COST	$65,888,902
FEE & CONTINGENCY 25%	16,472,226
PRICE	$82,361,128
AVG. COST/UNIT	$65,888,902

Figure 4.23
Example of Summary Sheet – Magnet Cost Estimate – CASK
(Total, Phases I – V)

```
GENERAL DYNAMICS    PROPRIETARY DATA - USE OR DISCLOSURE OF
CONVAIR DIVISION    PROPOSAL DATA IS SUBJECT TO THE RESTRICTION
                    ON THE TITLE PAGE OF THIS PROPOSAL        03/12/80

   78-182A      CASK COMMERCIAL DEMONSTRATION PLANT
   PVH
                             ONE UNIT

                         FREE FORM REPORT

  WBS LEVEL 2   3000      PHASE III MANUFACTURING

                 PROPOSAL  COST  SUMMARY

---------------------------------------------------------------------
COST                                        ESTIMATED     PERCENT
ELEMENTS                                     AMOUNT       OF TOTAL
---------------------------------------------------------------------

DIRECT LABOR HOURS
  PROGRAM MGMT                                    1224         .57
  ENGINEERING                                    23442       10.90
  TOOLING                                        21575       10.03
  MANUFACTURING                                 115323       53.62
  QUALITY ASSURANCE                              30180       14.03
  LOGISTICS                                       2796        1.30
  OTHER                                          20542        9.55
                                            ----------      ------
  TOTAL LABOR HOURS                             215082      100.00

---------------------------------------------------------------------

ESTIMATED COST
  LABOR & OVERHEADS                      $     6586860       25.88
   MATERIAL
    ENGINEERING                                   3600          .1
    TOOLING                                    1385356        5.44
    MANUFACTURING                             16456606       64.66
    SHIPPING                                     18560          .7
    OTHER                                         1551          .1
  OTHER DIRECT COSTS                            997479        3.92
                                           -----------      ------
  TOTAL ESTIMATED COST                   $    25450012      100.00
```

Figure 4.24
Example of Summary Sheet – Manufacturing Cost Estimate — CASK
(Phase III)

```
                  GENERAL DYNAMICS    PROPRIETARY DATA - USE OR DISCLOSURE OF
                  CONVAIR DIVISION    PROPOSAL DATA IS SUBJECT TO THE RESTRICTION
                                      ON THE TITLE PAGE OF THIS PROPOSAL        03/21/80

                     78-182A      CASK COMMERCIAL DEMONSTRATION PLANT
                     PVH
                                                 ONE UNIT

                                              FREE FORM REPORT


              WBS INPUT LV 3220       SUBSTRUCTURE

                                DD 633-4 FORMAT --- COST  BREAKDOWN

-------------------------------------------------------------------------------------------
COST                                             EFFECTIVE                          TOTAL
                                      HOURS OR     RATE      ESTIMATED           ESTIMATED
ELEMENTS                               BASE $    $ OR PCT       COST                COST
-------------------------------------------------------------------------------------------

DIRECT MATERIAL
  RAW MATERIAL
    TOOLING MATERIAL                                              62300
    MFG RAW MATERIAL                                            4735807
      SUBTOTAL RAW MATERIAL                                                        4798107
                                                                               -----------
    TOTAL DIRECT MATERIAL                                                      $   4798107

DIRECT LABOR

  MANUFACTURING LABOR
   MFG ENGINEERING (TOOLING)
    TOOL MANUFACTURING                  8900    $ 9.220           82058
                                  ----------                -----------
      SUBTOTAL MFG ENGR                 8900                $     82058
   FACTORY
    EXPERIMENTAL                       29769    $ 9.020          268516
                                  ----------                -----------
      SUBTOTAL FACTORY                 29769                $    268516
   MANUFACTURING SUPPORT
    PLANT ENGINEERING                   4420    $ 8.860           39161
                                  ----------                -----------
      SUBTOTAL MFG SUPPORT              4420                $     39161
   MFG QUALITY ASSURANCE
    QUAL ASSUR SERVICES                  693    $ 9.251            6411
    PROCMNT QUAL ASSUR                   576    $10.300            5933
    RECEIVE & SHIP INSP                  587    $ 8.440            4954
    QUALITY CONTROL                     3422    $ 8.870           30353
                                  ----------                -----------
      SUBTOTAL MFG QUAL ASSUR           5278                $     47651
                                  ----------
   TOTAL MANUFACTURING LABOR           48367    $ 9.043                        $    437386

    SUPPORT LABOR
     PROCMNT QUAL VERIF                  576    $10.300            5933
                                  ----------
   TOTAL SUPPORT LABOR                   576    $10.300                        $      5933
```

Figure 4.25
Example of Cost Breakdown – Substructure – Sheet 1, CASK

```
     GENERAL DYNAMICS    PROPRIETARY DATA - USE OR DISCLOSURE OF
     CONVAIR DIVISION    PROPOSAL DATA IS SUBJECT TO THE RESTRICTION
                         ON THE TITLE PAGE OF THIS PROPOSAL         03/21/80

       78-182A      CASK COMMERCIAL DEMONSTRATION PLANT
       PVH
                                  ONE UNIT

                                FREE FORM REPORT

     WBS INPUT LV 3220       SUBSTRUCTURE

                              ----------                                -----------
    TOTAL DIRECT LABOR             48943                                $    443319

LABOR OVERHEAD
  MANUFACTURING OVERHEAD     $    437386      121.00         529236
  SUPPORT OVERHEAD           $      5933       26.01           1543
    TOTAL LABOR OVERHEAD                                                $    530779

TRAVEL
  TRANSPORTATION & PER DIEM                                             $     14400

OTHER DIRECT COSTS
  DIR FRINGE BENEFITS        $    443319       44.90         199049
  ALLOCATIONS                                                 57762
  LABOR PREMIUM AMOUNT                                         8866
  GRAPHIC SERVICES                                            13215
    TOTAL OTHER DIRECT COSTS                                            $    278892

-----------------------------------------------------------------------------------

SUBTOTAL DIR COSTS & OVERHEAD                                           $   6065497

  GENERAL & ADMIN EXPENSE  $      443319       55.20                         244714

-----------------------------------------------------------------------------------

TOTAL ESTIMATED COST                                                    $   6310211

-----------------------------------------------------------------------------------
```

Figure 4.26

Example of Cost Breakdown – Substructure – Sheet 2, CASK

DATE: 3/9/81
Rev. 3/13/81

COST ESTIMATE BREAKDOWN[1,7]

ETF MAGNET SYSTEM - CONCEPTUAL DESIGN

ACCT. NO.	ACCOUNT DESCRIPTION	QUAN.	DESIGN & ANAL.	MAT'L & MFG.	SHOP ENG'G.	PACK & SHIP	MATERIAL COST[2]		INST COST	INDIR COST	ENG'G SERV.[8]	OTHER COST	CONTIN	TOTAL COST
							MJR COMP	BOA						
317.3.1	Magnet assembly													
317.3.1.1	On-site tools						2,070		400					
.2	Roll-aside track						621		150					
.3	Wind. contain vessels[3]						15,070		1,800					
.4	Main structure						5,244		800					
.5	Cold mass supp. struts						621		150					
.6	Therm. rad. shield						1,518		900					
.7	Vacuum vessel						3,036		1,200					
.8	Warm bore liner						621		80					
	Total magnet assembly	1	5,363	21,450	2,145	643	29,601	-	5,600	560	(2,861)	(966)	10,728	46,439
317.3.2	Support subsystems													
317.3.2.1	Hydro. actuator sys.						128		30					
.2	Cryogenic supp. system						1,536		250					
.3	Power supply & dis. sys.						1,152		150					
.4	Main vacuum pump sys.						256		70					
.5	Utility boom, contr.,misc.						640		100					
	Total support system	1 set	725	2,900	-	87	3,712	-	600	60	(350)	(118)	874	5,246
317.3.3	Magnet shakedown test	-	150[4]	60	20	2	232[5]	80[5]	300[6]	30	(51)	(17)	193	835
	Total						33,446	80	6,500	650			11,766	52,432
	Engineering Services										3,254		651	3,905
	Other cost											1,099	220	1,319
317.3	TOTAL													57,666

[1] This estimate does not include foundations.
[2] Material cost is FOB site.
[3] This item includes conductor, coil winding (in shop) and shop assembly.
[4] Includes 100 K$ eng'g. test supervision and analysis.
[5] Includes liquid nitrogen and liquid helium.
[6] On-site technician labor cost.
[7] Costs are K$; mid 1981
[8] Field engineering

Figure 4.27
Example – Summary Cost Estimate Including Power Site Special Costs and Contingency Allowance, ETF Magnet System

3/9/81
Rev. 3/13/81

SUMMARY COST ESTIMATE[1,2]

ETF MAGNET SYSTEM

CONCEPTUAL DESIGN

ACCT. NO.	ACCOUNT DESCRIPTION	QUANTITY	MATERIAL COST		INST. COST	INDIR COST	CONTIN	TOTAL COST
			MJR COMP	BOA				
317.3	MAGNET SYSTEM	1	33,446	80	6,500	650	11,766	52,442
	ENGINEERING SERVICES (FIELD)	-	-	-	3,254	-	651	3,905
	OTHER COSTS	-	-	-	1,099	-	220	1,319
	TOTAL ESTIMATED COSTS	-	33,446	80	10,853	650	12,637	57,666

[1] This cost estimate does not include foundations. Estimated costs of foundations for magnet system are to be supplied by Gilbert Associates, Inc.

[2] Costs are K$, mid 1981

Figure 4.28
Example – Cost Estimate Breakdown Including Plant Site Special Costs and Contingency Allowance
ETF Magnet System

To illustrate how plant site cost and contingency allowances were added in a particular magnet system estimate, Figures 4.27 and 4.28 are presented. These figures show the "Summary Cost Estimate" and the "Cost Estimate Breakdown" for the 6 T magnet system for the ETF MHD 200 MWe Power Plant[15] (estimates in 1981 $). On these estimate sheets the "Material Cost" columns contain the total cost of all magnet components f.o.b. plant site. Included are costs of design and engineering, tooling, manufacturing engineering, project management and associated fees and profit. The "Installation Cost" columns contain the direct costs (labor, overload, supplies, etc.) incurred in on-site assembly and installation work.

"Indirect Costs," "Engineering Services, Field" and "Other Costs" are plant site contractor costs calculated as percentages of installation cost. Contingency allowances are calculated as percentages of the totals of materials, installation and indirect costs. The cost estimates as shown in Figures 4.26 and 4.27 follow procedures established by the architect-engineer organization handling the overall power plant construction project.

4.4.4 Scaling Techniques and Computer Programs for Cost Estimating

Scaling techniques and computer programs were developed to make cost estimates of families of magnets of similar geometry but varying in size, winding build, etc. Weights of components were scaled from a baseline design. Costs were calculated using component cost algorithms as discussed in Section 4.2.3. This approach was used in the study of the impact of design current density on magnet cost and reliability, as summarized in Section 4.3.3 and reported in Appendix A of Reference 2.

In scaling the weights of magnetic force containment structure, it was assumed that structure weight varied directly as stored magnetic energy, assuming geometric similarity and same material and design stress.

In scaling magnet components with magnet bore size (for rough estimates) the following relationships were used, assuming constant peak-on-axis field, same geometry, same conductor and same design stress.

Conductor ampere meters	$\sim V^{2/3}$
Conductor weights	$\sim V^{2/3}$
Substructure weight	$\sim V^{2/3}$
Helium vessel weight	
a) if vessel is inside superstructure	$\sim V^{2/3}$
b) if vessel is outside superstructure	$\sim V$
Superstructure weight	$\sim V$
Radiation shield weight	$\sim V^{2/3}$
Vacuum vessel weight	$\sim V$

5.0 References

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APPENDIX A

Tables of Magnet Characteristics and Costs

This appendix contains data tables listing the characteristics and costs, where available, of a large number of representative magnets (approximately 55), the majority of which are MHD magnets.

Magnets designed in the period from 1965 to 1984 are included. MHD magnets from baseload size to relatively small test facility size are listed.

Data tables for selected fusion magnets and physics experiment magnets are included for comparison with MHD magnets.

All magnets are air-core superconducting magnets, except where noted.

Current density data are for the high-field region of the winding in magnets having graded windings.

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Tables of Magnet Characteristics and Costs

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Table A-1
Magnet Data Summary
MHD Commercial Scale Magnets (Superconducting)

Identification: ECAS 6 T MHD Magnet, Baseload, Budgetary Estimate
Application: DOE Study
Designer: GE
Date of design: 1977
Status: Prelim. design only

Field, peak-on-axis	T	6
Active length	m	25
Aperture[a], start of act. len.	m	2.87 dia
Aperture[a], end of act. len.	m	6.5 dia
Size parameter VB^2	m^3T^2	5822
Total weight	tonnes	4110
Est. cost, original	k$	130,000 (MIT est)
Est. cost, 1984 $	k$	205,500

a without warm bore liner

Table A-2 Sheet 1
Magnet Data Summary
MHD Commercial Scale Magnets (Superconducting)

tification: BL6-P1 6 T MHD Magnet, Baseload Ref. Design, Circ. Sad.
ication: DOE Studies
gner: AVCO
of design: 1977
ıs: Ref. design only

Channel power output	MWe	600
Magnet type		Circ. Sad.
Field, peak-on-axis	T	6
Active length	m	16 (17.4)
Field, start of act. len.	T	6 (4.8)
Field, end of act. len.	T	3.4 (3.6)
Aperture[a], start of act. len.	m	2.69 (2.25)
Aperture[a], end of act. len.	m	4.85
Size parameter VB^2	m^3T^2	(2491)
Vac. vessel overall len.	m	25.0
Vac. vessel O.D.	m	12.5
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	14.5
Winding current density	$10^7 A/m^2$	1.21
Ampere turns	$10^6 A$	37
Stored energy	MJ	6100
Total weight	tonnes	3483
Est. cost, original	k$	56,876
Est. cost, 1984 $	k$	89,920

hout warm bore liner

Table A-2 Sheet 2
Expanded Data Summary

Identification: BL6-P1 MHD Magnet

MHD Channel Data:		
Power output	MWe	600
Inlet dimensions	m	1.35 × 1.35
Exit dimensions	m	2.9 × 2.9
Magnet Data:		
Peak on-axis field, B	T	6
Active field length, L_a	m	16 (17.4)
Distance, ℓ_i, bore inlet to start of active length	m	4.14
On-axis field, start of active length	T	6.0 (4.8)
On-axis field, end of active length	T	3.4 (3.6)
Field variation across MHD channel, end of active length	%	+2, -4
Aperture, bore inlet (diameter or height and width)	m	2.25 dia
Aperture, start of active length (diameter or height and width)	m	2.69 dia
Aperture, end of active length (diameter or height and width)	m	4.84 dia
Aperture, bore exit (diameter or height and width)	m	5.5 dia
Overall length of magnet (over vacuum jacket ends)	m	25.0
Overall dia or height and width (over vac. jacket shell)	m	12.5
Winding build, inlet end (thickness $\perp$ field)	m	0.94
Winding overall length (over ends)	m	22.5
Winding volume	m^3	141
Number of winding modules (substructures) per half		14
Peak field in winding	T	8.0
Operating current, I	kA	14.5
Operating temperature	K	4.5
Average current density (overall winding)	$10^7 A/m^2$	1.21
Magnet size index, VB^2 (see Appendix B)	m^3T^2	(2491)

Table A-2 Sheet 3
Expanded Data Summary

Identification: BL6-P1 MHD Magnet

Magnet Data cont		
Total number of turns, N		2550
Ampere turns (region of peak field)	10^6NA	37
Total length of conductor	km	126.2
Ampere meters	10^8Am	18.3
Stored magnetic energy	MJ	6100
Inductance	H	57
Conductor volume, total	m^3	51.7
Stabilizer volume, total	m^3	49.5
Superconductor volume, total	m^3	2.2
Conductor type		built-up
Winding data high field region:		
Average packing factor		0.367
Average current density	$10^7 A/cm^2$	1.21
Conductor current density	$10^7 A/cm^2$	3.30
Superconductor current density	$10^8 A/cm^2$	5.30
Conductor dimensions	cm	3.49 × 1.43
Conductor design margin, oper. curr./crit. curr.		n.a.
Copper to superconductor ratio		14
Superconductor filament diameter	μ	100
Fraction of conductor surface exposed to coolant		0.40
Stabilizer heat flux	W/cm^2	0.40
Cooling passage dimensions	cm	0.36 × 3.18
Ratio, helium vol. in passages, local to conductor volume		0.40
Electrical system data:		
No. of vapor cooled power leads		4
No. of parallel circuits, power supply units		2
Dump resistor resistance (initial)	Ω	0.05
Dump time constant	min	9.5
Max. terminal voltage during dump	V	725
Max. power supply voltage	V	20
Min. charge time	hr	6

Table A-2 Sheet 4
Expanded Data Summary

Identification: BL6-P1 MHD Magnet

Cryogenic data:		
Coil operating temperature	K	4.5
Coil container operating pressure	Atm	1.3
Thermal radiation shield temperature	K	80
Thermal radiation shield coolant (LN_2 or He gas)		He gas
Heat load to helium in coil container, rad. & cond.	W	175
Heat load to helium in coil container, joint losses	W	90
Helium requirement for current leads	ℓ/hr	87
Liquid helium volume in magnet above winding (operating)	ℓ	1000
Total vol. liquid helium in magnet (operating)	ℓ	24,000
Heat load to thermal radiation shield	W	2000
Materials of construction:		
Winding substructure		Al. alloy 5083
Insulation		G10
Helium vessel		Al. alloy 5083
Force containment structure		Al. alloy 6061
Cold mass supports		Ti. alloy
Thermal radiation shield		Al. alloy 5083
Vacuum vessel		Al. alloy 5083
Design stresses:		
Force containment structure		
Bending	MPa	179
Cold mass supports		
Compresson	MPa	380
Conductor	MPa	79 compr.
Electrical insulation (compressive)	MPa	79 compr.
Winding substructure	MPa	97 tens.
Pressure rating:		
Helium vessel (coil container), normal oper.	atm	1.3

Table A-2 Sheet 5
Expanded Data Summary

Identification: BL6-P1 MHD Magnet

Weights:		
Conductor	tonnes	454
Winding substructure	tonnes	526
Electrical insulation	tonnes	40
Force containment structure	tonnes	1960
Helium vessel	tonnes	260
Total cold mass	tonnes	3240
Cold mass supports	tonnes	16
Radiation shield (incl. superinsulation)	tonnes	44
Vacuum vessel	tonnes	183
Misc.	tonnes	0
Total, magnet	tonnes	3483

Table A-2 Sheet 6
Expanded Data Summary
Summary of Estimated Component Costs and Assembly Labor
6 T Baseload Circular-Saddle Magnet Design BL6-P1 (AVCO)

Components	Estimated Weight 10^3 kg	First Unit Cost/kg $	First Unit Total Cost \$ × 10^3	Subsequent Units[a] Total Cost \$ × 10^3
Conductor: Region A	123^b	22.60	2780	
Region B	211^b	17.90	3777	
Region C	143^b	14.30	2045	
Total Conductor	477^b		8602	7895
Insulating spacers, etc.	30	10.00	300	
Core tube	133	8.40	1117	
Winding support shells	526	9.45	4971	
Outer shells	126	8.40	1058	
End plates	6	8.40	50	
Channel girders	60	8.40	50	
Main girders	1900	7.70	14630	
Total, cold structure			22630	19236
Radiation shield	40	8.40	336	
Thermal insulation and miscellaneous	4	35.00	140	
Vacuum jacket	183	8.60	1574	
Support posts, etc.	6	33.00	198	
Leads, piping, etc.	—		100	
Total, radiation shield, vacuum jacket, etc.			2348	2113
Total components (f.o.b. factory)			33580	29244
Misc. materials and supplies (on site)			100	100
Total component and material cost			33680	29344
Labor			Man Weeks	Man Weeks
Coil Winding and module assembly (factory) and assembly of magnet on plant site			4700	3700

[a] Unit cost, lot of five

[b] Includes 5% margin over net calculated weights

Table A-2 Sheet 7
Expanded Data Summary

Identification: BL6-P1 MHD Magnet

Single Unit Cost Summary

	Cost (k$)
Components	33,680
Assembly labor, etc. 4700 × 680	3,196
Tooling, engineering support	8,000
Design and analysis; program management	6,000[a]
Accessories & misc.	4,000[a]
Support development	2,000[a]
Total, 1977 $	56,876
Total, 1984 $	89,920

[a] MIT estimate

Table A-3 Sheet 1
Magnet Data Summary
MHD Commercial Scale Magnets (Superconducting)

Identification: BL6-P2 6T MHD Magnet, Baseload Ref. Design, Rect. Sad.
Application: DOE Studies
Designer: AVCO
Date of design: 1977
Status: Ref. design only

Channel power output	MWe	600
Magnet type		90° Rect. Sad.
Field, peak-on-axis	T	6
Active length	m	16 (17.4)
Field, start of act. len.	T	6 (4.8)
Field, end of act. len.	T	3.3 (3.6)
Aperture[a], start of act. len.	m	2.94 sq. (1.99 sq.)
Aperture[a], end of act. len.	m	4.42 sq.
Size parameter VB^2	m^3T^2	(2481)
Vac. vessel overall len.	m	26.4
Vac. vessel height & width	m	13.0 × 10.7
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	14.5
Winding current density	$10^7 A/m^2$	1.14
Ampere turns	$10^6 A$	40.6
Stored energy	MJ	8150
Total weight	tonnes	3580
Est. cost, original	k$	no est.
Est. cost, 1984 $	k$	no est.

a without warm bore liner

Table A-3 Sheet 2
Expanded Data Summary

Identification: BL6-P2 MHD Magnet

Magnet data:		
Peak on-axis b field, B	T	6
Active field length, L_a	m	16 (17.4)
Distance, ℓ_i, bore inlet to start of active length	m	4.75
On-axis field, start of active length	T	6.0 (4.8)
On-axis field, end of active length	T	3.3 (3.6)
Field variation across MHD channel, end of active length	%	+4.1; -4.4
Aperture, bore inlet (diameter or height and width)	m	1.99 × 1.99
Aperture, start of active length (diameter or height and width)	m	2.94 × 2.94
Aperture, end of active length (diameter or height and width)	m	4.42 × 4.42
Aperture, bore exit (diameter or height and width)	m	5.30 × 5.30
Overall length of magnet (over vacuum jacket ends)	m	26.4
Overall dia or height and width (over vac. jacket shell)	m	13.0 × 10.7
Winding build, inlet end (thickness $\perp$ field)	m	0.87
Winding overall length (over ends)	m	24.0
Winding volume	m^3	206
Number of winding modules (substructures) per half		16
Peak field in winding	T	8.0 +
Operating current, I (2 conductors in parallel)	kA	14.5
Operating temperature	K	4.5
Average current density (overall winding)	$10^7 A/m^2$	1.14
Magnet size index, VB^2 (see Appendix B)	m^3T^2	2481

Table A-3 Sheet 3
Expanded Data Summary

Identification: BL6-P2 6 T MHD Magnet

Magnet data cont		
Total number of turns, N (2 conductors per turn)		2820
Ampere turns (region of peak field)	10^6NA	40.6
Total length of conductor	km	350
Ampere meters	10^8Am	126
Stored magnetic energy	MJ	8150
Inductance	H	78
Conductor volume, total	m^3	77
Conductor type		built-up
Winding data high field region:		
Average packing factor		0.347
Average current density	$10^7 A/cm^2$	1.14
Conductor current density	$10^7 A/cm^2$	3.30
Superconductor current density	$10^8 A/cm^2$	5.30
Conductor dimensions	cm	1.74 × 1.43
Superconductor filament diameter	μ	100
Fraction of conductor surface exposed to coolant		0.31
Stabilizer heat flux	W/cm^2	0.41
Cooling passage dimensions	cm	0.36 × 3.18
Ratio, helium vol. in passages, local to conductor volume		0.40
Electrical system data:		
No. of vapor cooled power leads		8
No. of parallel circuits, power supply units		4
Dump resistor resistance (initial)	Ω	0.1
Dump time constant	min	4
Max. terminal voltage during dump	V	725
Max. power supply voltage per supply	V	20
Min. charge time	hr	8.2

Table A-3 Sheet 4
Expanded Data Summary

Identification: BL6-P2 6 T MHD Magnet

Cryogenic data:		
Coil operating temperature	K	4.5
Coil container operating pressure	Atm	1.3
Thermal radiation shield temperature	K	80
Thermal radiation shield coolant (LN_2 or He gas)		He gas
Heat load to helium in coil container, rad. & cond.	W	288
Heat load to helium in coil container, joint losses	W	in above
Helium requirement for current leads	ℓ/hr	87
Liquid helium volume in magnet above winding (operating)	ℓ	6500
Total vol. liquid helium in magnet (operating)	ℓ	33,500
Heat load to thermal radiation shield	W	2300
Materials of construction:		
Winding substructure		Al. alloy 5083
Insulation		G10
Helium vessel		Al. alloy 5083
Force containment structure		Al. alloy 5083
Cold mass supports		Ti. alloy
Thermal radiation shield		Al. alloy 5083
Vacuum vessel		Al. alloy 5083
Design stresses:		
Force containment structure		
Bending	MPa	179
Cold mass supports		
Compresson	MPa	380
Conductor	MPa	79 compr.
Electrical insulation (compressive)	MPa	79 compr.
Winding substructure	MPa	179
Pressure rating:		
Helium vessel (coil container), normal oper.	atm	1.3

Table A-3 Sheet 5
Expanded Data Summary

Identification: BL6-P2 6 T MHD Magnet

Weights:		
Conductor	tonnes	678
Winding substructure	tonnes	in f.c. str.
Electrical insulation & misc.	tonnes	40
Force containment structure	tonnes	2220
Helium vessel	tonnes	170
Total cold mass	tonnes	3108
Cold mass supports	tonnes	20
Thermal radiation shield (incl. superinsulation)	tonnes	76
Vacuum vessel	tonnes	376
Misc.	tonnes	0
Total, magnet	tonnes	3580

Table A-4 Sheet 1
Magnet Data Summary
MHD Commercial Scale Magnets (Superconducting)

Identification: BL6-MCA 6 T MHD Magnet, Baseload Ref. Design, Rect. Sad. and R.T.
Application: DOE Studies
Designer: MCA
Date of design: 1977
Status: Ref. design only

Channel power output	MWe	600
Magnet type		90° Rect. Sad. + R.T.'s
Field, peak-on-axis	T	6
Active length	m	16 (17.4)
Field, start of act. len.	T	6 (4.8)
Field, end of act. len.	T	3.5 (3.6)
Aperture[a], start of act. len.	m	1.57 sq.
Aperture[a], end of act. len.	m	3.36 sq.
Size parameter VB^2	m^3T^2	(1544)
Vac. vessel overall len.	m	26.1
Vac. vessel O.D.	m	9.6
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	20
Winding current density	$10^7 A/m^2$	1.78
Ampere turns	$10^6 A$	38
Stored energy	MJ	6710
Total weight	tonnes	2664
Est. cost, original	k$	75,300
Est. cost, 1984 $	k$	119,050

a without warm bore liner

Table A-4 Sheet 2
Expanded Data Summary

Identification: BL6-MCA 6T MHD Magnet

MHD Channel Data:		
Power output	MWe	600
Inlet dimensions	m	1.35 × 1.35
Exit dimensions	m	2.9 × 2.9
Magnet Data:		
Peak on-axis field, B	T	6
Active field length, L_a	m	16 (17.4)
On-axis field, start of active length	T	6.0 (4.8)
On-axis field, end of active length	T	3.5 (3.6)
Aperture, bore inlet (diameter or height and width)	m	1.57 sq.
Aperture, start of active length (diameter or height and width)	m	1.57 sq.
Aperture, end of active length (diameter or height and width)	m	3.36 sq.
Aperture, bore exit (diameter or height and width)	m	3.36 sq.
Overall length of magnet (over vacuum jacket ends)	m	26.1
Overall dia or height and width (over vac. jacket shell)	m	9.6
Winding build, inlet end (thickness $\perp$ field)	m	0.767
Winding overall length (over ends)	m	23.1
Number of winding modules (substructures) per half		4
Peak field in winding	T	8.88
Operating current, I	kA	20
Operating temperature	K	4.5
Average current density (overall winding)	$10^7 A/m^2$	1.78
Magnet size index, VB^2 (see Appendix B)	m^3T^2	1544

Table A-4 Sheet 3
Expanded Data Summary

Identification: BL6-MCA 6 T MHD Magnet

Magnet Data cont		
Total number of turns, N		1884
Ampere turns (region of peak field)	10^6NA	38
Total length of conductor	km	86.7
Ampere meters	10^8Am	17.3
Stored magnetic energy	MJ	6710
Inductance	H	33.6
Conductor type (See Note 3)		built-up
Winding data high field region:		
Conductor current density	10^7A/cm^2	5.02
Conductor dimensions	cm	3.81 × 1.25
Copper to superconductor ratio		6.29
Stabilizer heat flux	W/cm^2	1.0
Cooling passage dimensions	cm	0.127 × 3.08
Ratio, helium vol. in passages, local to conductor volume		0.19
Electrical system data:		
No. of vapor cooled power leads		2
No. of parallel circuits, power supply units		1
Dump resistor resistance (initial)	Ω	0.0125
Dump time constant	min	45
Max. terminal voltage during dump	V	250

Table A-4 Sheet 4
Expanded Data Summary

Identification: BL6-MCA 6 T MHD Magnet

Cryogenic data:		
Coil operating temperature	K	4.5
Coil container operating pressure	Atm	1.3
Thermal radiation shield temperature	K	102
Thermal radiation shield coolant (LN_2 or He gas)		He gas
Heat load to helium in coil container, rad. & cond.	W	93
Heat load to helium in coil container, joint losses	W	in above
Helium requirement for current leads	ℓ/hr	60
Liquid helium volume in magnet above winding (operating)	ℓ	13,900
Total vol. liquid helium in magnet (operating)	ℓ	24,000
Heat load to thermal radiation shield	W	1306
Liq. nitrogen consumption, normal oper.	ℓ/hr	0
Refrigerator/liquefier power, normal oper.	KW	750
Refrigerator/liquefier capacity margin	%	25
External helium storage:		
Liquid	ℓ	5000
Materials of construction:		
Winding substructure		St. steel 310S
Insulation		Epoxy glass
Helium vessel		St. steel 310S
Force containment structure		St. steel 310S
Cold mass supports		Epoxy glass
Thermal radiation shield		Al. alloy 5083
Vacuum vessel		Al. alloy 5083
Design stresses:		
Force containment structure		
Tension	MPa	379
Bending	MPa	379
Winding substructure	MPa	379
Pressure rating:		
Helium vessel (coil container), normal oper.	atm	1.3

Table A-4 Sheet 5
Expanded Data Summary

Identification: BL6-MCA 6 T MHD Magnet

Weights:		
Conductor	tonnes	324
Winding substructure	tonnes	450
Electrical insulation	tonnes	in above
Force containment structure	tonnes	1106
Helium vessel	tonnes	in above
Total cold mass	tonnes	1880
Cryostat	tonnes	384
Other	tonnes	400
Total, magnet	tonnes	2664

Table A-4 Sheet 6
Expanded Data Summary

Identification: BL6-MCA 6 T MHD Magnet

Cost Estimate

Material Costs ($$10^6$)

Conductor	16.20
Structure	12.84
Dewar	2.32
Tooling	5.43
Misc. and Shipping	5.52
Subtotal	42.3
Administrative Expenses	12.7
Subtotal	55.0
Labor for Design and Fabrication ($ × 10^6)	16.3
TOTAL	71.2
Accessories and Misc.	4.0 (MIT est.)
Total incl. access. 1977 $	75.3
Total incl. access. 1984 $	119.05

Table A-5 Sheet 1
Magnet Data Summary
MHD Commercial Scale Magnets (Superconducting)

Identification: PSPEC-GE 6 T MHD Magnet, Baseload, Budget Est.
Application: DOE Study
Designer: GE (scaled from BL6-P1)
Date of design: 1979
Status: Prelim. design only

Plant power output	MWe	1254
Channel power output	MWe	460
Magnet type		Circ. Sad.
Field, peak-on-axis	T	6
Active length	m	(24)
Field, start of act. len.	T	(4.8)
Field, end of act. len.	T	(3.6)
Aperture[a], start of act. len.	m	2.45 dia
Aperture[a], end of act. len.	m	5.4 dia
Size parameter VB^2	m^3T^2	4071
Stored energy	MJ	11,500 approx.
Total weight	tonnes	7320
Est. cost, original	k$	116,100
Est. cost, 1984 $	k$	157,900

a without warm bore liner

Table A-5 Sheet 2
Expanded Data Summary

Identification: PSPEC-GE 6 T MHD Magnet

Weights	tonnes
Conductor	865
Total, structure incl. He vessel	6080
Total, cryostat	375
Total, magnet	7320
Est. Cost	**Cost, k$**
Conductor @ 20 $/kg	17,300
Structure @ 10 $/kg	60,800
Cryostat @ 16 $/kg	6,000
Coil/struct. assem., 500,000 man hrs. @ 20 $/hr	10,000
Site labor, 333,333 man hrs. @ 30 $/hr	10,000
Design and analysis, prog. management, support development, tooling, accessories & other	12,000
TOTAL, magnet and accessories 1979 $	116,100
TOTAL, magnet and accessories 1984 $	156,735

Table A-6 Sheet 1
Magnet Data Summary
MHD Commercial Scale Magnets (Superconducting)

Identification: PSPEC-AVCO 6 T MHD Magnet, Baseload Circ. Sad., Budget Est.
Application: DOE Study
Designer: AVCO
Date of design: 1979
Status: Prelim. design only

Channel power output	MWe	495
Magnet type		Circ. sad.
Field, peak-on-axis	T	6
Active length	m	18.6 (16.6)
Field, start of act. len.	T	(4.8)
Field, end of act. len.	T	(3.6)
Aperture[a], start of act. len.	m	1.92×1.92
Aperture[a], end of act. len.	m	3.5×3.5
Size parameter VB^2	m^3T^2	(2203)
Stored energy	MJ	7800
Total weight	tonnes	4000
Est. cost, original	k$	60,000
Est. cost, 1984 $	k$	81,600

a without warm bore liner

Table A-6 Sheet 2
Expanded Data Summary

Identification: PSPEC-AVCO 6 T MHD Magnet

Weight	tonnes
Conductor, substructure and He vessel	2200
Force containment structure	1040
Cryostat	760
TOTAL, magnet	4000
Est. Cost	Cost, k$
TOTAL, magnet system cost 1979 $ (not incl. prog. mgt., D & E)	50,723

(From AVCO System Cost Summary, Case 1)

Table A-7 Sheet 1
Magnet Data Summary
MHD Commercial Scale Magnets (Superconducting)

Identification: CSM-1A 6 T MHD Magnet, Commercial Scale, Concept. Des., Rect. Sad.
Application: DOE Studies
Designer: MIT
Date of design: 1979
Status: Conceptual design only

Channel power output	MWe	250-500
Magnet type		60° Rect. Sad.
Field, peak-on-axis	T	6
Active length	m	14.5
Field, start of act. len.	T	4.8
Field, end of act. len.	T	3.6
Aperture[a], start of act. len.	m	2.2×2.8
Aperture[a], end of act. len.	m	4.0×4.2
Size parameter VB^2	m^3T^2	2526
Vac. vessel overall len.	m	21
Vac. vessel O.D.	m	12
Conductor type		Cable
Conductor material		NbTi/Cu
Design current	kA	52.2
Winding current density	$10^7 A/m^2$	1.145
Ampere turns	$10^6 A$	37.6
Stored energy	MJ	7200
Total weight	tonnes	1850
Est. cost, original	k$	75,590
Est. cost, 1984 $	k$	102,800

a without warm bore liner

Table A-7 Sheet 2
Expanded Data Summary

Identification: CSM-1A 6 T MHD Magnet Design

Magnet Data:

Peak on-axis field, B	T	6
Active field length, L_a	m	14.5
Distance, ℓ_i, bore inlet to start of active length	m	2.1
On-axis field, start of active length	T	4.8
On-axis field, end of active length	T	3.6
Field variation across MHD channel, end of active length	%	+9, -5
Aperture, bore inlet (diameter or height and width)	m	2.2×2.8
Aperture, start of active length (diameter or height and width)	m	2.2×2.8
Aperture, end of active length (diameter or height and width)	m	4.0×4.2
Overall length of warm bore	m	19.2
Active volume of warm bore (bore volume in length L_a)	m^3	162
Overall length of magnet (over vacuum jacket ends)	m	21.0
Overall dia or height and width (over vac. jacket shell)	m	12.0 dia.
Winding build, inlet end (thickness $\perp$ field)	m	1.08
Winding overall length (over ends)	m	19.9
Number of winding modules (substructures) per half		24
Peak field in winding	T	7.2
Operating current, I	kA	52.2
Operating temperature	K	4.5
Average current density (overall winding)	$10^7 A/m^2$	1.145
Magnet size index, VB^2 (see Appendix B)	m^3T^2	2526

Table A-7 Sheet 3
Expanded Data Summary

Identification: CSM-1A 6 T MHD Magnet

Magnet Data cont		
Total number of turns, N		720
Ampere turns (region of peak field)	10^6A	37.6
Total length of conductor	km	35.44
Ampere meters	10^8Am	18.5
Stored magnetic energy	MJ	7200
Inductance	H	5.28
Conductor type		cable
Winding data high field region:		
Average packing factor		0.34
Average current density	10^7A/cm^2	1.145
Conductor current density, overall/metal	10^7A/cm^2	3.39/5.95
Conductor dimensions, envelope	cm	4.44 dia.
Electrical system data:		
No. of vapor cooled power leads		2
No. of parallel circuits, power supply units		1
Cryogenic data:		
Coil operating temperature	K	4.5
Coil container operating pressure	Atm	1.3
Thermal radiation shield temperature	K	80
Thermal radiation shield coolant (LN_2 or He gas)		LN_2
Materials of construction:		
Winding substructure		Glass-polyester
Insulation		Above and G10
Helium vessel		St. steel 304 LN
Force containment structure		St. steel 304 LN
Cold mass supports		GRP G10
Thermal radiation shield		Al. alloy 6061
Vacuum vessel		St. steel 304 L
Design stresses:		
Force containment structure		
Bending	MPa	414

Table A-7 Sheet 4
Expanded Data Summary

Identification: CSM-1A 6 T MHD Magnet

Weights:		
Conductor	tonnes	300
Winding substructure	tonnes	155
Force containment structure	tonnes	930
Helium vessel	tonnes	incl. above
Total cold mass	tonnes	1385
Cold mass supports	tonnes	15
Thermal radiation shield (incl. superinsulation)	tonnes	50
Vacuum vessel	tonnes	400
Total, magnet	tonnes	1850

Table A-8 Sheet 1
Magnet Data Summary
MHD Commercial Scale Magnets (Superconducting)

Identification: CASK 6 T MHD Magnet, Conceptual Des., Mod. Circ. Sad.
Application: DOE Study
Designer: MIT/GD
Date of design: 1979
Status: Conceptual design only

Channel power output	MWe	250-500
Magnet type		Modified Circ. Sad.
Field, peak-on-axis	T	6
Active length	m	14.5
Field, start of act. len.	T	4.8
Field, end of act. len.	T	3.6
Aperture[a], start of act. len.	m	3.28 dia. (2.48 dia.)
Aperture[a], end of act. len.	m	4.50 dia.
Size parameter VB^2	m^3T^2	(2520)
Vac. vessel overall len.	m	23.6
Vac. vessel O.D.	m	7.11
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	50
Winding current density	$10^7 A/m^2$	1.276
Ampere turns	$10^6 A$	34.4
Stored energy	MJ	6300
Total weight	tonnes	2644
Est. cost, original	k$	87,000
Est. cost, 1984 $	k$	118,000

a without warm bore liner

Table A-8 Sheet 2
Expanded Data Summary

Identification: CASK 6 T MHD Magnet

Magnet Data:		
Peak on-axis field, B	T	6
Active field length, L_a	m	14.5
Distance, ℓ_i, bore inlet to start of active length	m	4.6
On-axis field, start of active length	T	4.8
On-axis field, end of active length	T	3.6
Aperture, bore inlet (diameter or height and width)	m	2.48 dia
Aperture, start of active length (diameter or height and width)	m	3.28 dia
Aperture, end of active length (diameter or height and width)	m	4.50 dia
Aperture, bore exit (diameter or height and width)	m	5.03 dia
Overall length of magnet (over vacuum jacket ends)	m	23.6
Active volume of warm bore (bore volume in length L_a)	m^3	139
Overall length of magnet (over vacuum jacket ends)	m	23.6
Overall dia or height and width (over vac. jacket shell)	m	7.11
Winding build, inlet end (thickness $\perp$ field)	m	0.74
Winding overall length (over ends)	m	20.2
Winding volume	m^3	101
Number of winding modules (substructures) per half		4
Peak field in winding	T	7.04
Operating current, I	kA	50
Operating temperature	K	4.5
Average current density (overall winding)	$10^7 A/m^2$	1.276
Magnet size index, VB^2 (see Appendix B)	m^3T^2	2512

Table A-8 Sheet 3
Expanded Data Summary

Identification: CASK 6 T MHD Magnet

Magnet Data cont		
Total number of turns, N		688
Ampere turns (region of peak field)	10^6NA	34.4
Total length of conductor	km	32.2
Ampere meters	10^8Am	14.52
Stored magnetic energy	MJ	6300
Inductance	H	5.04
Conductor volume, total	m^3	61.14
Stabilizer volume, total	m^3	59.4
Superconductor volume, total	m^3	1.74
Conductor type		built-up
Winding data high field region:		
Average packing factor		0.57
Average current density	10^7A/cm^2	1.276
Conductor current density	10^7A/cm^2	2.2
Superconductor current density	10^8A/cm^2	7.0
Conductor dimensions	cm	11.4 × 2.54
Copper to superconductor ratio		34
Superconductor filament diameter	μ	120
Fraction of conductor surface exposed to coolant		0.59
Stabilizer heat flux	W/cm^2	0.27
Cooling passage dimensions	cm	0.3 × 0.6
Ratio, helium vol. in passages, local to conductor volume		0.25

Table A-8 Sheet 4
Expanded Data Summary

Identification: CASK 6 T MHD Magnet

Cryogenic data:		
Coil operating temperature	K	4.5
Coil container operating pressure	Atm	1.36
Thermal radiation shield temperature	K	80
Thermal radiation shield coolant (LN_2 or He gas)		LN_2
Heat load to helium in coil container, rad. & cond.	W	182
Heat load to helium in coil container, joint losses	W	386
Helium requirement for current leads	ℓ/hr	140
Liquid helium volume in magnet above winding (operating)	ℓ	5000
Total vol. liquid helium in magnet (operating)	ℓ	36,000
Heat load to thermal shield	W	1421
Materials of construction:		
Winding substructure		St. steel 304 LN
Insulation		G10 CR
Helium vessel		St. steel 304 LN
Force containment structure		St. steel 304 LN
Cold mass supports		G10 CR
Thermal radiation shield		Al. alloy 6061-T6
Vacuum vessel		St. steel 304 LN
Design stresses:		
Force containment structure		
Tension	MPa	552
Bending	MPa	448
Conductor	MPa	130
Electrical insulation (compressive)	MPa	94
Winding substructure	MPa	681
Pressure rating:		
Helium vessel (coil container), normal oper.	atm	1.36
Helium vessel (coil container), max. oper.	atm	6.8

Table A-8 Sheet 5
Expanded Data Summary

Identification: CASK 6 T MHD Magnet

Weights:		
Conductor	tonnes	552
Winding substructure	tonnes	664
Electrical insulation	tonnes	55
Force containment structure	tonnes	689
Helium vessel	tonnes	267
Total cold mass	tonnes	2227
Cold mass supports	tonnes	15
Thermal radiation shield (incl. superinsulation)	tonnes	21
Vacuum vessel	tonnes	343
Misc.	tonnes	38
Total, magnet	tonnes	2644
Seismic loads:		
Seismic zone		4
Seismic load factor	G	± 0.28

Table A-8 Sheet 6
Expanded Data Summary

Identification: CASK 6 T MHD Magnet

Cost Estimate 1979	k$
Magnet:	
Conductor	15,383
Insulation	3407
Substructure	6310
Coil fabrication (winding)	9645
Total, wound coil	34,745
Helium vessel	966
Superstructure	2999
Total, cold mass	38,710
Cold mass supports	incl below
Thermal shield	4183
Vacuum vessel	4436
Other (iron frame, etc.) He man.	1290
Total, containment items	48,619
Manufacturing, engineering and tooling	2988
Total, magnet assembly/ comp. fob fact.	51,607
Accessories, Total	4525 MIT est.
Pack and ship to site	973
Site assemble and install magnet and system	4235
System shakedown test	incl above
Total, magnet system installed and tested (before project mgt., etc.)	61,340

Table A-8 Sheet 7
Expanded Data Summary

Identification: CASK 6 T MHD Magnet

Cost Estimate cont.	k$
Balance from Sheet 6	61,340
Project:	
Project management, Q.A., etc.	5170
Design and anaalysis	4275
Total, project	70,785
Overall:	
Total, incl. G & A	70,785
Fee (prime contractor)	16,366
Contingency allowance	in fee
Total, incl. contingency allowance	87,151 (1979 $)
Total, incl. contingency allowance	117,654 (1984 $)

Source of technical data:

General Dynamics Convair Division Report No. CASK-GDC-031, Cask Commercial Demo Plant MHD Superconducting Magnet Systems: Conceptual Design Final Report, MIT PO ML 67466, December 1979.

Source of cost data:

General Dynamics Convair Division Report No. PIN78-182 Cask Commercial Demo Plant MHD Magnet: Budgetary (Cost Estimate) and Planning, Final Report, MIT PO ML 68221, February 1980.

Table A-9 Sheet 1

Magnet Data Summary

MHD Commercial Scale Magnets (Superconducting)

Identification: CSM Adv. Des. 6 T MHD Magnet
Application: DOE Study
Designer: MIT
Date of design: 1980
Status: Conceptual design only

Channel power output	MWe	250-500
Magnet type		Rect. Sad., ICCS Wind.
Field, peak-on-axis	T	6
Active length	m	14.5
Field, start of act. len.	T	4.8
Field, end of act. len.	T	3.6
Aperture[a], start of act. len.	m	2.2 sq.
Aperture[a], end of act. len.	m	4.4 sq.
Size parameter VB^2	m^3T^2	2526
Vac. vessel overall len.	m	25.2
Vac. vessel O.D.	m	12.3
Conductor type		ICCS
Conductor material		NbTi/Cu, 304 sheath
Design current	kA	20
Winding current density	$10^7 A/m^2$	1.265
Ampere turns	$10^6 A$	33.8
Stored energy	MJ	5800
Total weight	tonnes	1621
Est. cost, original	k$	no est.
Est. cost, 1984 $	k$	no est.

a without warm bore liner

Table A-9 Sheet 2
Expanded Data Summary

Identification: CSM-Adv. Des. 6 T MHD Magnet

Magnet Data:		
Peak on-axis field, B	T	6
Active field length, L_a	m	14.5
On-axis field, start of active length	T	4.8
On-axis field, end of active length	T	3.6
Field variation across MHD channel, end of active length	%	+5, -5
Aperture, bore inlet (diameter or height and width)	m	2.2×2.2
Aperture, start of active length (diameter or height and width)	m	2.2×2.2
Aperture, end of active length (diameter or height and width)	m	4.4× 4.4
Aperture, bore exit (diameter or height and width)	m	4.4×4.4
Overall length of magnet (over vacuum jacket ends)	m	25.2
Overall dia or height and width (over vac. jacket shell)	m	12.3 dia.
Winding build, inlet end (thickness $\perp$ field)	m	1.0275
Number of winding modules (substructures) per half		4
Peak field in winding	T	7.1
Operating current, I	kA	20
Average current density (overall winding)	$10^7 A/m^2$	1.265
Magnet size index, VB^2 (see Appendix B)	m^3T^2	2526

Table A-9 Sheet 3
Expanded Data Summary

Identification: CSM-Adv. Des. 6 T MHD Magnet

Magnet Data cont		
Total number of turns, N		1660
Ampere turns (region of peak field)	10^6NA	33.2
Total length of conductor	km	84.23
Ampere meters	10^8Am	16.84
Stored magnetic energy	MJ	5800
Inductance	H	29.0
Conductor type		ICCS
Winding data high field region:		
Average current density	10^7A/cm^2	1.265
Conductor current density	10^7A/cm^2	5.54
Superconductor current density	10^8A/cm^2	6.06
Conductor dimensions	cm	3.14 × 3.14
Copper to superconductor ratio		9.93
Ratio, helium vol. in passages, local to cond. vol.		0.54
Materials of construction:		
Winding substructure		G10 & al. alloy
Insulation		G10
Conductor conduit		St. steel 304 LN
Force containment structure		St. steel 304 LN
Thermal radiation shields		St. steel 304 LN
Vacuum vessel		St. steel 304 LN
Design stresses:		
Force containment structure		
Tension	MPa	414

Table A-9 Sheet 4
Expanded Data Summary

Identification: CSM-Adv. Des. 6 T MHD Magnet

Weights:		
Conductor (cable and conduit)	tonnes	555
Winding substructure (filler wedges and plates)	tonnes	100
Electrical insulation	tonnes	177
Force containment structure	tonnes	269
Thermal radiation shield, inner	tonnes	28
Total cold mass	tonnes	1129
Cold mass supports	tonnes	3
Thermal radiation shield, outer (incl. superinsulation)	tonnes	60
Vacuum vessel	tonnes	362
Misc.	tonnes	67
Total, magnet	tonnes	1621

Table A-10
Magnet Data Summary
MHD Commercial Scale Magnets (Superconducting)

Identification: Disk Gen. 7 T MHD Magnet
Application: DOE/Westinghouse Study Report DOE/NASA/0139-1 Oct 1980
Designer: MIT
Date of design: 1980
Status: Design only

Plant power output	MWe	1000
Channel power output	MWe	600
Magnet type		single solenoid
Field, peak-on-axis	T	7
Vac. vessel O.D.	m	15.3
Conductor type		ICCS
Conductor material		Nb_3Sn/Cu
Design current	kA	50
Winding current density	$10^7 A/m^2$	2.5
Stored energy	MJ	6000
Total weight	tonnes	1352
Est. cost, original	k$	60,000
Est. cost, 1984 $	k$	74,000

Table A-11
Magnet Data Summary
MHD Large Test Facility Magnets (Superconducting)

Identification: EPP 4.3 T MHD Magnet
Application: Proposal for experimental power plant
Designer: AVCO
Date of design: 1967
Status: Prelim. design only

Magnet type		Circ. sad.
Field, peak-on-axis	T	4.3
Active length	m	5.0
Aperture[a], start of act. len.	m	1 dia.
Size parameter VB^2	m^3T^2	73
Conductor type		Built-up
Conductor material		NbTi/Cu
Stored energy	MJ	138
Est. cost, original	k$	5405
Est. cost, 1984 $	k$	15,000

a without warm bore liner

Table A-12

Magnet Data Summary

MHD Large Test Facility Magnets (Superconducting)

Identification: EPP 3 T MHD Magnet
Application: Proposal for experimental power plant
Designer: AVCO
Date of design: 1970
Status: Prelim. design only

Channel power output	MWe	50
Magnet type		Circ. sad.
Field, peak-on-axis	T	3
Active length	m	5.5
Aperture[a], start of act. len.	m	1
Aperture[a], end of act. len.	m	2
Size parameter VB^2	m^3T^2	39
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	3.6
Winding current density	$10^7 A/m^2$	2.8
Stored energy	MJ	75
Total weight	tonnes	65
Est. cost, original	k$	no est.
Est. cost, 1984 $	k$	no est.

a without warm bore liner

Table A-13
Magnet Data Summary
MHD Large Test Facility Magnets (Superconducting)

Identification: Emergency Generator 3 T MHD Magnet
Application: Proposal
Designer: AVCO
Date of design: 1969
Status:

Channel power output	MWe	50
Magnet type		Circ. sad.
Field, peak-on-axis	T	3
Active length	m	4.6
Aperture[a], start of act. len.	m	1
Aperture[a], end of act. len.	m	2
Winding current density	$10^7 A/m^2$	3.8
Ampere turns	$10^6 A$	6.23
Stored energy	MJ	51
Est. cost, original	k$	no est.
Est. cost, 1984 $	k$	no est.

[a] without warm bore liner

Table A-14
Magnet Data Summary
MHD Large Test Facility Magnets (Superconducting)

Identification: IGT 3.8 T MHD Magnet
Application: Proposal, MHD generator for coal gasifier
Designer: AVCO
Date of design: 1969
Status: Proposal design only

Magnet type		Circ. sad.
Field, peak-on-axis	T	3.8
Active length	m	2.5
Aperture[a], start of act. len.	m	0.5
Size parameter VB^2	m^3T^2	7
Conductor type		Built-up
Conductor material		NbTi
Design current	kA	2.7
Winding current density	$10^7 A/m^2$	4.2
Ampere turns	$10^6 A$	4.5
Stored energy	MJ	17
Est. cost, original	k$	1566
Est. cost, 1984 $	k$	4070

a without warm bore liner

Table A-15 Sheet 1
Magnet Data Summary
MHD Large Test Facility Magnets (Superconducting)

Identification: ETF6-P1 6 T MHD Magnet, Ref. Design
Application: DOE Studies, Engineering Test Facility
Designer: AVCO
Date of design: 1977
Status: Reference design only

Magnet type		Circ. sad.
Field, peak-on-axis	T	6
Active length	m	7 (8)
Field, start of act. len.	T	6 (4.8)
Field, end of act. len.	T	4 (4.0)
Aperture[a], start of act. len.	m	1.06 dia. (0.9 dia.)
Aperture[a], end of act. len.	m	1.75 dia.
Size parameter VB^2	m^3T^2	(183)
Vac. vessel overall len.	m	12.6
Vac. vessel O.D.	m	6.6
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	5.5
Winding current density	$10^7 A/m^2$	1.5
Ampere turns	$10^6 A$	19.2
Stored energy	MJ	820
Total weight	tonnes	535
Est. cost, original	k$	15,100
Est. cost, 1984 $	k$	23,900

[a] without warm bore liner

Table A-15 Sheet 2

Expanded Data Summary

Identification: ETF6-P1 6 T MHD Magnet, Ref. Design

Magnet Data:		
Type		Circ. sad.
Iron pole and yoke (yes, no)		No
Warm bore liner (yes, no)		No
Peak on-axis field, B	T	6.0
Active field length, ℓ_a (ℓ_a adj.)	m	7.0 (8.0)
Field at start of active length, B_i (adj.)	T	6.0 (4.8)
Field at end of active length, B_e (adj.)	T	4.0 (4.0)
Aperture, warm bore inlet, sans liner	m	0.9 dia.
Aperture, start of active length, sans liner	m	1.06 dia.
Aperture, end of active length, sans liner	m	1.75 dia.
Aperture, warm bore exit, sans liner	m	1.75 dia.
Vacuum vessel overall length	m	12.6
Vacuum vessel outside diameter	m	6.6
Warm bore volume, sans liner (adj. V_b)	m^3	10 (11.4)
Size parameter, VB^2	m^3T^2	(183)
Conductor materials, supercond./stabilizer		NbTi/Cu
No. of winding modules (or layers) per half		36
Conductor type		Built-up
Conductor dimensions	cm	1.52×0.89
Operating current, I_{op}	kA	5.5
Winding current density (JA)	10^7A/m^2	1.5
Conductor current density (J) (cond. envel.)	10^7A/m^2	4.52
Superconductor current density (oper.)	10^7A/m^2	18
Heat flux, stabilizer	W/cm^2	0.45
Ampere turns	10^6A	19.2
Ampere meters	10^8Am	4.4
Inductance	H	54
Turns, total		3490
Length, conductor, total	km	80
Insulation, conductor		
Material		G10
Substructure		
Material		Al 5083
He vessel		
Material		Al 5083
Design pressure	atm	1.3

Table A-15 Sheet 3
Expanded Data Summary

Identification: ETF6-P1 6 T MHD Magnet, Ref. Design

Magnet Data cont		
Superstructure		
Material		Al 6061
Design stress	MPa	179
Thermal shield		
Material		Al 6061
Vacuum jacket		
Material		AL 5083
Weights:		
Conductor	tonnes	86
Insulation	tonnes	9
Substructure	tonnes	131
Superstructure	tonnes	238
He vessel	tonnes	37
Total cold mass	tonnes	501
Cold mass supports	tonnes	in below
Thermal shield	tonnes	7
Vacuum vessel	tonnes	27
Total magnet weight	tonnes	535
Cryogenic data:		
Operating temperature, winding	K	4.5
Operating pressure winding (or ICCS)	atm.	1.3
Heat leak to LHe region:		
Rad. & cond.	W	100
Leads, LHe boil-off	ℓ/hr	16.5
Shield temperature	K	80
Shield coolant		He gas

Table A-15 Sheet 4
Expanded Data Summary

Identification: ETF6-P1 6 T MHD Magnet, Ref. Design

Power supply and dump data:		
Rated voltage, power supply	V	20
Minimum charge time	min	240
Resistance, emergency dump resistor	Ω	0.11
Maximum discharge voltage	kV	0.61

Table A-15 Sheet 5
Expanded Data Summary

Identification: ETF6-P1 6 T MHD Magnet, Ref. Design

Cost Estimate: 1977	Weight tonnes	Unit Cost $/kg	Cost k$
Magnet			
Conductor	90	19.00	1710
Insulation	9	10.00	90
Substructure	131	9.45	1240
Coil fabrication (winding)			3000
Helium vessel	37	8.40	310
Assembly, coil and helium vessel			in 4
Superstructure	238	7.70	1830
Cold mass supports, thermal insulation, miscellaneous	2	20.00	40
Thermal shield	5	8.40	40
Vacuum vessel	27	8.60	230
Instruments, controls, piping			30
TOTAL, containment items			8520
Manufacturing engineering and tooling			1000
TOTAL, magnet assembly/comp. fob factory			9520
Total, accessories			1500
Site assembly and install magnet and system			2200
TOTAL, magnet system installed and tested (before proj. mgt., etc.)			13,220
Design and analysis, proj. mgt.			1900
Total			15,120
TOTAL, rounded, 1977 $			15,100
Total, rounded, 1984 $			23,900

Table A-16 Sheet 1
Magnet Data Summary
MHD Large Test Facility Magnets (Superconducting)

Identification: ETF6-P2 6 T MHD Magnet
Application: DOE Study (Reference Designs)
Designer: AVCO
Date of design: 1977
Status: Reference design only

Magnet type		90° rect. sad.
Field, peak-on-axis	T	6
Active length	m	7 (8)
Field, start of act. len.	T	6 (4.8)
Field, end of act. len.	T	4 (4.0)
Aperture[a], start of act. len.	m	0.8 sq.
Aperture[a], end of act. len.	m	1.6 sq.
Size parameter VB^2	m^3T^2	(184)
Vac. vessel overall len.	m	12.1
Vac. vessel height and width	m	5.8×6.0
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	5.5
Winding current density	$10^7 A/m^2$	1.2
Ampere turns	$10^6 A$	18.7
Stored energy	MJ	684
Total weight	tonnes	449
Est. cost, original	k$	21,423
Est. cost, 1984 $	k$	33,870

a without warm bore liner

Table A-16 Sheet 2
Expanded Data Summary

Identification: ETF6-P2 6 T MHD Magnet

Magnet Data:		
Type		90° rect. sad.
Magnetic field:		
Direction		hor.
Peak on-axis field,	T	6.0
Active field length, ℓ_a (ℓ_a adj.)	m	7.0 (8.0)
Field at start of active length, B_i (adj.)	T	6.0 (4.8)
Field at end of active length, B_e (adj.)	T	4.0 (4.0)
Maximum field in winding	T	6.7
Aperture, warm bore inlet, sans liner	m	0.8 sq.
Aperture, start of active length, sans liner	m	0.8 sq.
Aperture, end of active length, sans liner	m	1.6 sq.
Aperture, warm bore exit, sans liner	m	1.6 sq.
Vacuum vessel overall length	m	12.1
Vacuum vessel outside height and width	m	5.8×6.0
Warm bore volume, sans liner (adj. V_b)	m^3	10.5 (12)
Size parameter, VB^2	m^3T^2	(184)
Conductor materials, supercond./stabilizer		NbTi/Cu
Winding build, inlet end, b	m	0.8
Conductor type		Built-up
Conductor dimensions	cm	1.52×0.89
Operating current, I_{op}	kA	5.5
Winding current density ($J\lambda$)	$10^7 A/m^2$	1.2
Ampere turns	$10^6 A$	18.7
Stored energy	MJ	684
Insulation, conductor		
Material		G10
Substructure		
Material		Al 5083
He vessel		
Material		Al 5083

Table A-16 Sheet 3
Expanded Data Summary

Identification: ETF6-P2 6 T MHD Magnet

Magnet Data cont		
Superstructure		
Material		Al 6061
Thermal shield		
Material		Al 6061
Vacuum jacket		
Material		AL 5083
Weights:		
Conductor	tonnes	124
Insulation, substructure, superstructure, He vessel	tonnes	255
Total cold mass	tonnes	379
Thermal shield, vacuum vessel, c.m.s.	tonnes	70
Total magnet weight	tonnes	449
Cryogenic data:		
Operating temperature, winding	K	4.5
Operating pressure winding	atm.	1.3
Liquid helium boil-off, leads	ℓ/hr	16.5
Shield temperature	K	80
Shield coolant		He gas

Table A-16 Sheet 4
Expanded Data Summary

Identification: ETF6-P2 6 T MHD Magnet

Cost Estimate: 1977	k$
Total, wound coil	2782
Superstructure, He vessel	10,784
Cryostat	5489
Accessories	
cryogenic & vacuum equipment	1349
Power supply and discharge equipment	1019
TOTAL, magnet system installed and tested (before des. & anal., proj. mgt., etc.)	21,423 (1977 $)
TOTAL, magnet system installed and tested	33,870 (1984 $)

Table A-17 Sheet 1
Magnet Data Summary
MHD Large Test Facility Magnets (Superconducting)

Identification: ETF-MCA 6 T MHD Magnet
Application: DOE Study (Reference Designs)
Designer: MCA
Date of design: 1977
Status: Reference design only

Magnet type		90° rect. sad. & racetracks
Field, peak-on-axis	T	6
Active length	m	7 (8.0)
Field, start of act. len.	T	6 (4.8)
Field, end of act. len.	T	4 (4.0)
Aperture[a], start of act. len.	m	0.64 sq.
Aperture[a], end of act. len.	m	1.24 sq.
Size parameter VB^2	m^3T^2	(118)
Vac. vessel overall len.	m	13
Vac. vessel O.D.	m	6
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	20
Winding current density	$10^7 A/m^2$	2.39
Ampere turns	$10^6 A$	16.0
Stored energy	MJ	1160
Total weight	tonnes	376
Est. cost, original	k$	16,600
Est. cost, 1984 $	k$	26,400

[a] without warm bore liner

Table A-17 Sheet 2
Expanded Data Summary

Identification: ETF-MCA 6 T MHD Magnet

Magnet Data:		
Type		90^o rect. sad. & racetracks
Peak on-axis field,	T	6.0
Active field length, ℓ_a	m	7.0 (8.0)
Field at start of active length,	T	6.0 (4.8)
Field at end of active length,	T	4.0 (4.0)
Aperture, warm bore inlet, sans liner	m	0.64 sq.
Aperture, start of active length, sans liner	m	0.64 sq.
Aperture, end of active length, sans liner	m	1.24 sq.
Aperture, warm bore exit, sans liner	m	1.24 sq.
Vacuum vessel overall length	m	13
Vacuum vessel outside diameter	m	6
Size parameter, VB^2	m^3T^2	(118)
Conductor materials, supercond./stabilizer		NbTi/Cu
Conductor type		Built-up
Operating current, I_{op}	kA	20
Winding current density ($J\lambda$)	$10^7A/m^2$	2.39
Conductor current density (J) (cond. envel.)	$10^7A/m^2$	4.0
Heat flux, stabilizer	W/cm^2	1.0
Ampere turns	10^6A	16.0
Ampere meters	10^8Am	4.0
Stored energy	MJ	1160
Turns, total		792
Length, conductor, total	km	19.9
Insulation, conductor		
Material		Glass-epoxy
Substructure		
Material		SS 310S
Design stress, bend	MPa	379
He vessel		
Material		SS 310S

Table A-17 Sheet 3
Expanded Data Summary

Identification: ETF-MCA 6 T MHD Magnet

Magnet Data cont		
Superstructure		
Material		SS 310S
Design stress (tens., bend)	MPa	379
Thermal shield		
Material		Al 5083
Vacuum jacket		
Material		AL 5083
Weights:		
Conductor	tonnes	83
Insulation, substructure, superstructure, He vessel	tonnes	221
Total cold mass	tonnes	304
Thermal shield, vecuum vessel	tonnes	72
Total magnet weight	tonnes	376
Cryogenic data:		
Operating temperature, winding	K	4.5
Operating pressure winding (or ICCS)	atm.	1.3
Heat leak to LHe region:		
rad. & cond.	W	39
leads, LHe boil-off	ℓ/hr	60
Shield temperature	K	102
Shield coolant		He gas

Table A-17 Sheet 4
Expanded Data Summary

Identification: ETF-MCA 6 T MHD Magnet

<u>Cost Estimate</u>: 1977	k$
Magnet	
Conductor	4980
Superstructure	2190
Vacuum vessel, thermal shield	520
manufacturing, engineering, tooling	1080
Pack and ship to site and misc.	1320
Project management, Q.A., etc. (admin. exp.)	3000
Design and analysis, manufacturing labor	2900
Total	15,990
TOTAL, rounded, 1977 $	16,000
TOTAL, rounded, 1984 $	26,000

Table A-18
Magnet Data Summary
MHD Large Test Facility Magnets (Superconducting)

Identification: ETF 6 T GE/GD MHD Magnet
Application: DOE Study
Designer: GE/GD
Date of design: 1977
Status: Prelim. design only

Magnet type		Circ. sad.
Field, peak-on-axis	T	6
Active length	m	7 (7.8)
Field, start of act. len.	T	6 (4.8)
Field, end of act. len.	T	4 (3.6)
Aperture[a], start of act. len.	m	0.9
Aperture[a], end of act. len.	m	1.75
Size parameter VB^2	m^3T^2	(180)
Vac. vessel overall len.	m	11.5
Vac. vessel O.D.	m	6.6
Conductor type		built-up
Conductor material		NbTi/Cu
Design current	kA	9
Winding current density	$10^7 A/m^2$	1.5
Ampere turns	$10^6 A$	19.2
Stored energy	MJ	820
Total weight	tonnes	437
Est. cost, original	k$	42,080
Est. cost, 1984 $	k$	67,000

a without warm bore liner

Table A-19 Sheet 1
Magnet Data Summary
MHD Large Test Facility Magnets (Superconducting)

Identification: ETF 6 T Westinghouse MHD Magnet
Application: DOE Study
Designer: Westinghouse
Date of design: 1977
Status: Prelim. design only

Magnet type		Circ. sad.
Field, peak-on-axis	T	6
Active length	m	9 (12)
Field, start of act. len.	T	6 (4.8)
Field, end of act. len.	T	5 (3.6)
Aperture[a], start of act. len.	m	2.6 dia.
Aperture[a], end of act. len.	m	2.6 dia.
Size parameter VB^2	m^3T^2	1719
Vac. vessel overall len.	m	13.5
Vac. vessel O.D.	m	6.6
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	10
Winding current density	$10^7 A/m^2$	2.0
Ampere turns	$10^6 A$	35.8
Stored energy	MJ	3400
Total weight	tonnes	380[b]
Est. cost, original	k$	30,440
Est. cost, 1984 $	k$	48,340

a without warm bore liner
b design questionable; inadequate structure

Table A-19 Sheet 2
Expanded Data Summary

Identification: ETF 6 T Westinghouse MHD Magnet

Magnet Materials:	
Superstructure	Al. alloy
Helium vessel	St. steel
Thermal shield	Cu
Vacuum vessel	Al. alloy

Cost Estimate:	k$
Conductor	7360
Superstructure	938[a]
Cryostat	2802
Magnet/cryostat assembly	14,540
On-site assembly	4800
Total 1977 $	30,440
Total 1984 $	48,340

a MIT design review showed superstructure inadequate, Superstructure cost shown is unrealistically low.

Table A-20 Sheet 1
Magnet Data Summary
MHD Large Test Facility Magnets (Superconducting)

Identification: ETF 6 T AVCO MHD Magnet
Application: Proposal
Designer: AVCO
Date of design: 1978
Status: Proposal design only

Magnet type		45° rect. sad.
Field, peak-on-axis	T	6
Active length	m	9
Field, start of act. len.	T	5.3
Field, end of act. len.	T	3
Aperture[a], start of act. len.	m	2.0 sq.
Aperture[a], end of act. len.	m	2.6 sq.
Size parameter VB^2	m^3T^2	729
Vac. vessel overall len.	m	14.9
Vac. vessel O.D.	m	10.2×10.5
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	13.1
Winding current density	$10^7 A/m^2$	1.44
Ampere turns	$10^6 A$	26.6
Stored energy	MJ	1888
Total weight	tonnes	1429
Est. cost, original	k$	21,094
Est. cost, 1984 $	k$	31,000

a without warm bore liner

Table A-20 Sheet 2
Expanded Data Summary

Identification: ETF 6 T AVCO MHD Magnet

Magnet Data:		
Peak on-axis field,	T	6.0
Active field length, ℓ_a	m	9.0
On-axis field, start of active length,	T	5.3 (4)
On-axis field, end of active length,	T	3.0 (4)
Peak field in winding	T	7.25
Ratio of peak field on axis to peak field in winding		1.21
Warm Bore:		
Aperture, bore inlet	m	1.5×1.5
Aperture, start of active length	m	1.5×1.5
Aperture, end of active length	m	2.28×2.28
Active volume	m^3	33
Winding:		
Inside height and width, inlet end	m	2.0 sq.
Inside height and width, plane of peak field	m	2.1 sq.
Inside height and width, exit end	m	2.6 sq.
Overall length (over ends)	m	13.1
Build, inlet end	m	1.6
Overall Magnet Dimensions:		
Inlet end	m	10.2×10.5
Outlet end	m	10.2×10.5
Overall length	m	14.9
Magnet Size Factor, VB^2	m^3T^2	729
Conductor:		
Conductor material		NbTi/Cu
Average current density ($J\lambda$)	$10^7 A/m^2$	1.44
Conductor current density	$10^7 A/m^2$	3.61
Copper to superconductor ratio		12
Average winding packing factor		0.4
Ampere turns	$10^6 A$	26.6
Number of turns (N)		2030
Operating current (I)	A	13,100
Ampere meters	$10^8 Am$	8.8
Conductor volume	m^3	23.1
Conductor cross section dimensions (overall envelope)	cm	0.33×0.11

Table A-20 Sheet 3
Expanded Data Summary

Identification: ETF 6 T AVCO MHD Magnet

Cooling Environment:		
Stabilizer heat flux	W/cm^2	0.4
Ratio, helium volume in passages to conductor volume		0.25
Electrical:		
Inductance	H	22
Stored energy	MJ	1888
Weights:		
Conductor	tonnes	215
Winding substructure (incl. insulation)	tonnes	215
Force containment structure	tonnes	309
Helium vessel	tonnes	330
Total cold mass	tonnes	1069
Cold mass supports	tonnes	20
Radiation shield (incl. superinsulation)	tonnes	13
Vacuum vessel	tonnes	327
TOTAL MAGNET	tonnes	1429
Cryogenic:		
Radiation heat load and conductive heat load to helium	W	40
Helium requirement for current leads	ℓ/hr	39
Total volume liquid helium in magnet (operating)	ℓ	20,000
Radiation heat load and conductive heat load to shield	W	3500
External helium storage		
Liquid	ℓ	28,000
Materials of Construction:		
Winding substructure		SS 310
Helium vessel		SS 310
Force containment structure		Al. 2021-T8151
Cold mass supports		SS
Radiation shields		SS
Vacuum vessel		SS
Maximum Design Stress:		
Force containment structure		
Bending	MPa	317

Table A-20 Sheet 4
Expanded Data Summary

Identification: ETF 6 T AVCO MHD Magnet

Cost Estimate: 1978	k$
Design and analysis	902
Tooling	74
Conductor	3133
Winding substructure	953
Electrical insulation	41
Coil winding	167
Force containment structure	1164
Helium vessel	3640
Radiation shiled and superinsulation	189
Vacuum vessel	3880
Cold mass support	73
Magnet/cryostat assembly	91
Refrigerator/liquefier system	955
Installation and control	141
Power supply and dump	240
Pack and ship	174
Install and test	135
Other vacuum system and misc.	180
Total Construction	15,210
Total direct costs	16,112
Indirect costs	114
Contingencies	4868
TOTAL 1978 $	21,094
TOTAL 1984 $	31,000

Table A-21 Sheet 1
Magnet Data Summary
MHD Large Test Facility Magnets (Superconducting)

Identification: ETF 6 T MIT MHD Magnet
Application: DOE/NASA Conceptual Design 200 MWe P.P.
Designer: MIT
Date of design: 1980
Status: Conceptual design only

Plant power output	MWe	202
Channel power output	MWe	87
Magnet type		60° rect. sad.
Field, peak-on-axis	T	6
Active length	m	12.1 (11.7)
Field, start of act. len.	T	4.0 (4.8)
Field, end of act. len.	T	3.5 (3.6)
Aperture[a], start of act. len.	m	1.53×1.93 (1.53 sq.)
Aperture[a], end of act. len.	m	2.19×2.82
Size parameter VB^2	m^3T^2	(986)
Vac. vessel overall len.	m	16.6
Vac. vessel O.D.	m	8.4
Conductor type		cable
Conductor material		NbTi/Cu
Design current	kA	24.4
Winding current density	$10^7 A/m^2$	1.42
Ampere turns	$10^6 A$	27.9
Stored energy	MJ	2900
Total weight	tonnes	909
Est. cost, original	k$	55,578
Est. cost, 1984 $	k$	68,600

a without warm bore liner

Table A-21 Sheet 2
Expanded Data Summary

Identification: ETF 6 T MIT MHD Magnet

Plant net power output	MWe	202
Channel Data:		
Power output, gross	MWe	87
Preheat temperature	F	1100
Oxygen enrichment	%	30
Thermal power input	MWt	532
Mass flow	kg/sec	133
Mach no.		0.9
Peak-on-axis field, B	T	6.0
Inlet field	T	4.0
Exit field	T	3.5
Channel length (channel adj. len.)	m	12.1 (11.7)
Channel inlet dimensions	m	0.535 sq.
Channel exit dimensions	m	1.6 sq.
Volume (nominal - assumes straight sides)	m^3	(14.43)
Power density	MWe/m^3	(6)
Magnet Data:		
Type		60° rect. sad.
Iron pole and yoke (yes, no)		no
Warm bore liner (yes, no)		yes
Magnetic field:		
Direction		hor.
Peak-on-axis field	T	6.0
Active field length, ℓ_a	m	12.1 (11.7)
Field at start of active length, B_i (adj.)	T	4.0 (4.8)
Field at end of active length, B_e (adj.)	T	3.5 (3.6)
Field uniformity at end of active length	%	+2 -2
Maximum field in winding	T	7.6
Aperture, start of active length, inside liner	m	1.4×1.8
Aperture, end of active length, inside liner	m	2.06×2.69
Thickness of warm bore liner, incl. clear	m	0.065
Aperture, warm bore inlet, sans liner	m	1.53×1.93 (1.53 sq.)
Aperture, start of active length, sans liner	m	1.53× 1.93
Aperture, end of active length, sans liner	m	2.19× 2.82
Aperture, warm bore exit, sans liner	m	2.32× 2.95
Length of warm bore	m	15.2
Distance, bore inlet to start of active length	m	1.07

Table A-21 Sheet 3
Expanded Data Summary

Identification: ETF 6 T MIT MHD Magnet

Magnet Data cont		
Gap (winding to inside surface of warm bore)	m	0.34
Vacuum vessel overall length	m	16.6
Vacuum vessel outside diameter	m	8.4
Warm bore volume, sans liner	m^3	(52.25)
Size parameter, VB^2	m^3T^2	(986)
Channel volume utilization, F_u		(0.28)
Conductor materials, supercond./stabilizer		NbTi/Cu
Winding build, inlet end, b	m	0.952
Winding half depth or half arc, d	m	1.033
Winding quadrant area, a	m^2	0.983
No. of winding modules (or layers) per half		26
Conductor type		Cable
Conductor dimensions	cm	2.54 dia.
Operating current, I_{op}	kA	24.4
I_{op}/I_{crit}		0.85
No. of grades of conductor		2
Winding current density ($J\lambda$)	$10^7 A/m^2$	1.42
Conductor current density (J) (cond. envel.)	$10^7 A/m^2$	4.8
Stabilizer current density	$10^7 A/m^2$	9.8
Superconductor current density (oper.)	$10^7 A/m^2$	72.2
Stabilizer to superconductor ratio		6.0
LHe to conductor ratio (vol.)		1.1
Heat flux, stabilizer (100% surf. cool.)	W/cm^2	0.145
Ampere turns	$10^6 A$	27.9
Ampere meters	$10^8 Am$	11.15
Inductance	H	9.7
Stored energy	MJ	2900
Turns, total		1144
Length, mean turn	m	39.95
Length, conductor, total	km	45.7
Packing factor, λ		0.29
Packing factor, stabilizer in cond. envel., λ_{ev}		0.49

Table A-21 Sheet 4
Expanded Data Summary

Identification: ETF 6 T MIT MHD Magnet

Magnet Data cont		
Substructure		
Material		GRP
Design stress, compressive	MPa	95
He vessel		
Material		SS 316 LN
Design pressure	atm	3
Design stress	MPa	414
Superstructure		
Material		SS 316 LN
Design stress	MPa	414
Thermal shield		
Material		Al 6061 T6
Cold mass supports		
Material		SS + G10
Design stress	MPa	100
Vacuum jacket		
Material		SS 304L
Weights:		
Conductor	tonnes	102
Substructure	tonnes	90
Superstructure	tonnes	273
He vessel	tonnes	227
Total cold mass	tonnes	692
Cold mass supports	tonnes	9
Thermal shield	tonnes	30
Vacuum vessel	tonnes	157
Miscellaneous	tonnes	21
Total magnet weight	tonnes	909
Cryogenic data:		
Operating temperature, winding	K	4.5
Heat leak to LHe region:		
Rad. and cond.	W	65
Leads, LHe boil-off	ℓ/hr	75
Shield temperature	K	80

Table A-21 Sheet 5
Expanded Data Summary

Identification: ETF 6 T MIT MHD Magnet

Magnet Data cont		
Heat leak to shield, rad. and cond.	W	2500
Shield coolant		LN_2
Refrigerator capacity, rated, 4.5 K (666 w equiv.)	W	250 W and 125 ℓ/hr
Cooldown time	hr	<672
Weight	tonnes	170
Power supply and dump data:		
Rated power (max.)	kW	2630
Rated voltage, power supply	V	108
Minimum charge time	min	45
Resistance, emergency dump resistor	Ω	0.41 (main)
Discharge time constant (via resistor)	sec	<180
Maximum discharge voltage	kV	10
Winding temp. rise, all energy into conductor	K	~200
Weight	tonnes	12
Warm bore liner:		
Material		SS + GRP
Weight	tonnes	14

Table A-21 Sheet 6
Expanded Data Summary

Identification: ETF 6 T MIT MHD Magnet

Cost estimate 1980	Weight tonnes	Cost Mag. only k$	Cost Mag. & Acc. k$	Cost Total Sy k$
Magnet:				
Conductor	102	6164		
Conductor - AmT	(6.69×10^9)			
Insulation & other				
Piping & instr.		429		
Substructure	90	849		
Coil fabrication (winding)		1479		
Total, coil & substr.		8921		
Helium vessel	227	3729		
Assem. coil & helium vessel		(in 4)		
Total, coil & helium vessel	419	12650		
Superstructure	273	4180		
Assem., coil & coil ves./superstr.		2600		
Total, cold mass	692	19430		
Cold mass supports	(in 13)	495		
Thermal shield	39	1210		
Vacuum vessel	178	2420		
Other (iron frame, etc.)				
Instruments, controls, piping		(incl. above)		
Total, cont. items	217	4125		
Shop assem. & misc.				
Total, magnet comp. & shop	909	23555		
Mfg. eng.		(incl. above)		
Tooling		1650		
Total, mag. fob factory		25205		
Pack & ship to site		619		
Mag. on-site assem. & install		3368		
Mag. shakedown test		380		
Total, mag. sans access.		29572	29572	29572

1 Cost, total sys. = cost magnet, accessories, roll-aside sys.

Table A-21 Sheet 7
Expanded Data Summary

Identification: ETF 6 T MIT MHD Magnet

Cost estimate	Weight tonnes	Cost Mag. only k$	Cost Mag. & Acc. k$	Cost Total Sys.[1] k$
Accessories:				
Cryo. & vac. equip.			1400	1400
Power supply & discharge equip.			900	900
Warm bore liner			494	495
Instr. & controls			incl.	incl.
Other: Roll-aside sys.				1095
Total acc.			2795	3890
Pack & ship access. to site			82	114
Acc. on-site install			550	830
Other				
Total access., etc.			3427	4834
Grand total, before proj. costs		29572	32999	34406
Project:				
Program mgt., Q.A., etc.		5287	5977	6237
Design & analysis		(included	above)	
Supporting development		(assume	separately	funded)
Total, incl. pr. mgt., etc.		34859	38976	40643
G & A		(included	above)	
Total, incl. G & A		34859	38976	40643
Fee (prime contr.)		(included	above)	
Total, incl. G & A and fee		34859	38976	40643
Site special costs		3765	4209	4348
Total, incl. s.s.c.		38624	43185	44991
Contingency allowance		11587	12393	12624
Total, incl. conting. allow. 1980 $		50211	55578	57615
Total, incl. conting. allow. 1984 $		62262	68600	71443
Unit costs: 1984 $				
Total cost/wt. $/kg		68.49	75.47	78.60
Total cost /st. energy $/kJ		21.47	23.66	24.64

Source of technical data:

Final Report, Conceptual Design of S.C. Magnet for MHD ETF 200 MWe Power Plant, MIT Nov. 1981, FBNML Report No. NAS-E-2

Source of cost data:

As above, supplemented by MIT notes

Table A-22 Sheet 1
Magnet Data Summary
MHD Large Test Facility Magnets (Superconducting)

Identification: ETF 4 T MIT MHD Magnet
Application: DOE/NASA Conceptual Design 200 MWe PP
Designer: MIT
Date of design: 1981
Status: Conceptual design only

Magnet type		60° rect. sad.
Field, peak-on-axis	T	4
Active length	m	12.1 (11.7)
Field, start of act. len.	T	2.67 (3.2)
Field, end of act. len.	T	2.33 (2.4)
Aperture[a], start of act. len.	m	1.53×1.92 (1.53 sq.)
Aperture[a], end of act. len.	m	2.19×2.82
Size parameter VB^2	m^3T^2	(438)
Vac. vessel overall len.	m	16.6
Vac. vessel O.D.	m	7.9
Conductor type		cable
Conductor material		NbTi/Cu
Design current	kA	25
Winding current density	$10^7 A/m^2$	1.4
Ampere turns	$10^6 A$	18
Stored energy	MJ	1300
Total weight	tonnes	568
Est. cost, original	k$	47,000
Est. cost, 1984 $	k$	51,000

a without warm bore liner

Table A-22 Sheet 2
Expanded Data Summary

Identification: ETF 4 T MIT MHD Magnet

Magnet Data:		
Type		60° rect. sad.
Warm bore liner (yes, no)		yes
Magnetic field:		
Direction		hor.
Peak-on-axis field	T	4.0
Active field length, ℓ_a (adj.)	m	12.1 (11.7)
Field at start of active length, B_i (adj.)	T	2.67 (3.2)
Field at end of active length, B_e (adj.)	T	2.33 (2.4)
Maximum field in winding	T	5.3
Aperture, start of active length, inside liner	m	1.4×1.8
Aperture, end of active length, inside liner	m	2.06×2.69
Thickness of warm bore liner, incl. clear	m	0.065
Aperture, warm bore inlet, sans liner	m	1.53×1.92
Aperture, start of active length, sans liner	m	1.53× 1.92
Aperture, end of active length, sans liner	m	2.19× 2.82
Aperture, warm bore exit, sans liner	m	2.32× 2.95
Length of warm bore	m	15.2
Distance, bore inlet to start of active length	m	1.07
Gap (winding to inside surface of warm bore)	m	0.34
Vacuum vessel overall length	m	16.6
Vacuum vessel outside diameter	m	7.9
Size parameter, VB^2	m^3T^2	(438)

Table A-22 Sheet 3
Expanded Data Summary

Identification: ETF 4 T MIT MHD Magnet

Magnet Data cont		
Conductor materials, supercond./stabilizer		NbTi/Cu
Winding build, inlet end, b	m	0.63
Winding half depth or half arc, d	m	1.03
Winding quadrant area, a	m^2	0.65
Conductor type		Cable
Conductor dimensions	cm	2.54 dia.
Operating current, I_{op}	kA	25
Winding current density ($J\lambda$)	$10^7 A/m^2$	1.4
Superconductor current density (oper.)	$10^7 A/m^2$	116
Stabilizer to superconductor ratio		12
LHe to conductor ratio (vol.)		1.1
Ampere turns	$10^6 A$	18
Ampere meters	$10^8 Am$	7
Inductance	h	4.2
Stored energy	MJ	1300
Turns, total		720
Length, mean turn	m	39.38
Length, conductor, total	km	28,353
Packing factor, λ		0.29
Substructure		
Material		GRP
He vessel		
Material		SS 316 LN
Design pressure	atm	3

Table A-22 Sheet 4
Expanded Data Summary

Identification: ETF 4 T MIT MHD Magnet

Magnet Data cont		
Superstructure		
Material		SS 316 LN
Thermal shield		
Material		Al 6061 T6
Cold mass supports		
Material		SS + G10
Vacuum jacket		
Material		SS 304L
Weights:		
Conductor	tonnes	68
Substructure	tonnes	60
Superstructure and He vessel	tonnes	254
Total cold mass	tonnes	382
Thermal shield, cold mass supports	tonnes	27
Vacuum vessel	tonnes	150
Miscellaneous	tonnes	9
Total magnet weight	tonnes	568
Cryogenic data:		
Operating temperature, winding	K	4.5
Operating pressure, winding	atm	1.2
Heat leak to LHe region:		
Rad. and cond.	W	170
Leads, LHe boil-off	ℓ/hr	75
Shield temperature	K	80
Shield coolant		LN_2
Power supply and dump data:		
Rated power (max.)	kW	1125
Rated voltage, power supply	V	45
Minimum charge time	min	45
Resistance, emergency dump resistor (initial)	Ω	0.17
Discharge time constant (via resistor)	sec	180
Maximum discharge voltage	kV	4.3

Table A-23 Sheet 1
Magnet Data Summary
MHD Large Test Facility Magnets (Superconducting)

Identification: Retrofit Size 4.5 T MHD Magnet
Application: PETC Study Development of ICCS
Designer: MIT
Date of design: 1984 Rev. 1986
Status: Conceptual design only

Channel power output	MWe	35 to 40
Magnet type		Rect. sad., ICCS Wind.
Field, peak-on-axis	T	4.5
Active length	m	9.0
Field, start of act. len.	T	3.0 (3.6)
Field, end of act. len.	T	3.0 (2.7)
Aperture[a], start of act. len.	m	0.8×1.0
Aperture[a], end of act. len.	m	1.3×1.6
Size parameter VB^2	m^3T^2	(141)
Vac. vessel overall len.	m	12.3
Vac. vessel O.D.	m	5.0
Conductor type		ICCS
Conductor material		NbTi/Cu
Design current	kA	18
Winding current density	$10^7 A/m^2$	3.2
Ampere turns	$10^6 A$	12
Stored energy	MJ	487
Total weight	tonnes	320
Est. cost, original	k$	41,000
Est. cost, 1984 $	k$	41,000

a inside warm bore liner

Table A-23 Sheet 2
Expanded Data Summary

Identification: Retrofit Size 4.5 T MHD Magnet

Magnet Data:		
Type		60° Rect. sad. (ICCS wind.)
Warm bore liner		yes
Peak on-axis field, B	T	4.5
Active field length, L_a	m	9.0
Field at start of active length	T	3.0 (3.6)
Field at end of active length	T	3.0 (2.7)
Maximum field in winding	T	6.9
Aperture, start of active length, inside liner	m	0.8×1.0
Aperture, end of active length, inside liner	m	1.3×1.6
Thickness of warm bore liner	m	0.04
Aperture, warm bore inlet, sans liner	m	0.88×1.08
Aperture, start of active length, sans liner	m	0.88×1.08
Aperture, end of active length, sans liner	m	1.38×1.68
Gap (winding to inside surface of warm bore)	m	0.31
Vacuum vessel overall length	m	12.3
Vacuum vessel outside diameter	m	5
Size parameter, VB^2	m^3T^2	(148)

Table A-23 Sheet 3
Expanded Data Summary

Identification: Retrofit Size 4.5 T MHD Magnet

Magnet Data cont		
Conductor materials, supercond./stabilizer		NbTi/Cu
Winding build, inlet end, b	m	0.316
Winding half depth	m	0.61
Conductor type		ICCS
Conductor dimensions	cm	2.08 sq.
Operating current, I_{op}	kA	18
Winding current density ($J\lambda$)	$10^7 A/m^2$	3.2
Ampere turns	$10^6 A$	12
Ampere meters	$10^8 Am$	3.24
Stored energy	MJ	487
Turns, total		672
Length, mean turn	m	26.8
Length, conductor, total	km	18
Superstructure		
Material		304 LN
Thermal shield		
Material		Al alloy
Vacuum jacket		
Material		304L
Weights:		
Conductor	tonnes	47
Insulation	tonnes	5
Superstructure	tonnes	110
Guard vac. shell	tonnes	32
Misc.	tonnes	11
Total cold mass	tonnes	205
Thermal shield	tonnes	15
Vacuum vessel	tonnes	100
Total magnet weight	tonnes	320
Cryogenic data:		
Operating pressure, ICCS	atm	2.5

Table A-23 Sheet 4
Expanded Data Summary

Identification: Retrofit Size 4.5 T MHD Magnet

Cost Estimate:	k$
Conductor	3645
Insulation	100
Coil fabrication	705
Guard vac. shell	800
Superstructure	2750
Coil, vessel, structure assembly	1845
Other	275
Cold mass total	10,120
Thermal shield	1125
Vacuum vessel	2000
Total, all components	13,245
Manufacturing, engineering, tooling	1600
Pack and ship	320
Total, components on site	15,165
Final assembly, install on site	4800
Shakedown test	incl. above
Total, magnet installed and tested	19,965
Accessories, incl. installation	3990
Total, magnet and accessories installed	23,955
Other costs	2000
Total, magnet system installed	25,955
Design and analysis, manufacturing plan	3110
Program management	2600
Total before contingency allowance	31,665
Contingency allowance	9500
TOTAL, including contingency	41,165
(does not incl. conceptual design and prelim. develop.)	

Note: All costs are 1984 k$

Table A-24
Magnet Data Summary
MHD Component Test Facility Magnets (Superconducting)

Identification: 12" Model Saddle Coil, 4 T, AVCO MHD Magnet
Application: Experimental Test Magnet, AEP/AVCO MHD Program
Designer: AVCO
Date of design: 1965
Status: Tested to 4 T, 1966

Magnet type		Circ. sad.
Field, peak-on-axis	T	4
Active length	m	1.3
Field, start of act. len.	T	3.8
Field, end of act. len.	T	3.8
Aperture[a], start of act. len.	m	0.3
Aperture[a], end of act. len.	m	0.3
Size parameter VB^2	m^3T^2	0.9
Cold structure, overall length	m	3.12
Cold structure, O.D.	m	1.43
Conductor type		Built-up
Conductor material		NbZr/Cu
Design current	kA	0.785
Winding current density	$10^7 A/m^2$	2.8
Ampere turns	$10^6 A$	3.5
Stored energy	MJ	4.6
Total weight, coil and cold structure	tonnes	7.12
Est. cost, original	k$	800
Est. cost, 1984 $	k$	2000

a Aperture is inside cold structure (no warm bore)

Table A-25
Magnet Data Summary
MHD Component Test Facility Magnets (Superconducting)

Identification: Toshiba 1 T MHD Magnet
Application: Experimental Test Magnet
Designer: Toshiba Central Research Lab
Date of design: 1968
Status: Built and Tested to 1 T, 1968

Magnet type		Circ. sad.
Field, peak-on-axis	T	1
Active length	m	0.8
Aperture[a], start of act. len.	m	0.2
Stored energy	MJ	0.3
Est. cost, original	k$	not avail.
Est. cost, 1984 $	k$	

a Aperture inside cold structure (no warm bore)

Table A-26
Magnet Data Summary
MHD Component Test Facility Magnets (Superconducting)

Identification: Hitachi 4.5 T MHD Magnet
Application: Experimental Test Magnet
Designer: Hitachi
Date of design: 1968
Status: Built and Tested to 4.7 T in 1969

Magnet type		Circ. sad.
Field, peak-on-axis	T	4.5
Active length	m	0.6
Aperture, start of act. len.	m	0.38
Conductor type		Built-up
Conductor material		NbTiVa/Cu
Stored energy	MJ	4.5
Est. cost, original	k$	not avail.
Est. cost, 1984 $	k$	

Table A-27
Magnet Data Summary
MHD Component Test Facility Magnets (Superconducting)

Identification: Gardner/Jülich 4 T MHD Magnet
Application: Test Magnet for Julich KFA
Designer: Gardner Cryogenics
Date of design: 1969
Status: Built and Tested to 3.5 T in 1970

Magnet type		Racetrack
Field, peak-on-axis	T	4
Active length	m	1.4
Maximum field at winding	T	6
Aperture[a], start of act. len.	m	0.22×0.44
Aperture[a], end of act. len.	m	0.22×0.44
Size parameter VB^2	m^3T^2	2.2
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	0.95
Total weight	tonnes	2.7 approx.
Est. cost, original	k$	not avail.
Est. cost, 1984 $	k$	

[a] without warm bore liner

Table A-28
Magnet Data Summary
MHD Component Test Facility Magnets (Superconducting)

Identification: ETL 5 T MHD Magnet
Application: Mk. V MHD Test Facility, Japan
Designer: Hitachi
Date of design: 1971
Status: Built and tested

Magnet type		Racetrack, vert.
Field, peak-on-axis	T	5
Active length	m	1.2
Field, start of act. len.	T	4.5
Field, end of act. len.	T	4.5
Maximum field at winding	T	7.5
Aperture[a], start of act. len.	m	0.39×1.3
Aperture[a], end of act. len.	m	0.39×1.3
Size parameter VB^2	m^3T^2	4.6
Vac. vessel overall height	m	4.33
Vac. vessel O.D.	m	3.1
Conductor type		Built-up
Conductor material		NbTiZr
Design current	kA	1.28
Winding current density	$10^7 A/m^2$	2.7
Stored energy	MJ	70
Est. cost, original	k$	not avail.
Est. cost, 1984 $	k$	

a without warm bore liner

Table A-29
Magnet Data Summary
MHD Component Test Facility Magnets (Superconducting)

Identification: Stanford 6 T MHD Magnet (Sol. Pair)
Application: Experimental Test Magnet
Designer: Stanford
Date of design: 1971
Status: Built and Tested to 5.4 T (air core) Feb. 1972

Magnet type		Sol. pair with iron yoke
Field, peak-on-axis	T	6 with iron
Active length	m	0.2
Aperture[a], start of act. len.	m	0.10×0.05
Aperture[a], end of act. len.	m	0.10×0.05
Coil I.D.	m	0.18
Coil height	m	0.66
Est. cost, original	k$	not avail.
Est. cost, 1984 $	k$	

a Warm aperture, no liner

Table A-30 Sheet 1
Magnet Data Summary
MHD Component Test Facility Magnets (Superconducting)

Identification: USSCMS 5 T MHD Magnet (U25 Bypass)
Application: MHD Channel Testing in USSR
Designer/Builder: ANL
Date of design: 1976
Status: Built and Tested to 5 T

Magnet type		Circ. sad.
Field, peak-on-axis	T	5
Active length	m	2.56
Field, start of act. len.	T	4.0
Field, end of act. len.	T	3.2
Aperture[a], start of act. len.	m	0.4
Aperture[a], end of act. len.	m	0.6
Size parameter VB^2	m^3T^2	8
Vac. vessel overall len.	m	4.4
Vac. vessel O.D.	m	2.29
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	0.892
Winding current density	$10^7 A/m^2$	2.82
Ampere turns	$10^6 A$	6.7
Stored energy	MJ	34.2
Total weight	tonnes	37.9
Est. cost, original	k$	3900
Est. cost, 1984 $	k$	6590

a without warm bore liner

Table A-30 Sheet 2
Expanded Data Summary

Identification: USSCMS 5 T MHD Magnet

Magnet data:		
Peak-on-axis, B	T	5.0
Active field length, ℓ_a	m	2.56
Distance, bore inlet to start of active length	m	0.72
On-axis field, start of active length	T	4.0
On-axis field, end of active length	T	3.2
Field variation across MHD channel, start of active length	%	< ±5.0
Field variation across MHD channel, plane of peak on-axis field	%	< ±5.0
Field variation across MHD channel, end of active length	%	< ±5.0
Peak field in winding	T	6.0
Ratio of peak field on-axis to peak field in winding		0.83
Warm bore:		
Circular or rectangular		circ.
Aperture, bore inlet (diameter)	m	0.4
Aperture, start of active length (diameter)	m	0.4
Aperture, end of active length (diameter)	m	0.6
Aperture, bore exit (diameter)	m	0.67
Overall length, ℓ_b	m	4.2
Active volume (bore volume in length ℓ_a)	m^3	0.509
Winding overall:		
Diameter, inside winding, start of straight section	m	0.67
Diameter, inside winding, plane of peak on-axis field	m	0.67
Diameter, inside winding, end of straight section	m	0.87
Overall length (over ends)	m	3.76
Build, inlet end	m	0.364
Number of winding modules (substructures) per half		23 layers
Overall Magnet Dimensions:		
Inlet end	m	2.29
Outlet end	m	2.29
Overall length	m	4.4
Magnet Size Factor, VB^2	m^3T^2	8

Table A-30 Sheet 3
Expanded Data Summary

Identification: USSCMS 5 T MHD Magnet

Cooling Environment:		
% conductor surface exposed to coolant	%	8
Stabilizer heat flux, steady state recovery	W/cm^2	0.7
Cooling passage dimensions		
Width	cm	1.0
Height	cm	0.6
Helium volume in cooling passages	ℓ	1600
Ratio, helium volume in passages (local) to conductor volume		1.43
Overall Winding Data:		
Average current density	$10^7 A/m^2$	2.82
Operating current	A	892
Ampere turns, total	$10^6 A$	6.7
Number of turns, total		7560
Ampere meters	$10^8 Am$	0.50
Conductor length, total	m	56,360
Conductor volume, total	m^3	1.12
Stabilizer volume, total	m^3	1.05
Superconductor volume, total	m^3	0.07
Electrical:		
Inductance	H	84.5
Stored energy	MJ	34.2
Dipole moment	$10^6 Am^2$	16
Number of current leads		2
Number of parallel circuits		1
Dump resistor resistance	Ω	0.2
Dump time constant	min.	7
Maximum terminal voltage during dump	V	178
Maximum power supply voltage	V	12
Minimum charge time	min.	153

Table A-30 Sheet 4
Expanded Data Summary

Identification: USSCMS 5 T MHD Magnet

Weights:		
Conductor	tonnes	10.0
Winding substructure	tonnes	2.1
Force containment structure	tonnes	10.1
Total cold mass (not incl. He vessel)	tonnes	22.2
Cold mass supports	tonnes	
Thermal shield (incl. superinsulation)	tonnes	3.0
Vacuum vessel and He vessel	tonnes	12.6
TOTAL MAGNET	tonnes	37.8
Cryogenic:		
Coil operating temperature	K	4.3
Coil container operating pressure	psi	15.7
Radiation shield temperature	K	80
Radiation shield coolant (LN_2 or He gas)		LN_2
Radiation heat load to helium in coil container (calc.)	W	1.3
Conductive heat load to helium in coil container (calc.)	W	1.3
Helium requirement for current leads (calc.)	ℓ/hr	4.2
Liquid helium volume in magnet above winding (operating)	ℓ	25
Total volume liquid helium in magnet (operating)	ℓ	1800
Radiation shield surface area (incl. bore)	m^2	32.7
Radiation heat load to shield	W	21.0
Conductive heat load to shield	W	3.4
Refrigerator/liquefier capacity	ℓ/hr	20-25
External helium storage		
Liquid	ℓ	1500
Gas	$10^6 m^3$ n.t.p.	24
Materials of Construction:		
Winding substructure (fillers)		phenolic lam.
Insulation		mylar & teflon
Helium vessel		SST 316
Force containment structure core tube; banding		SST 316; SST 303
Cold mass supports		glass epoxy
Radiation shield		copper & SST 304
Vacuum vessel		SST 304

Table A-30 Sheet 5
Expanded Data Summary

Identification: USSCMS 5 T MHD Magnet

Design Stress:		Max. Design Stress	Factor of Safety on Yield S.	Factor of Safety on Ult. S.
Force containment structure				
Bending (core tube)	psi	78,000	0.92	1.77
Cold mass supports				
Tension	psi	30,000	3.0	3.0
Pressure rating		**Normal Operating Pressure**	**Design Pressure**	**Test Pressure**
Vacuum vessel	psi	1 atm ext.	18.5 psi int.	none
Helium vessel (coil container)	psi	15.7 psig int.	65 psi int.	50 psig

Table A-30 Sheet 6
Expanded Data Summary

Identification: USSCMS 5 T MHD Magnet

Cost Estimate: 1976	k$
Conductor	255
Substructure	85
Coil fabrication	200
Superstructure	150
Total cold mass	690
Cold mass supports	12
Vacuum vessel, He vessel, thermal shield	400
Cryostat (incl. He vessel)	412
Factory test	50
Final assembly and installation	350
Magnet subtotal	1502
On site assembly and installation	562
Tooling	300
Total, magnet installed and tested	2364
Design and analysis	950
Total, magnet (not incl. accessories)	3314
Accessories	586
TOTAL, including accessories 1976 $	3900
TOTAL, including accessories 1984 $	6590

Table A-31 Sheet 1
Magnet Data Summary
MHD Component Test Facility Magnets (Superconducting)

Identification: Stanford 7.3 T MHD Magnet (Proposal)
Application: MHD Channel Testing
Designer: MIT/GD
Date of design: 1978
Status: Proposal design only

Magnet type		Circ. sad. with iron shield
Field, peak-on-axis	T	7.3 (7.0)
Active length	m	1.5 (2.0)
Field, start of act. len.	T	7.0 (5.6)
Field, end of act. len.	T	7.0 (4.2)
Aperture[a], start of act. len.	m	0.55 dia.
Aperture[a], end of act. len.	m	0.55 dia.
Size parameter VB^2	m^3T^2	(23)
Vac. vessel overall len.	m	4.45
Vac. vessel O.D.	m	3.8
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	5
Winding current density	$10^7 A/m^2$	2.08
Ampere turns	$10^6 A$	11.5
Stored energy	MJ	79
Total weight, magnet	tonnes	101
Total weight, shield	tonnes	500
Est. cost, original	k$	5419 (not incl. shield)
Est. cost, 1984 $	k$	8000

[a] without warm bore liner

Table A-31 Sheet 2
Expanded Data Summary

Identification: Stanford 7.3 T MHD Magnet (Proposal)

Magnet data:		
Peak-on-axis, B	T	7.3 (7.0)
Active field length, ℓ_a	m	1.5 (2.00)
On-axis field, start of active length	T	7.0 (5.6)
On-axis field, end of active length	T	7.0 (4.2)
Peak field in winding	T	8.37
Ratio of peak field on-axis to peak field in winding		1.10
Warm bore:		
Aperture, bore inlet (diameter)	m	0.55
Aperture, start of active length (diameter)	m	0.55
Aperture, end of active length (diameter)	m	0.55
Aperture, bore exit (diameter)	m	0.55
Winding:		
Inside diameter, inlet end	m	0.7
Inside diameter or height and width, exit end	m	0.7
Overall length (over ends)	m	4.45
Build	m	0.465
Number of winding modules (substructures) per half		15
Overall Magnet Dimensions:		
Inlet end, dia.	m	3.8
Outlet end, dia.	m	3.8
Overall length	m	4.45
Magnet Size Factor, VB^2	m^3T^2	(23)
Conductor:		
Conductor material		NbTi/Cu
Average current density ($J\lambda$)	$10^7 A/m^2$	2.08
Conductor current density	$10^7 A/m^2$	7.7
Average winding packing factor		0.27
Ampere turns	$10^6 A$	11.5
Number of turns		2304
Ampere meters	$10^8 Am$	0.9
Conductor volume	m^3	1.26

Table A-31 Sheet 3
Expanded Data Summary

Identification: Stanford 7.3 T MHD Magnet (Proposal)

Cooling Environment:		
% conductor surface exposed to coolant		72
Stabilizer heat flux	W/cm^2	0.7
Cooling passage dimensions		
Width	cm	0.822
Height	cm	0.061
Effective length	cm	2.56
Ratio, helium volume in passages to conductor volume		0.25
Electrical:		
Inductance	H	6.35
Stored energy	MJ	79.4
Dipole moment	10^6Am^2	118
Number of current leads		2
Number of parallel circuits		1
Dump resistor resistance	Ω	0.2
Dump time constant	s	29.6
Maximum terminal voltage during dump	V	1034
Energy released into helium volume during charging, max.	MJ	0.2
Energy released into helium volume during dump	MJ	15.2
Minimum charge time	min	90
Weights		
Conductor and insulation	tonnes	11.27
Winding substructure	tonnes	8.23
Force containment structure	tonnes	27.64
Helium vessel	tonnes	34.10
Total cold mass (incl. He vessel)	tonnes	81.24
Cold mass supports	tonnes	0.025
Radiation shield (incl. superinsulation)	tonnes	1.4
Vacuum vessel	tonnes	13.9
Miscellaneous, stack, support feet	tonnes	3.975
TOTAL MAGNET	tonnes	100.57
Shield, magnetic	tonnes	500.00

Table A-31 Sheet 4
Expanded Data Summary

Identification: Stanford 7.3 T MHD Magnet (Proposal)

Cryogenic:		
Coil operating temperature	K	4.2
Radiation shield temperature	K	77
Radiation heat load to helium	W	2.3
Conductive heat load to helium	W	17.1
Helium requirement for current leads	ℓ/hr	14
Total volume liquid helium in magnet (operating)	ℓ	4900
Radiation heat load to shield	W	122
Conductive heat load to shield	W	56
Estimated cooldown time	days	43
External helium storage		
Gas 18 atm. 60°F	gal.	10,000
Materials of Construction:		
Winding substructure		Al. alloy
Insulation		G10
Helium vessel		Al. alloy
Force containment structure		Al. alloy
Cold mass supports		glass epoxy
Radiation shield		copper & SS
Vacuum vessel		SS
Maximum Design Stress:		
Force containment structure		
Bending	MPa	229
Tension	MPa	12
Cold mass supports		
Tension	MPa	101
Conductor	MPa	58
Electrical insulation (compressive)	MPa	225
Winding substructure	MPa	175
Maximum Pressure Rating:		
Vacuum vessel	atm.	1
Helium vessel	atm.	14

Table A-31 Sheet 5
Expanded Data Summary

Identification: Stanford 7.3 T MHD Magnet (Proposal)

Cost Estimate: 1978	k$
Analysis and design	896
Tooling	70
Conductor	469
Substructure	445
Coil winding	393
Superstructure	355
Cryostat	427
Refrigerator/liquefier	309
Pack and ship	143
Quality assurance	59
Magnetic shield	491
Assemble, install, test	917
	4974
Fee, contingency allowance	445
Total, orig	5419
Total 1984 $	8000

Table A-32 Sheet 1
Magnet Data Summary
MHD Component Test Facility Magnets (Superconducting)

Identification: Stanford 7.3 T MHD Magnet (CASK prototype)
Application: MHD Channel Testing
Designer: GD
Date of design: 1980
Status: Conceptual design only

Magnet type		Mod. circ. sad. (CASK)
Field, peak-on-axis	T	7.3
Active length	m	1.5 (2.1)
Field, start of act. len.	T	7.0 (5.6)
Field, end of act. len.	T	7.0 (4.2)
Aperture[a], start of act. len.	m	0.55 dia.
Aperture[a], end of act. len.	m	0.55 dia.
Size parameter VB^2	m^3T^2	(27)
Vac. vessel overall len.	m	4.83
Vac. vessel O.D.	m	3.15
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	7.36
Winding current density	$10^7 A/m^2$	1.875
Ampere turns	$10^6 A$	12.2
Stored energy	MJ	93.5
Total weight	tonnes	99.9
Est. cost, original	k$	no est.
Est. cost, 1984 $	k$	

a without warm bore liner

Table A-32 Sheet 2
Expanded Data Summary

Identification: Stanford 7.3 T MHD Magnet (CASK prototype)

Magnet data:		
Peak-on-axis, B	T	7.35
Active field length, ℓ_a	m	1.50
Distance, bore inlet to start of active length	m	1.29
On-axis field, start and end of active length	T	7.00
Field variation across MHD channel, start and end of active length, plane of peak on-axis field	%	±2.5
Ratio of peak field on-axis to peak field in winding		0.916
Warm bore:		
Circular or rectangular		Circular
Aperture, bore inlet and exit, start and end of active length	m	0.55 dia.
Overall length	m	4.08
Active volume (bore volume in length ℓ_a)	m^3	0.36
Winding overall:		
Diameter inside winding, start and end of straight section, plane of peak on-axis field	m	0.67
Overall length (over ends)	m	3.44
Build, inlet end	m	0.514
Winding volume	m^3	9.98
Number of winding modules (substructures) per half		36
Overall Magnet Dimensions:		
Inlet end dia.	m	3.15
Outlet end dia.	m	3.15
Overall length	m	4.834
Winding data:		
Peak field in winding	T	8.24
Conductor material		NbTi/Cu
Average current density ($J\lambda$)	$10^7 A/m^2$	1.875
Operating current	kA	7.358
Ampere turns	$10^6 A$	12.2
Number of turns		1658
Ampere meters	$10^6 Am$	87.59
Average winding packing factor		0.258

Table A-32 Sheet 3
Expanded Data Summary

Identification: Stanford 7.3 T MHD Magnet (CASK prototype)

Conductor data:		
Conductor current density	10^7A/m^2	3.49
Superconductor filament current density	10^8A/m^2	5.0
Copper to superconductor ratio		12.43
Conductor volume	m^3	2.51
Conductor length	km	11.905
Conductor cross section dimensions (substrate & insert envelope)	cm	3.35×0.815
Cooling Environment:		
% conductor surface exposed to coolant		67
Stabilizer heat flux	W/cm^2	0.27
Cooling passage dimensions		
Width	cm	0.1524
Height	cm	3.05
Effective length	cm	1
Helium volume in cooling passages	ℓ	874
Ratio, helium volume in passages (local) to conductor volume		0.2
Electrical:		
Inductance	H	3.41
Stored energy	MJ	93.5
Dipole moment	10^7Am^2	1.88
Number of current leads		2
Dump resistor resistance	Ω	0.0223
Dump time constant	min.	2.55
Maximum terminal voltage during dump	V	165
Maximum power supply voltage	V	12
Minimum charge time	min.	50

Table A-32 Sheet 4
Expanded Data Summary

Identification: Stanford 7.3 T MHD Magnet (CASK prototype)

Weights		
Conductor and insulation	tonnes	24.5
Winding substructure	tonnes	27.2
Electrical insulation	tonnes	1.8
Force containment structure	tonnes	21.8
Helium vessel	tonnes	3.6
Total cold mass	tonnes	78.9
Cold mass supports	tonnes	1.8
Radiation shield (incl. superinsulation)	tonnes	0.9
Vacuum vessel	tonnes	17.3
Miscellaneous	tonnes	0.9
Total Magnet	tonnes	99.8
Cryogenic:		
Coil operating temperature	K	4.2
Coil container operating pressure	psi	14.7
Radiation shield temperature	K	80
Radiation shield coolant (LN_2 or He gas)		LN_2
Radiation heat load to helium in coil container	W	6.5
Conductive heat load to helium in coil container	W	22.2
Helium requirement for current leads	ℓ/hr	25.5
Liquid helium volume in magnet above winding (operating)	ℓ	66
Total volume liquid helium in magnet (operating)	ℓ	940
Radiation shield surface area (incl. bore)	m^2	44.6
Radiation heat load to shield	W	126
Conductive heat load to shield	W	84
Refrigerator/liquefier capacity	W	150 (or 45 ℓ/hr @ 4.2 K)
External helim storage		
Liquid	ℓ	946
Gas	m^3 n.t.p.	26.5

Table A-32 Sheet 5
Expanded Data Summary

Identification: Stanford 7.3 T MHD Magnet (CASK prototype)

Materials of Construction:		
Winding substructure		SS 304L
Insulation		G10
Helium vessel		SS 304L
Force containment structure		SS 304L
Cold mass supports		epoxy fiberglass
Radiation shield		Al alloy 6061 T6
Vacuum vessel		SS 304L
Maximum Design Stress:		
Force containment structure		
Tension	MPa	259
Compression	MPa	265
Cold mass supports		
Tension	MPa	44
Conductor, tension	MPa	103
Electrical insulation (compressive)	MPa	97
Winding substructure	MPa	268

Pressure Rating	Normal Operating Pressure	Maximum Operating Pressure	Test Pressure
Vacuum vessel (atm.)	vacuum		
Helium vessel and coil container (atm.)	1.0	2.0	4.3

Table A-33 Sheet 1
Magnet Data Summary
MHD Component Test Facility Magnets (Superconducting)

Identification: CDIF/SM 6 T MHD Magnet
Application: MHD flow train testing at CDIF
Designer: MIT/GE
Date of design: 1979 Date of cost estimate: 1981
Status: Components fabricated, assembly held up

Channel power output	MWe	1 to 5
Magnet type		45° rect. sad.
Field, peak-on-axis	T	6
Active length	m	3 (3.4)
Field, start of act. len.	T	4.8 (4.8)
Field, end of act. len.	T	4.8 (3.6)
Aperture[a], start of act. len.	m	0.85×1.05 (0.85 sq.)
Aperture[a], end of act. len.	m	1.05×1.05
Size parameter VB^2	m^3T^2	(88)
Vac. vessel overall len.	m	6.45
Vac. vessel O.D.	m	4.11
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	6.13
Winding current density	$10^7 A/m^2$	1.83
Ampere turns	$10^6 A$	14.22
Stored energy	MJ	240
Total weight	tonnes	144.3
Est. cost, 1981	k$	22,300
Est. cost, 1984 $	k$	24,300

a without warm bore liner

Table A-33 Sheet 2
Expanded Data Summary

Identification: CDIF/SM 6 T MHD Magnet

Channel data:		
Power output, gross	MWe	1-5
Magnet data:		
Type		45° rect. sad.
Magnetic field:		
Direction		Hor.
Peak on-axis field	T	6.0
Active field length, ℓ_a (ℓ_a adj.)	m	3 (3.4)
Field at start of active length, B_i (adj.)	T	4.8 (4.8)
Field at end of active length, B_e (adj.)	T	4.8 (3.6)
Maximum field in winding	T	6.94
Aperture, start of active length, inside liner	m	0.78×0.98
Aperture, end of active length, inside liner	m	0.98×0.98
Thickness of warm bore liner, incl. clear.	m	0.038
Aperture, warm bore inlet, sans liner	m	0.85×1.05 (0.85 sq.)
Aperture, start of active length, sans liner	m	0.85× 1.05
Aperture, end of active length, sans liner	m	1.05× 1.05
Aperture, warm bore exit, sans liner	m	1.05×1.05
Length of warm bore	m	5.76
Gap (winding to inside surface of warm bore)	m	0.148
Vacuum vessel overall length	m	6.45
Vacuum vessel outside diameter	m	4.11
Size parameter, VB^2	m^3T^2	(88)
Conductor materials, supercond./stabilizer		NbTi/Cu
Winding build, inlet end	m	0.630
Winding half depth	m	0.615
Winding quadrant area	m^2	0.388
Number of winding modules (or layers) per half		40
Conductor type		Built-up
Conductor dimensions	cm	1.28 sq.
Operating current, I_{op}	kA	6.13
I_{op}/I_{crit}		0.77
Number of grades of conductor		1
Winding current density ($J\lambda$)	$10^7 A/m^2$	1.83
Conductor current density (J)	$10^7 A/m^2$	6.23
Superconductor current density (oper.)	$10^7 A/m^2$	64.2

Table A-33 Sheet 3
Expanded Data Summary

Identification: CDIF/SM 6 T MHD Magnet

Magnet Data cont		
Stabilizer to superconductor ratio		11.1
LHe to conductor ratio (vol.)		0.19
Heat flux, stabilizer	W/cm^2	0.4
Ampere turns	10^6A	14.22
Ampere meters	10^8Am	1.89
Inductance	H	12.8
Stored energy	MJ	240
Turns, total		2320
Length, mean turn	m	13.28
Length, conductor, total	km	130.8
Packing factor, λ		0.30
Substructure		
Material		G10
He vessel		
Material		SS 304 LN
Design pressure, max.	atm.	4
Superstructure		
Material		SS 304 LN
Design stress	MPa	379
Thermal shield		
Material		SS 304 LN + Cu
Vacuum jacket		
Material		SS 304
Weights:		
Conductor	tonnes	35.7
Insulation	tonnes	—
Substructure	tonnes	7.9
Superstructure	tonnes	45.7
He vessel	tonnes	24.5
Total cold mass	tonnes	113.8
Cold mass supports	tonnes	incl. below
Thermal shield	tonnes	4.2
Vacuum vessel	tonnes	24.5
Iron frame	tonnes	—
Miscellaneous	tonnes	1.8
Total magnet weight	tonnes	144.3

Table A-33 Sheet 4
Expanded Data Summary

Identification: CDIF/SM 6 T MHD Magnet

Cryogenic data:		
Operating temperature, winding	K	4.5
Heat leak to LHe region:		
Rad. and cond.	W	38.7
Leads, LHe boil-off	ℓ/hr	20.0
Shield temperature	K	77
Shield coolant		LN_2
Refrigerator capacity, rated	ℓ/hr	35
Power supply and dump data:		
Rated voltage, power supply	V	10
Minimum charge time	min	2
Resistance, emergency dump resistor	Ω	0.16
Discharge time constant (via resistor)	sec	60
Maximum discharge voltage	kV	1.0
Warm bore liner:		
Material		SS/GRP

Table A-33 Sheet 5

Expanded Data Summary

Identification: CDIF/SM 6 T MHD Magnet

Cost Estimate 1981	Weight tonnes	Unit Cost $/kg	Cost 1981 k$
Magnet:			
Conductor	35.7	73.36	2619
Insulation			370
Substructure	7.7	132.21	1018
Coil fabrication (winding)	(35.9)	21.23	762
Total, wound coil			
Helium vessel (outer)	24.5	12.78	313
Assem., coil & superstructure	(89.3)	5.15	460
Total, coil			
Superstructure	45.7		601
Assem., coil & coil ves./superstr.			
Total, cold mass	113.8		
Cold mass supports			incl. below
Thermal shield	4.2	234.00	983
Vacuum vessel	24.5	18.69	458
Other	1.8		
Instruments, controls, piping			29
Total, containment items			
QA, V.T.,			1503
Tooling			1019
Assemble magnet at factory	(144.3)	3.64	525
Total magnet assembly/comp. fob factory	144.3		10,660
Accessories:			
Cryogenic & vaccum equipment			600
Power supply & discharge equip.			618
Warm bore liner			347
Total, accessories			1565
Test			401
Pack & ship to site			205

Table A-33 Sheet 6
Expanded Data Summary

Identification: CDIF/SM 6 T MHD Magnet

Cost, cont.	Unit Cost $/kg	Cost 1981 k$
Site:		
Assemble & install magnet & system		186
Special costs, operator training		42
Sys. shakedown test (incl. in install)		
Special costs, support engineering		1054
Total, magnet sys. installed & tested (before proj. mgt., etc.)		14,113
Project:		
Project mgt., GE 1371+MIT 2027		3398
Design and analysis		3366
Supporting development, GE 473+MIT 375		848
Total, project		7612
Special costs (factory shutdown, startup)		96
Total, incl. s.c.		
Overall:		
Total, before markups		21,821
G & A (prime contractor) (2374)		incl. above
Fee (prime contractor)		505
Total (144.3 tonnes)	154.72	22,326
Total, rounded 1981 $		22,300
Total, rounded 1984 $		24,300

Table A-34 Sheet 1
Magnet Data Summary
MHD Component Test Facility Magnets (Superconducting)

Identification: CFFF 6 T MHD Magnet
Application: MHD flow train testing at CFFF (Coal-Fired Flow Facility)
Designer/Builder: ANL
Date of design: 1980
Status: Built and Tested to 6 T

Magnet type		Circ. sad.
Field, peak-on-axis	T	6
Active length	m	3 (3.35)
Field, start of act. len.	T	4.8 (4.8)
Field, end of act. len.	T	4.8 (3.6)
Aperture[a], start of act. len.	m	0.85 (0.80) dia.
Aperture[a], end of act. len.	m	1.00 dia.
Size parameter VB^2	m^3T^2	(61)
Vac. vessel overall len.	m	6.4
Vac. vessel O.D.	m	3.6
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	3.622
Winding current density	$10^7 A/m^2$	2.0
Ampere turns	$10^6 A$	13.7
Stored energy	MJ	216
Total weight	tonnes	172
Est. cost, original	k$	10,370
Est. cost, 1984 $	k$	12,900

a without warm bore liner

Table A-34 Sheet 2
Expanded Data Summary

Identification: CFFF 6 T MHD Magnet

Magnet data:		
Type		
Peak on-axis field	T	6.0
Active field length, ℓ_a	m	3.0 (3.35)
Field at start of active length	T	4.8 (4.8)
Field at end of active length	T	4.8 (3.6)
Field uniformity at end of active length	%	±5%
Maximum field in winding	T	6.9
Aperture, warm bore inlet, sans liner	m	0.80 dia.
Aperture, start of active length, sans liner	m	0.85 dia.
Aperture, end of active length, sans liner	m	1.00 dia.
Aperture, warm bore exit, sans liner	m	1.09 dia.
Length of warm bore	m	5.62
Distance, bore inlet to start of active length	m	1.67
Gap (winding to inside surface of warm bore)	m	0.195
Vacuum vessel overall length	m	6.4
Vacuum vessel outside diameter	m	3.6
Warm bore volume, sans liner	m^3	2.02
Size parameter, VB^2	m^3T^2	(61)
Conductor materials, supercond./stabilizer		NbTi/Cu
Winding build, inlet end, b	m	0.53
Winding quadrant area, a	m^2	0.343
Number of winding modules (or layers) per half		14
Conductor type		Built-up
Conductor dimensions	cm	3.1×0.47
Operating current, I_{op}	kA	3.622
I_{op}/I_{crit}		0.80
Number of grades of conductor		3
Winding current density ($J\lambda$)	$10^7 A/m^2$	2.0
Conductor current density (J) (cond. envel.)	$10^7 A/m^2$	2.63
Stabilizer current density	$10^7 A/m^2$	2.89
Superconductor current density (oper.)	$10^7 A/m^2$	64

Table A-34 Sheet 3
Expanded Data Summary

Identification: CFFF 6 T MHD Magnet

Magnet Data cont		
Stabilizer to superconductor ratio		21
Heat flux, stabilizer	W/cm^2	0.142
Ampere turns	10^6A	13.7
Ampere meters	10^8Am	1.45
Inductance	H	32
Stored energy	MJ	216
Dipole moment	10^8Am	1.8
Turns, total		3728
Length, mean turn	m	10.6
Length, conductor, total	km	39.5
Packing factor, λ		0.76
Packing factor, stabilizer in cond. enevl., λ_{cu}		0.95
Conductor design stress, tens.	MPa	44.8
Insulation, conductor		
Material		Epoxy-glass
Thickness, turn-turn	mm	0.81
Thickness, layer-layer	mm	7.1
Substructure		
Material		Epoxy-glass, micarta
He vessel		
Material		SS 316
Design pressure, max.	atm.	3.33
Normal oper. pressure	atm	1.3
Superstructure		
Material		SS 316, Al 2219 T87
Design stress	MPa	234 (SS)
Thermal shield		
Material		SS 304/Cu
Vacuum jacket		
Material		SS 304

Table A-34 Sheet 4
Expanded Data Summary

Identification: CFFF 6 T MHD Magnet

Weights:		
Conductor	tonnes	45.4
Insulation	tonnes	0.5
Substructure (micarta forms, banding)	tonnes	9.5
Superstructure	tonnes	68.6
He vessel	tonnes	7.1
Total cold mass	tonnes	131.1
Cold mass supports	tonnes	incl. below
Thermal shield	tonnes	2.2
Vacuum vessel	tonnes	17.5
Miscellaneous	tonnes	21.0
Total magnet weight	tonnes	171.8
Cryogenic data:		
Operating temperature, winding	K	4.5
Heat leak to LHe region:		
Rad. and cond.	W	14
Leads, LHe boil-off	ℓ/hr	11
Shield temperature	K	80
Shield coolant		LN_2
Refrigerator capacity, rated	ℓ/hr	50
Cooldown time	days	42
Power supply and dump data:		
Rated power (max.)	kW	100
Rated voltage, power supply	V	20
Minimum charge time	min	288
Resistance, emergency dump resistor	Ω	0.05
Discharge time constant (via resistor)	sec	640
Maximum discharge voltage	kV	200

Table A-34 Sheet 5
Expanded Data Summary

Identification: CFFF 6 T MHD Magnet

Costs:	Weight tonnes	Unit Cost $/kg	Cost 1980 k$
Magnet:			
Conductor	45.4	18.85	856
Insulation	0.5	84.00	42
Substructure (micarta forms, bands)	9.5	51.89	493
Coil fabrication (winding)	(45.4)	9.74	442
Superstructure spool	13.2	40.83	539
Superstructure, girders, etc.	53.4	14.1	753
Assem., coil & coil superstr.			
Cryostat incl. He vessel	47.8	17.07	816
Manufacturing, engineering & tooling			384
Assemble magnet at factory	(171.8)	6.83	1174
Accessories:			
Cryogenic & vaccum equipment (MIT est.)			578
Power supply & discharge equip.			265
Warm bore liner			463
Test, factory			164
Pack & ship to site			225
Site:			
Assemble & install magnet & system			164
Total, magnet sys. installed & tested (before proj. mgt., etc.)			7796
Project:			
Project mgt.			153
Design and analysis			2037
Supporting development			384
Total, 1980 $			10,370
Total, 1984 $			12,900

Source of technical data:

Report, Design, Construction and Performance Test of a 6 T Superconducting Dipole Magnet System for MHD Energy Conversion Research, ANL, June 1984 (Report No. ANL/MHD-84-2)

Table A-35
Magnet Data Summary
MHD Component Test Facility Magnets (Superconducting)

Identification: CDIF 6 T MHD Test Magnet
Application: Laboratory testing at MIT
Designer: MIT/GE
Date of design: 1979
Status: Built and tested

Magnet type		Racetrack
Field, peak-on-axis	T	6
Active length	m	0.8
Field, start of act. len.	T	6
Field, end of act. len.	T	6
Aperture, start of act. len.	m	0.1×0.3^a
Aperture, end of act. len.	m	0.1×0.3^a
Size parameter VB^2	m^3T^2	0.3
Vac. vessel overall len.	m	3.5
Vac. vessel O.D.	m	1.2
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	4.1
Winding current density	$10^7 A/m^2$	3.6
Ampere turns	$10^6 A$	6
Stored energy	MJ	11
Total weight, cold mass	tonnes	3.7
Est. cost, original	k$	no est.
Est. cost, 1984 $	k$	no est.

a Dimension perpendicular to field. Aperture inside cold structure (no warm bore).

Table A-36
Magnet Data Summary
MHD Water-Cooled and Cryogenic Magnets

Identification: Lo Rho Gen. 2 T MHD Magnet (AVCO)
Application: MHD Channel Test Facility at AVCO
Designer: AVCO/MEA
Date of design: 1964
Status: Built and tested to 2 T

Magnet type		Rect. sad. with iron
Field, peak-on-axis	T	2
Active length	m	5.2
Aperture, start of act. len.	m	1.16×1.14
Coil power	MW	3
Conductor type		hollow, square
Conductor material		copper
Stored energy	MJ	24
Est. cost, original[a] (1964)	k$	500
Est. cost, 1984 $	k$	1400

a Including power supply and cooling system

Table A-37
Magnet Data Summary
MHD Water-Cooled and Cryogenic Magnets

Identification: Mk. VI 3 T MHD Magnet (AVCO)
Application: MHD Channel Test Facility at AVCO
Designer: AVCO/MEA
Date of design: 1969
Status: Built and tested to 3 T

Magnet type		Rect. sad. with iron
Field, peak-on-axis	T	3
Active length	m	1.3
Field, start of act. len.	T	3
Field, end of act. len.	T	2.5
Aperture, start of act. len.	m	0.38×0.20
Aperture, end of act. len.	m	0.45×0.40
Size parameter VB^2	m^3T^2	0.97
Conductor type		hollow, water-cooled
Conductor material		copper
Design current	kA	8.4
Voltage	V	393
Ampere turns	10^6A	1.15
Power supply rating	MW	3.3
Cooling water flow	kg/sec	16
Cooling water pressure drop	psi	<200
Coil weight	tonnes	2.3
Iron weight	tonnes	25.0
Total weight	tonnes	27.3
Est. cost, original (coil and iron)	k$	100
Est. cost, 1984 $	k$	260

a without warm bore liner

Table A-38
Magnet Data Summary
MHD Water-Cooled and Cryogenic Magnets

Identification: HPDE 6.7/3.7 MHD Test Magnet (dual mode)
Application: Channel High Performance Demonstration Experiment, AEDC, Tullahoma, TN
Designer: MEA/ARO
Date of design: 1976
Status: Built and tested; structure failed at <5 T

Magnet type		Rect. sad. with iron
Field, peak on-axis, cryogenic mode	T	6.7
Field, peak on-axis, r.t. mode	T	3.7
Active length	m	6.1
Field, start of act. len.	T	5.36
Field, end of act. len.	T	4.02
Aperture[a], start of act. len.	m	0.89[a] × 0.71
Aperture[a], end of act. len.	m	1.40[a] × 1.17
Size parameter VB^2	m^3T^2	138
Iron pole length	m	7.1
Iron frame width, exit	m	4.2
Iron frame height	m	3.25
Conductor type		hollow, square
Conductor material		copper
Design current	kA	17 (7)
Winding current density	$10^7 A/m^2$	2.31 (0.95)
Ampere turns	$10^6 A$	
Coil power	MW	27 (27)
Conductor	tonnes	83.5
Structure	tonnes	24.6
Iron frame and poles	tonnes	500
Total	tonnes	608.1
Est. cost, original	k$	4417
Est. cost, 1984 $	k$	7400

a Dimension perpendicular to field

Table A-39 Sheet 1
Magnet Data Summary
MHD Water-Cooled and Cryogenic Magnets

Identification: AERL-CM 4 T MHD Magnet
Application: MHD Channel Test Facility at AVCO
Designer: MIT
Date of design: 1978
Status: Built and tested to 4 T

Magnet type		Rect. sad. with iron
Field, peak-on-axis	T	4
Active length	m	1.8
Field, start of act. len.	T	3.2
Field, end of act. len.	T	2.4
Aperture, start of act. len.	m	0.44×0.40
Aperture, end of act. len.	m	0.60×0.50
Size parameter VB^2	m^3T^2	5
Power supply rating	MW	6.6
Voltage	V	600
Cooling water flow	kg/sec	44
Coil average temperature	C	58
Conductor type		hollow, water-cooled
Conductor material		Cu
Design current	kA	11
Winding current density	$10^7 A/m^2$	1.06
Ampere turns	$10^6 A$	2.86
Coil weight	tonnes	14
Iron weight	tonnes	54
Total weight, incl. support structure	tonnes	82
Est. cost, original 1979	k$	636
Est. cost, 1984 $	k$	937

Table A-39 Sheet 2
Expanded Data Summary

Identification: AERL-CM 4 T MHD Magnet

Ampere meters	10^8 Am	0.226
Weight:		
Conductor	tonnes	14
Superstructure & miscellaneous	tonnes	14
Iron frame	tonnes	54
Total	tonnes	82
Cost:		
Coil pack (incl. coil fab.)	$	220
Superstruct., iron frame & misc.	$	178
Final assem. & install	$	117
Subtotal	$	515
Pack & ship	$	5
Total, magnet on site	$	520
Project management	$	75
Design and analysis	$	70
Total	$	665

Table A-40
Magnet Data Summary
MHD Water-Cooled and Cryogenic Magnets

Identification: CDIF/CM 3 T MHD Magnet
Application: MHD Flow Train Test Facility at CDIF
Designer: MIT/MCA
Date of design: 1978
Status: Built and tested to 3 T

Magnet type		Rect. sad. with iron
Field, peak-on-axis	T	3
Active length	m	(3.22)
Field, start of act. len.	T	(1.82)
Field, end of act. len.	T	(1.69)
Aperture, start of act. len.	m	0.7×0.4
Aperture, end of act. len.	m	0.7×0.72
Size parameter VB^2	m^3T^2	8
Pole length	m	3.5
Iron frame width	m	2.0
Iron frame height	m	2.6
Conductor type		Hollow, water-cooled
Conductor material		Cu
Design current	kA	8.25
Winding current density	$10^7 A/m^2$	0.69
Ampere turns	$10^6 A$	2.38
Coil power	MW	5.34
Cooling water flow	kg/sec	38
Weight, conductor	tonnes	27
Weight, structure & misc.	tonnes	21
Weight, iron	tonnes	104
Total weight	tonnes	152
Est. cost, original	k$	950
Est. cost, 1984 $	k$	1400

Table A-41
Magnet Data Summary
MHD Airborne Magnets (Superconducting)

Identification: USAF "Brilliant" 5 T MHD Magnet (AIRCO)
Application: Airborne Prototype
Designer: AIRCO
Date of design: 1970
Status: Tested to 3.5 T 1970, 1972

Magnet type		Circ. sad.
Field, peak-on-axis	T	5
Active length	m	0.76
Aperture, start of act. len.	m	0.18 dia.
Aperture, end of act. len.	m	0.18 dia.
Conductor type		Monolith
Conductor material		NbTi/Cu
Design current	kA	0.422
Stored energy	MJ	2
Total weight	tonnes	2
Est. cost, original	k$	250 approx.
Est. cost, 1984 $	k$	630

Table A-42
Magnet Data Summary
MHD Airborne Magnets (Superconducting)

Identification: USAF 5 T MHD Magnet (MCA)
Application: Airborne prototype
Designer: MCA
Date of design: 1970
Status: Coil & struct. built & tested to 3.9 T 1972; cryostat not built

Magnet type		Circ. sad.
Field, peak-on-axis	T	5
Active length	m	0.76
Aperture	m	0.18 dia.
Overall len., wind. & struct.	m	1.47
Envelope dia., wind & struct.	m	0.66
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	0.52
Winding current density	$10^7 A/m^2$	16.6
Stored energy	MJ	0.9
Total weight	tonnes	0.84
Est. cost, original	k$	345
Est. cost, 1984 $	k$	875

Table A-43
Magnet Data Summary
MHD Airborne Magnets (Superconducting)

Identification: USAF 4 T MHD Magnet (Ferranti)
Application: Airborne prototype
Designer: Ferranti-Packard
Date of design: 1971
Status: Partially built, 1972

Magnet type		Circ. sad.
Field, peak-on-axis	T	4
Active length	m	1.0
Aperture	m	0.25 dia.
Overall length. wind. & struct.	m	1.65
Envelope dia., wind. & struct.	m	0.91
Conductor type		Built-up
Conductor material		NbTi
Total weight	tonnes	0.455
Est. cost, original	k$	360
Est. cost, 1984 $	k$	880

Table A-44
Magnet Data Summary
Physics Experiment Magnets (Superconducting)

tification: LRL 1.5 T Balloon Coil (Dipole)
lication: Physics experiment
gner: LRL
e of design: 1967
us: Built and tested to slightly over 1 T

Magnet type		Circ. sad.
Field, central	T	1.5
Dimensions:		
Bore	m	1
Height	m	1.8 approx
Conductor type		Cable
Conductor material		NbZr/Cu

Table A-45
Magnet Data Summary
Physics Experiment Magnets (Superconducting)

Identification: ANL 1.8 T (12 ft.) Bubble Chamber Magnet
Application: H_2 bubble chamber
Designer: ANL
Date of design: 1967
Status: Built and tested to 1.8 T in 1968

Magnet type		Sol. pair with iron
Field, central	T	1.8
Field, maximum	T	1.9
Dimensions:		
Bore	m	3.7
Height	m	3.04
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	2.2
Winding current density	$10^7 A/m^2$	0.775
Stored energy	MJ	80
Weight:	tonnes	
Conductor	tonnes	45.4
Iron	tonnes	1450
Est. cost, original	k$	3000 approx.
Est. cost, 1984 $	k$	8000

Table A-46
Magnet Data Summary
Physics Expariments Magnets (Superconducting)

Identification: Brookhaven 2.8 T Bubble Chamber Magnet
Application: H_2 bubble chamber
Designer: Brookhaven National Laboratory
Date of design: 1970
Status: Built and tested to 2.82 T, 1971

Magnet type		solenoid pair
Field, central	T	2.8
Field, maximum	T	3
Dimensions:		
Bore	m	3.58
Height	m	4.1
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	5.6
Ampere turns	10^6A	5.76
Stored energy	MJ	72
Weight, conductor	tonnes	7.86
Est. cost, original	k$	600
Est. cost, 1984 $	k$	1500

Table A-47
Magnet Data Summary
Physics Experiment Magnets (Superconducting)

Identification: Mitsubishi 7.5 T Solenoid
Application: Physics experiment
Designer: Mitsubishi
Date of design: 1968
Status: Built and tested.

Magnet type		Solenoid (air core)
Field, central	T	7.5
Dimensions:		
Bore	m	0.4 approx.
O.D.	m	0.8
Height	m	1.0 approx.
Conductor type		Built-up
Conductor material		NbTiTa/Cu
Weight, coil and struct.	tonnes	1.6

Table A-48
Magnet Data Summary
Physics Experiment Magnets (Superconducting)

Identification: Stanford 7 T Solenoid Pair (Brechna)
Application: Physics experiment
Designer: Stanford/Brechna
Date of design: 1970
Status: Built and tested to 6.8 T, 1972

Magnet type		Helmholz Pair
Field, central	T	7
Field, maximum	T	0.3
Dimensions, bore	m	0.66 dia.
Stored energy	MJ	4.8

Table A-49
Magnet Data Summary
Physics Experiment Magnets (Superconducting)

Identification: Vanderbilt-Geneva 8.5 T Solenoid
Application: Physics experiment
Designer/Builder: American Magnetics
Date of design: 1970
Status: Built and tested to 8.5 T, 1971

Magnet type		Solenoid
Field, central	T	8.5
Dimensions:		
Bore	m	0.17
Height	m	0.61
Conductor type		Monolith
Conductor material		NbTi./Cu
Winding current density	$10^7 A/m^2$	6.8
Stored energy	MJ	2

Table A-50
Magnet Data Summary
Physics Experiment Magnets (Superconducting)

Identification: NAL 3 T Bubble Chamber Magnet
Application: H_2 bubble chamber
Designer: ANL/NAL
Date of design: 1969
Status: Built and tested to 3 T, 1972

Magnet type		Solenoid pair, air core
Field, central	T	3
Field, maximum	T	5
Dimensions:		
Bore	m	3.7 dia.
Height	m	2.5
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	5
Winding current density	$10^7 A/m^2$	3.0
Stored energy	MJ	375
Cost:		
Total, original	k$	3000
Total, 1984 $	k$	7000

Table A-51
Magnet Data Summary
Physics Experiment Magnets (Superconducting)

Identification: CERN 3.5 T BBC
Application: H_2 bubble chamber
Designer/Builder: CERN
Date of design: 1970
Status: Built and tested to 3.5 T

Magnet type		Solenoid pair, air core
Field, maximum	T	3.5
Dimensions:		
I.D.	m	4.72
Height	m	4.52
O.D.	m	6.02
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	8
Ampere turns	10^6A	20.5
Stored energy	MJ	750
Cost:		
Total, original	k$	2000
Total, 1984 $	k$	5000

Table A-52
Magnet Data Summary
Physics Experiment Magnets (Superconducting)

Identification: Rutherford 7 T Bubble Chamber Magnet
Application: H_2 bubble chamber
Designer: Rutherford Lab. U.K.
Date of design: 1970
Status: Design only

Magnet type		Solenoid with iron
Field, central	T	7
Dimensions:		
Bore	m	2
Height	m	2.4
Conductor material		NbTi/Cu
Winding current density	$10^7 A/m^2$	1.4
Stored energy	MJ	300
Weight:		
Conductor	tonnes	68
Iron	tonnes	927
Total	tonnes	1030
Total, original	k$	4000
Total, 1984 $	k$	10,000

Table A-53
Magnet Data Summary
Fusion Experiment Magnets (Superconducting)

Identification: NASA 5 T Solenoids (4)
Application: Plasma containment experiment
Designer/Builder: AVCO
Date of design: 1967
Status: Close-coupled pair tested to 8.8 T, 1969

Magnet type		Solenoid, air core
Field, central	T	single 5 , pair 8.8
Field, maximum	T	pair 10.3
Dimensions:		
Bore	m	0.5
O.D.	m	1.0
Height	m	0.3
Conductor type		Inner, ribbon; outer, monolith
Conductor material		Inner, Nb_3Sn; outer, NbTi/Cu
Design current	kA	Inner, 0.3; outer, 0.43
Winding current density	$10^7 A/m^2$	Inner, 5.6; outer, 6.8
Stored energy	MJ	pair, 8.5
Weight, total single coil	tonnes	0.45

Table A-54
Magnet Data Summary
Fusion Experiment Magnets (Superconducting)

Identification: LRL 2 T "Baseball" Magnet (Alice)
Application: Plasma containment experiment
Designer: LRL
Date of design: 1970
Status: Built and tested to 73% of design field in 1971

Magnet type		Baseball seam config.
Field, central	T	2
Field, maximum	T	7.5
Dimensions, mean I.D.	m	1.2
Conductor dimensions	cm	0.56 sq.
Conductor material		NbTi/Cu
Design current	kA	2.4
Stored energy	MJ	17
Total weight	tonnes	11.8

Table A-55
Magnet Data Summary
Fusion Experiment Magnets (Superconducting)

Identification: MFTF-B 7.8 T (Yin-Yang) Magnet
Application: Mirror Fusion Test Facility
Designer: LLNL
Date of design: 1983
Status:

Magnet type		Yin-Yang
Field, central	T	7.8
Conductor type		Mono. with Cu wrap
Conductor material		NbTi/Cu
Weight:		
Conductor	tonnes	62.7
Casing	tonnes	264
Cost:		
Conductor	1984 k$	6646
Casing	1984 k$	7920
Coil wind.	1984 k$	5455
Power terms etc.	1984 k$	1003

Table A-56
Magnet Data Summary
Fusion Experiment Magnets (Superconducting)

Identification: LCP/GD 8 T D-Coil
Application: Large Coil Test Facility, DOE
Designer/Builder: GD
Date of design: 1980
Status: Built 1983

Magnet type		D-coil
Field, central	T	8
Dimensions, aperture	m	2.5× 3.5
Conductor type		Built-up
Conductor material		NbTi/Cu
Design current	kA	10.3
Ampere turns	10^6A	6.49

Table A-57
Symbols and Abbreviations

Abbreviations used in the magnet data tables include the following:

Symbols	
AEDC	Arnold Engineering Development Center
AEP	American Electric Power Co.
AERL	Avco Everett Research Laboratories (now Textron, Avco Res. Lab.)
ANL	Argonne National Laboratory
AVCO	Avco Corp. (now AVCO Res. Lab., Div. of Textron Corp.)
AIRCO	AIRCO Corp.
BL	Baseload
CM	Copper Magnet
CSM	Commercial Scale Magnet
CMS	Cold Mass Supports
CDIF	Component Development and Integration Facility
CFFF	Coal Fired Flow Facility
CASK	Name identifying a particular design of winding and structure developed by General Dynamics for MHD magnets
Circ. Sad.	Circular Saddle Configuration
BNL	Brookhaven National Laboratory
CERN	Central European Research Facility
EPP	Emergency Power Plant
ETF	Engineering Test Facility
ETL	Electrical Test Laboratory (Japan)
ECAS	DOE Study of Commercial MHD Power Plants
GD	General Dynamics Corp.
GE	General Electric Co.
HPDE	High Performance Demonstration Experiment
IGT	Institute of Gas Technology
ICCS	Internally Cooled Cabled Superconductor
LCP	Large Coil Program (Fusion)
LLNL	Lawrence Livermore National Laboratory
LRL	Lawrence Radiation Laboratory
MCA	Magnetic Corp. of America
MEA	Magnetic Engineering Assoc.
MFTF	Mirror Fusion Test Facility
SM	Superconducting Magnet
USAF	U.S. Air Force
USSCMS	U.S. Superconducting Magnet System (for U25 bypass)

Table A-57
Symbols and Abbreviations cont.

Abbreviations

r.t.	Room Temperature
PSPEC	DOE Study of Early Commercial MHD Systems (Parametric Study of Prospective Early Commercial ...)
Rect. Sad.	Rectangular Saddle Configuration
Sol.	Solenoid
R.T.	Racetrack Configuration

APPENDIX B

Definition of Magnet Size Parameter, VB^2

In investigating costs of MHD magnets, it is important to determine how magnet system cost varies with magnet size. For example, a curve of magnet cost vs. size based on cost data available for smaller magnets can be extrapolated to indicate the expected costs for larger magnets.

The magnet size parameter, VB^2, is a convenient measure of magnet size for use in examining cost vs. size effects. The V is a nominal warm bore active volume and the B is peak on-axis magnetic field. These terms are defined in Figure B-1. (It should be noted that the volume, V, as defined in Figure B-1 is not the actual volume of the warm bore, but is only a "characteristic" volume, which is the product of the nominal bore cross-sectional area at the inlet and the active length.)

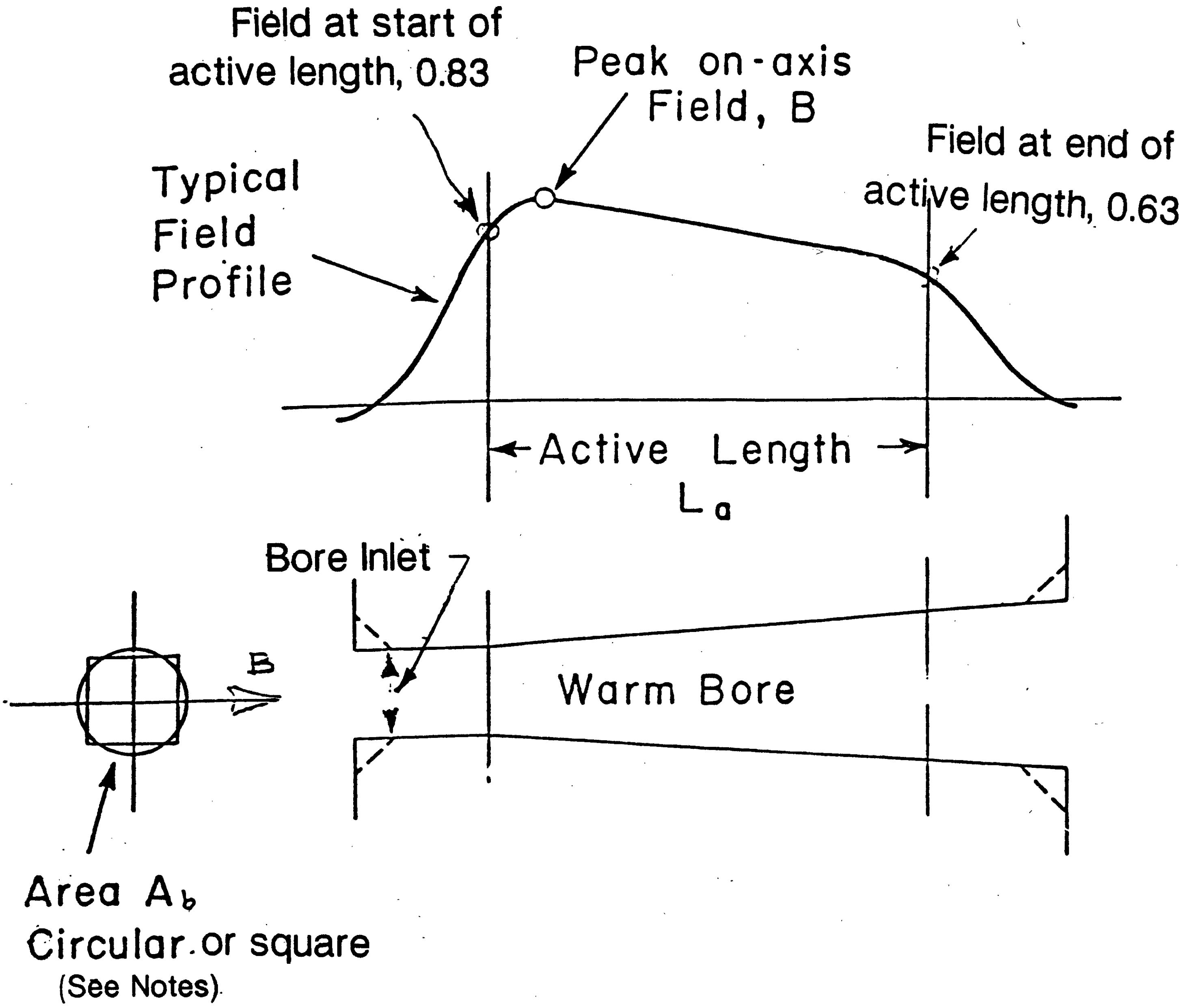
The parameter is appropriate because the power generated in an MHD duct is theoretically proportional to the duct volume and to the square of the magnetic field. It is an easy value to calculate because peak on-axis field, active length and bore area at plane of channel inlet are generally available, even for preliminary magnet designs.

A more rigorous size parameter would be that given below:

$$\text{Size Parameter} = \int_{\ell=0}^{\ell=L_a} b^2 a d\ell$$

where ℓ is the distance along axis from channel inlet, a and b are the warm bore area and on-axis field, respectively, at distance ℓ and L_a is the active length. However, experience has shown that the two methods of determining the parameter give results that are in reasonably close agreement and the method shown in Figure B-1 is more convenient, particularly for preliminary studies where exact field profiles are not determined.

In actual cases, the power generated in particular MHD channel/magnet combinations may not always be proportional to the magnet size parameter. Power will vary with the effectiveness of packaging of the channel in the bore (how much of the available bore volume is actually utilized for plasma) and with the specific design of the channel itself.



Characteristic Volume, $V = A_b \times L_a$. (m^3)

Magnetic Size Parameter VB^2 $(m^3\,T^2)$

Notes:

1. For air-core magnets with rectangular bores, use square area based on height dimension (⊥ to field)
2. Use area at start of active length or area at bore inlet, whichever is smaller

Fig. B-1 Method of Calculating Magnet Size Parameter, VB^2

APPENDIX C

Detailed Plots of Magnet System Costs (1984 $) and Cost Algorithms vs.Size Parameter, VB^2 and Stored Energy

The plots contained in this appendix, Figures C1, C2, C3, and C4 supplement similar but more general plots contained in Section 4.1.3 of the report (Figures 4.2, 4.3, 4.4 and 4.5, respectively).

The detailed plots include points for 18 MHD magnet systems of various sizes; these points, obtained from historical data (see Table C-I) were used in drawing the average curves shown.

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Item	Title	Page No.
Fig. C1	Plot of Estimated MHD Magnet Cost (1984 $) vs. Size Parameter VB^2 showing Points used in Drawing Average Curve	C–3
Fig. C2	Plot of Estimated MHD Magnet Cost (1984 $) vs. Stored Magnetic Energy, showing Points used in Drawing Average Curve	C–4
Fig. C3	Plot of MHD Magnet Cost Algorithm, $ /kg vs. Size Parameter, VB^2, with Points Used in Drawing Average Curve (1984 $)	C–5
Fig. C4	Plot of MHD Magnet Cost Algorithm, $ /kJ, vs. Size Parameter, VB^2, with Points Used in Drawing Average Curve (1984 $)	C–6
Table C-I	Characteristics, Costs and Cost Algorithms of Representative MHD Magnet Systems	C–7

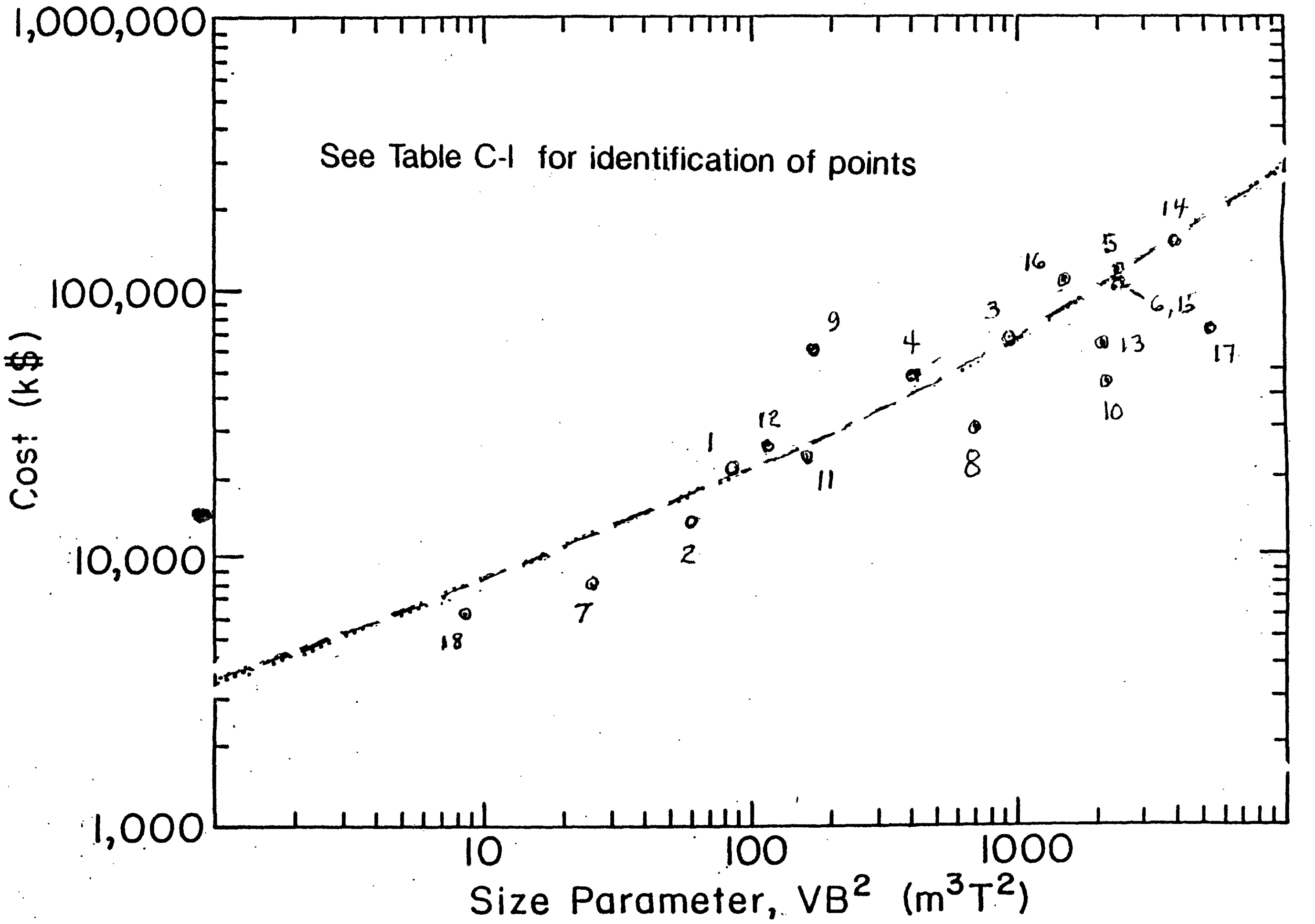

Fig. C-1 Plot of Estimated MHD Magnet Costs (1984 \$) vs. Magnet Size Parameter, VB^2, Showing Points Used in Drawing Average Curve

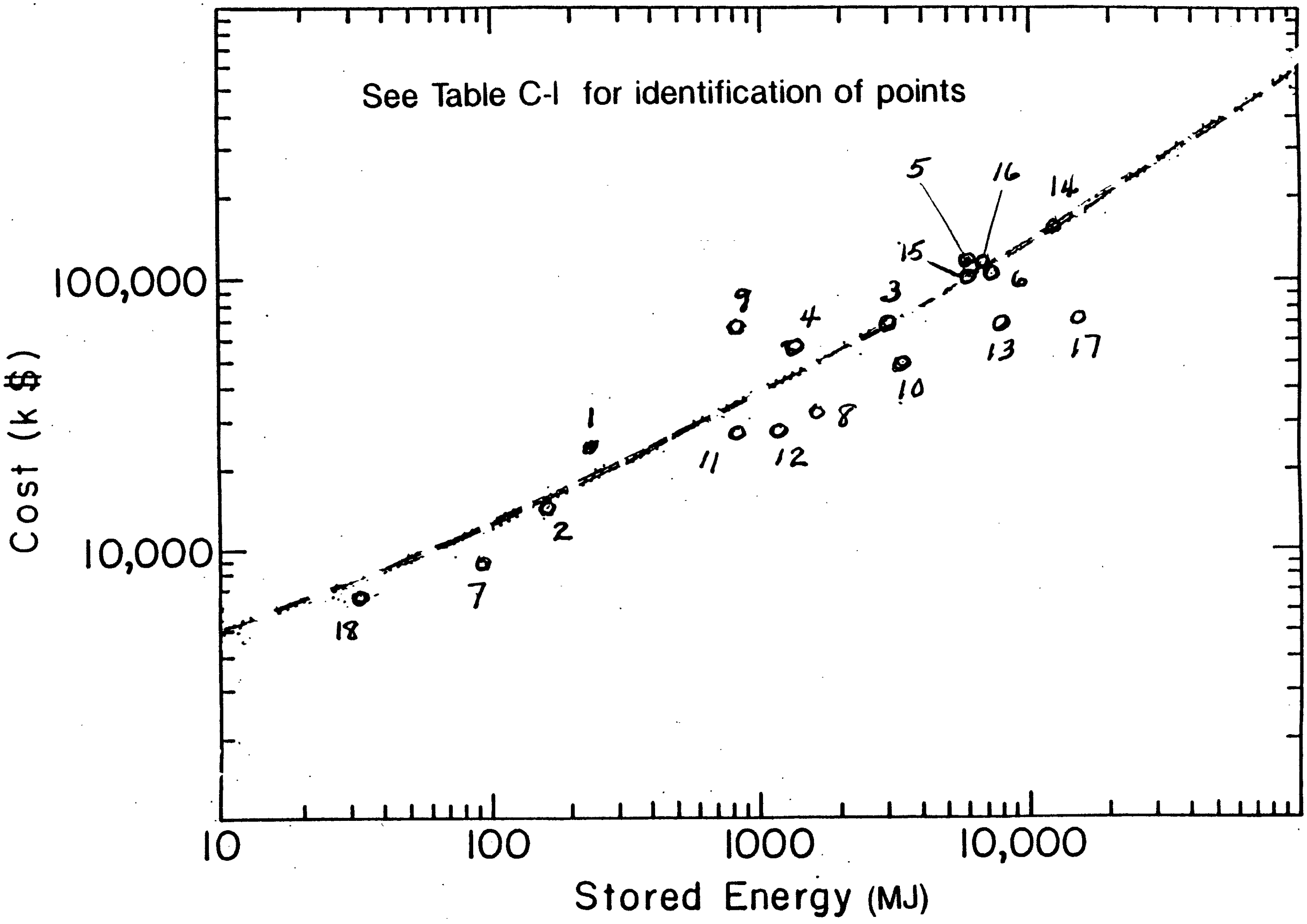

Fig. C-2 Plot of Estimated MHD Magnet Costs (1984 $) vs. Stored Energy, Showing Points Used in Drawing Average Curve

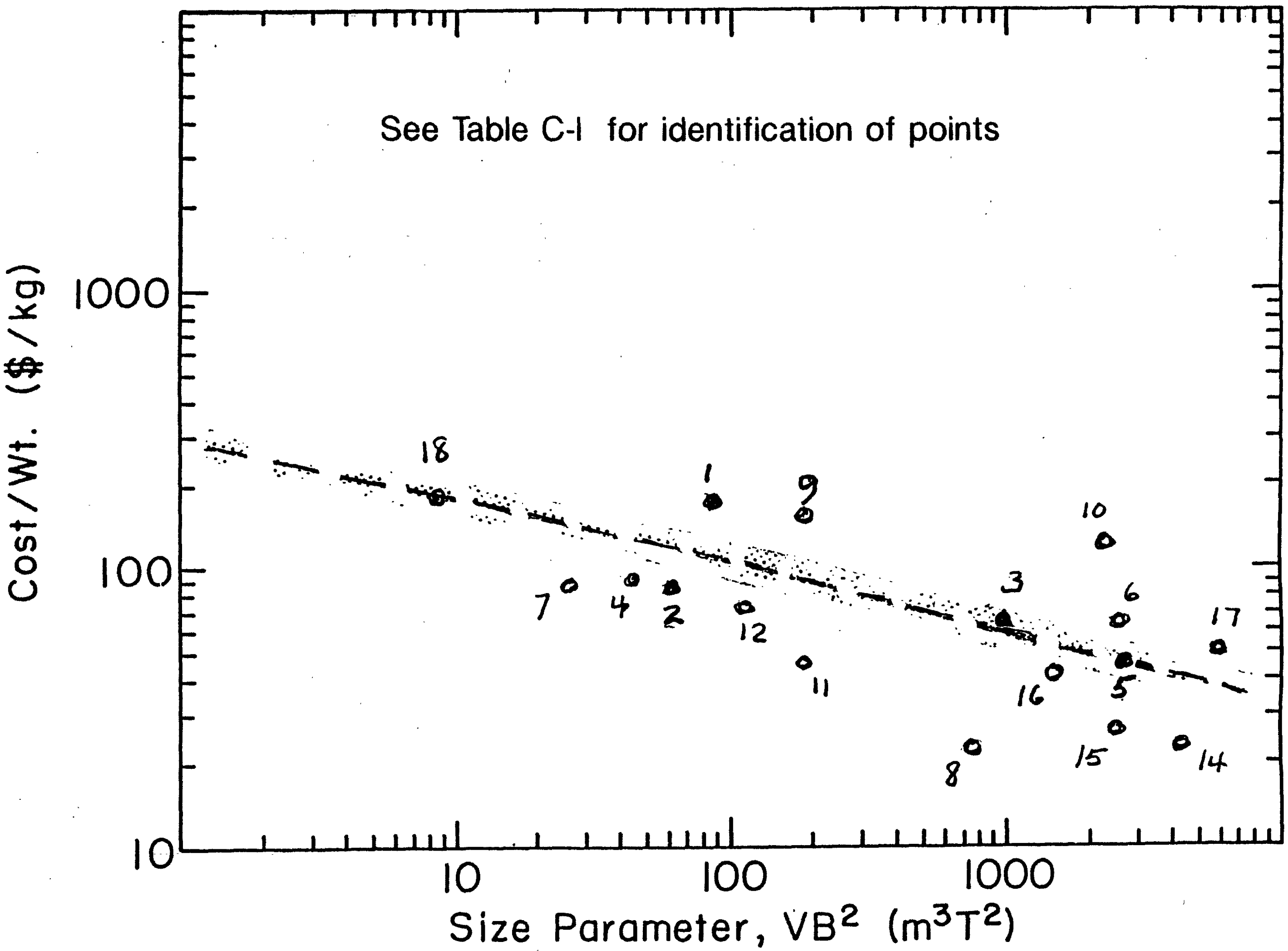

Fig. C-3 Plot of MHD Magnet Cost Algorithm, $ /kg, vs. Size Parameter, VB^2, with Points Used in Drawing Average Curve (1984 $)

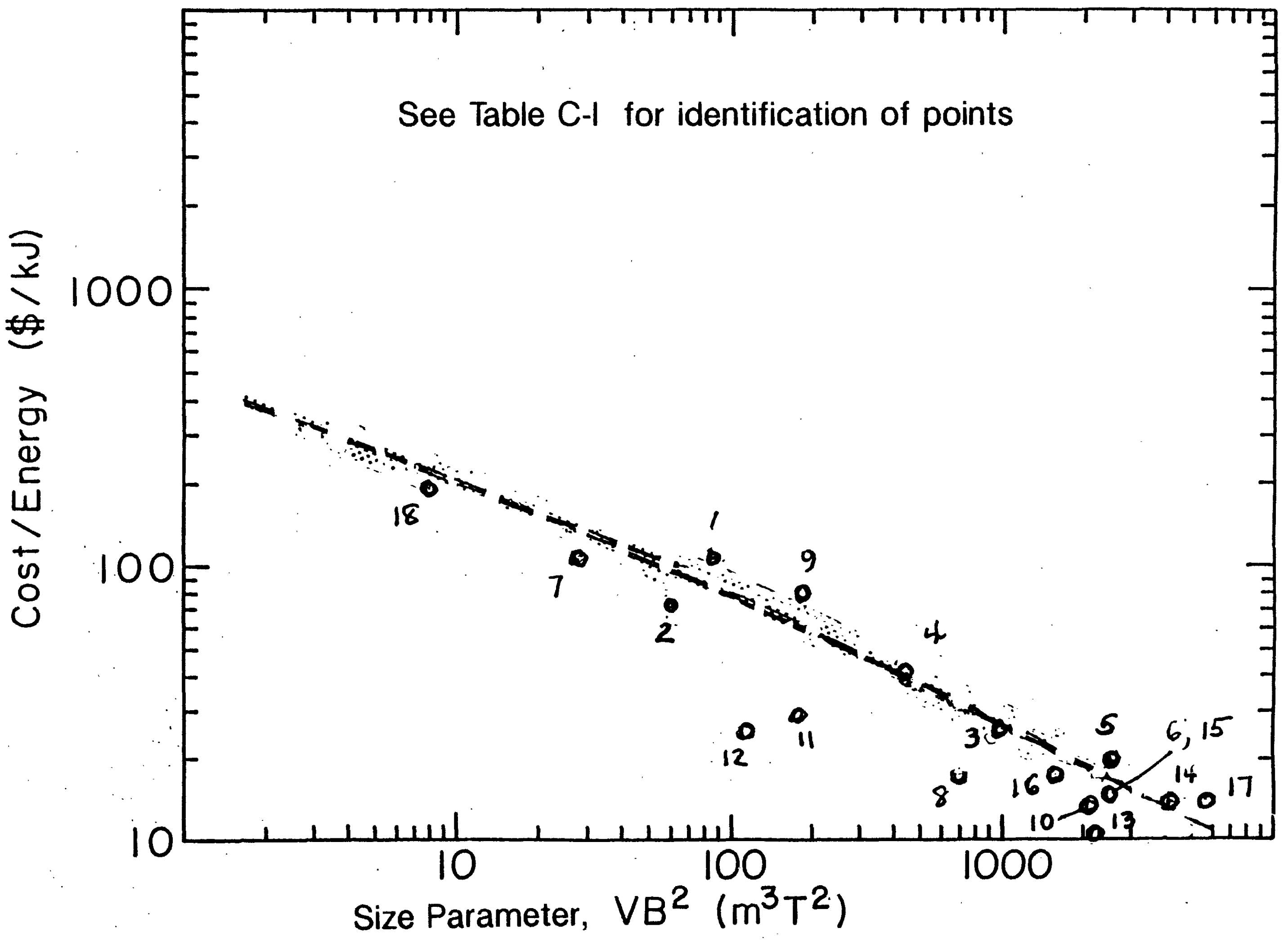

Fig. C-4 Plot of MHD Magnet Cost Algorithm, $ /kJ, vs. Size Parameter, VB^2, with Points Used in Drawing Average Curve (1984 $)

Table C-I
Characteristics, Costs and Cost Algorithms for Representative MHD Magnet Systems

Item No.	Magnet Identification	Year	Original Cost k$	Escal. Factor	1984 Cost k$	Size Param. VB^2 m^3T^2	Total Weight tonnes	Stored Energy MJ	Algorithms (1984 $)	
									$/kg	$/kJ
1	CDIF/SM 6T	1981	22300	1.09	24300	88	144	240	169	101
2	CFFF 6T	1979	10370	1.36	14100	61	172	210	82	67
3	ETF-MIT 6T	1980	55580	1.24	68600	986	909	2900	76	24
4	ETF-MIT 4T	1981	47000	1.09	51000	438	568	1300	90	39
5	CASK 6T	1979	87000	1.36	118000	2520	2644	6300	45	19
6	CSM-1A 6T	1979	75590	1.36	102800	2526	1850	7200	56	14
7	Stanford 7T	1978	5800	1.48	8600	27	101	79	85	109
8	ETF-AVCO 6T	1978	21100	1.48	31000	729	1429	1888	22	16
9	ETF-GE/GD 6T	1977	42100	1.59	67000	180	437	820	153	82
10	ETF West.[a] 6T	1977	36000	1.59	57200	1719	380	3400	151	17
11	ETF6-P1 6T	1977	15100	1.59	24000	183	535	820	45	29
12	ETF-MCA 6T	1977	16600	1.59	26400	118	376	1160	70	23
13	PSPEC-AVCO 6T	1979	60000	1.36	81600	2203	4000	7800	20	10
14	PSPEC-GE 6T	1979	116100	1.36	157900	4071	7320	11500	22	14
15	BL6-P1 6T	1977	56900	1.59	89900	2491	3483	6100	26	15
16	BL6-MCA 6T	1977	75300	1.59	119100	1544	2664	6710	45	18
17	ECAS-GE 6T	1977	130000	1.59	205500	5822	4110	15200	50	14
18	USSCMS 5T	1976	3900	1.69	6600	8	38	34	174	194

[a] Questionable design; structure inadequate

APPENDIX D

Tables of Magnet Component Data and Cost Algorithms

Tables listing component weights, costs and cost algorithms for eight representative MHD magnets are contained in this appendix. The magnets include:

ETF-MIT 6 T (for 200 MWe power plant)
CASK 6 T
CDIF/SM 6 T
CFFF 6 T
Stanford 7.3 T
USSCMS 5 T (U-25 Bypass)
AERL/CM 4 T
HPDE 6.7 T/3.7 T (dual mode)

Weight used in calculating algorithms is listed in weight column on same line as algorithm. Total cost used in calculating "percentage of total magnet cost" (right hand column) is the preceding total in cost column.

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Appendix D
Component Data Tables

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Table D-1 Sheet 1
Magnet Component Data Summary

Identification: ETF-MIT 6 T MHD Magnet

Magnet type:60° rect. sad.
Conductor type: Cable
Ampere meters: 11.5×10^8 Am

Year: 1980
Escal. factor to '84: 1.24
Stored energy: 2900 MJ

	Weight tonnes	Cost, Orig. k$	Algorithm orig. $/kg	Algorithm '84 $/kg	% of Total Mag. Cost %
Conductor NbTi/Cu	102	6164	60.43 (0.92 $/kAmT)	74.93 (1.14 $/kAmT)	
Substruct. GRP	90	1278	14.20	17.61	
Coil fab	(102)	1479	14.50	17.98	
Total coil pack	(102)	8921	87.41	108.45	
He vessel SS	227	3729	16.43	20.37	
Superstruct. SS	273	4180	15.31	18.99	
Coil, struct. assembly	(692)	2600	3.76	4.66	
Total cold mass	692	19430	28.08	34.82	
Thermal shield Al.	39	1705	43.72	54.21	
Vacuum vessel	178	2420	13.60	16.86	
Total, cryostat	(217)	4125	19.01	23.59	
Final assembly & install.	(909)	3368	3.71	4.59	
Magnet subtotal	909	26923	29.62	36.73	
Pack & ship	(909)	619	0.68	0.84	
Shakedown test	(909)	380	0.42	0.52	
Total	(909)	27922	30.72	38.09	
Mfg. engineering, tooling		1650			5.9
Total, magnet installed & tested	(909)	29572	32.53	40.34	

Table D-1 Sheet 2
Magnet Component Data Summary

Identification: ETF-MIT 6 T MHD Magnet

	Cost orig k$	Algorithm orig $/kg	Algorithm '84 $/kg	% of Total Mag. Cost %
Total magnet (Sheet 1) (909 tonnes)	29572	32.53	40.34	
Design & anal.; proj. mgt.	5287			17.9
Total before spec. costs	34859	38.35	47.55	
Site special costs	3765			10.8
Total before contingency	38624			
Contingency allow.	11587			30.0
Total (without access.)	50211	55.24	68.50	
Accessories, direct costs	3427			
Accessories, indirect costs	1937			
Total, accessories	5364			10.7
Total mag. and access.	55575	61.14	75.81	

Note: G & A and fee are included in above items. All costs are estimates.

Table D-2 Sheet 1
Magnet Component Data Summary

Identification: CASK 6 T MHD Magnet (GD)

Magnet type:Mod. Circ. Sad.
Conductor type: Built-up
Ampere meters: 14.5 × 10^8 Am

Year: 1979
Escal. factor to '84: 1.36
Stored energy: 6300 MJ

	Weight tonnes	Cost, Orig. k$	Algorithm orig. $/kg	Algorithm '84 $/kg	% of Total Mag. Cost %
Conductor NbTi/Cu	552	15383	27.87 (1.77 $/kAmT)	37.90 (2.41 $/kAmT)	
Insulation G10	55	3407	61.94	84.25	
Substruct. SS	664	6310	9.50	12.92	
Coil fab	(552)	9645	17.47	23.76	
Total, coil pack	(552)	34745	62.94	85.60	
He vessel SS	267	966	3.62	4.92	
Superstruct.	689	2999	4.34	5.90	
Total cold mass	2227	38710	17.38	23.64	
Cold mass supp. G10	15	1681	112.07	152.42	
Thermal shield Al. alloy	21	2502	119.14	162.03	
Vacuum vessel SS	343	4436	12.93	17.58	
Instruments, etc.	38	1290			
Total, cryostat	417	9909	23.76	32.31	
Final assembly & install.	(2644)	4235	1.60	2.18	
Magnet subtotal	2644	52854	19.99	27.19	
Pack & ship	(2644)	973	0.37	0.50	
Total	(2644)	53827	20.36	27.69	
Mfg. engineering, tooling		2988			5.6
Total, magnet installed & tested	(2644)	56815	21.49	29.23	

Table D-2 Sheet 2
Magnet Component Data Summary

Identification: CASK 6 T MHD Magnet (GD)

	Cost orig k$	Algorithm orig $/kg	Algorithm '84 $/kg	% of Total Mag. Cost %
Total magnet (Sheet 1) (2644 tonnes)	56815	21.49	29.23	
Program mgt.	5170			9.1
Design & anal.	4275			7.5
Total before contingency	66260	25.06		
Contingency allow.	16366			25.0
Total, magnet (no access.)	82626	31.25		
Total, accessories	4525			5.5
Total mag. and access.	87151	32.96	44.83	

Note: G & A and fee are included in above items. All costs are estimates.

Table D-3 Sheet 1
Magnet Component Data Summary

Identification: CDIF/SM 6 T MHD Magnet (MIT/GE)

Magnet type:45° rect. sad.	Year: 1981 (final est.)
Conductor type: Built-up	Escal. factor to '84: 1.09
Ampere meters: 1.89×10^8 Am	Stored energy: 240 MJ

	Weight tonnes	Cost, Orig. k$	Algorithm orig. $/kg	Algorithm '84 $/kg	% of Total Mag. Cost %
Conductor	35.7	2619	73.36 (2.31 $/kAmT)		
Insul., misc.		370			
Substruct. G10	7.7	1018	132.21	144.11	
Coil fab	(35.7)	772	21.34	23.26	
Shop eng., mfg. eng.		2522			
He vessel SS	24.5	313	12.78	13.93	
Superstruct. SS	45.7	601	13.15	14.33	
Coil, struct. assembly	(113.8)	460	4.04	4.40	
Total cold mass	113.8	8665			
Thermal shield Cu + SS	4.2	983	234.05	255.11	
Vacuum vessel SS	24.5	458	18.69	20.37	
Instruments, etc.	1.8	29			
Total, cryostat	30.5	1470	48.20	52.54	
Final assembly & install.	(144.3)	525	3.64	3.97	
Magnet subtotal	144.3	10660	73.87	80.52	
Pack & ship	(144.3)	205	1.42	1.55	
Shakedown test	(144.3)	401	2.78	3.03	
Total, mag. tested	144.3	11266	78.07	85.10	
Site assem. & other		1282			11.4
Total, mag. incl. tool.	144.3	12548	86.96	94.79	

Table D-3 Sheet 2
Magnet Component Data Summary

Identification: CDIF/SM 6 T MHD Magnet (MIT/GE)

	Cost orig k$	Algorithm orig $/kg	Algorithm '84 $/kg	% of Total Mag. Cost %
Total mag. incl. tools (Sheet 1) (144.3 tonnes)	12548	86.96	94.79	
Program mgt.	3398			27.1
Design & analysis	3366			26.8
Support development	848			6.8
Special costs	96			0.7
Total before fee	20256			
Fee	500			2.5
Total, magnet (no access.)	20761	143.87	156.82	
Total, accessories	1565			7.5
Total mag. and access.	22326	154.72	168.64	

Note: G & A and fee are included in above items. Costs for most components are actual costs. Other costs are estimate of 1981.

Table D-4 Sheet 1
Magnet Component Data Summary

Identification: CFFF 6 T MHD Magnet (ANL)

Magnet type:Circ. sad.	Year: 1979
Conductor type: Built-up	Escal. factor to '84: 1.36
Ampere meters: 1.45 × 10^8 Am	

	Weight tonnes	Cost, Orig. k$	Algorithm orig. $/kg	Algorithm '84 $/kg	% of Tot Mag. C %
Conductor NbTi/Cu	48	781	16.27 (0.02 $/kAmT)	22.13 (1.22 $/kAmT)	
Insul., misc. GRP		38			
Substruct. Lam. plas.		450			
Coil fab	(48)	403	8.40	11.42	
Shop eng.	(48)	550	11.46	15.59	
Total coil pack	(48)	2222	46.29	62.95	
He vessel SS		in superst.			
Instr. & piping		242			
Superstruct. SS	83	1179	14.20	19.31	
Coil, struct. assembly	(131)	475	3.63	4.94	
Total cold mass	131	4118	31.44	42.76	
Cold mass support		in vac. ves.			
Thermal shield SS.		in vac. ves.			
Vacuum vessel SS	41	744			
Instruments, etc.		422			
Total, cryostat	(41)	1166	28.44	38.68	
Final assembly & install.	(172)	596	3.47	4.72	
Magnet subtotal	172	5880	34.19	46.50	
Pack & ship	(172)	225	1.31	1.78	
Shakedown test		150			
Total, mag. tested	(172)	6255	36.37	49.46	
Mfg. engineering, tooling		350			5.6
Total, mag. incl. tool.	172	6605	38.40	52.22	

Table D-4 Sheet 2
Magnet Component Data Summary

Identification: CFFF 6 T MHD Magnet (ANL)

	Cost orig k$	Algorithm orig $/kg	Algorithm '84 $/kg	% of Total Mag. Cost %
Total mag. incl. tools (Sheet 1) (172 tonnes)	6605	38.40	52.22	
Program mgt.	140			2.1
Design & analysis	1857			28.1
Support development	350			5.3
Total before G & A	8952	52.05	70.78	
G & A	855			9.6
Total, incl. G & A	9807	57.02	77.55	
Total, accessories	760[a]			7.7
Total mag. and access.	10567	61.44	83.55	

[a] MIT estimate. All other costs are actual.

Table D-5 Sheet 1
Magnet Component Data Summary

Identification: Stanford 7.3 T MHD Magnet (GD)

Magnet type:Circ. sad.	Year: 1978
Conductor type: Built-up	Escal. factor to '84: 1.48
Ampere meters: 0.9 × 10^8 Am	

	Weight tonnes	Cost, Orig. k$	Algorithm orig. $/kg	Algorithm '84 $/kg	% of Total Mag. Cost %
Conductor NbTi/Cu	11.27	469	41.61 (0.714 $/kAmT)	61.58 (1.06 $/kAmT)	
Substruct. Al. alloy	8.23	445	54.07	80.02	
Coil fab	(11.27)	393	34.87	51.61	
He vessel Al. alloy	34.10				
Superstruct. Al. alloy	27.64	355	12.84	19.00	
Total cold mass	81.24	1662	20.46	30.28	
Cold mass support	0.03				
Thermal shield SS	1.4				
Vacuum vessel SS	17.9				
Total, cryostat[a]	53.43	427	7.99	11.83	
Final assembly & install.		917	9.12	13.50	
Magnet subtotal	(100.57)	3006	29.89	44.24	
Pack & ship	(100.57)	143	1.42	2.10	
Total, mag. tested	100.57	3149	31.31	46.34	
Mfg. engineering, tooling		70			2.2
Total, mag. incl. tool.	100.57	3219	32.01	47.37	

[a] Including He vessel

Table D-5 Sheet 2
Magnet Component Data Summary

Identification: Stanford 7.3 T MHD Magnet (GD)

	Cost orig k$	Algorithm orig $/kg	Algorithm '84 $/kg	% of Total Mag. Cost %
Total mag. incl. tools (Sheet 1) (100.57 tonnes)	3219	32.01	47.37	
Program mgt. & QA	59			1.8
Design & analysis	896			27.8
Support development, other	309			9.6
Total before contingency	4483	44.58	65.97	
Contingency allow.	445			10.0
Total, magnet (no access.)	4928	49.00	72.52	
Total, accessories	340			6.9
Total mag. and access.	5268	52.38	77.52	
Magnetic shield (500 tonnes)	491	0.98	1.45	
Total, incl. shield	5759			

Note: G & A and fee are included in above items. All costs are estimates.

Table D-6 Sheet 1
Magnet Component Data Summary

Identification: USSCMS (U25 Bypass) 5 T MHD Magnet (ANL)

Magnet type: Circ. sad.
Conductor type: Built-up
Ampere meters: 0.5×10^8 Am

Year: 1976
Escal. factor to '84: 1.69

	Weight tonnes	Cost, Orig. k$	Algorithm orig. $/kg	Algorithm '84 $/kg	% of Total Mag. Cost %
Conductor NbTi/Cu	10	255	25.50 (1.02 $/kAmT)	43.10 (1.72 $/kAmT)	
Substruct., insul.	2.1	85	40.48	68.41	
Coil fab	(10)	200	20.00	33.80	
Superstruct. SS	10.1	150	14.85	25.10	
Total cold mass[a]	22.2	690	31.08	52.53	
Cold mass support		12			
Vac. ves., He ves., th. shield	15.6	400	25.64	43.33	
Total, cryostat[b]	15.6	412	26.41	44.63	
Final assembly & install.	(37.8)	350	9.26	15.65	
Factory test	(37.8)	50	1.32	2.23	
Magnet subtotal	37.8	1502	39.74	67.16	
On-site install. & test		562			
Total, mag. tested		2064			
Mfg. engineering, tooling		300			14.5
Total, mag. incl. tool.	37.8	2364	62.54	105.69	

[a] Not including He vessel

[b] Including He vessel

Table D-6 Sheet 2
Magnet Component Data Summary

Identification: USSCMS (U25 Bypass) 5 T MHD Magnet (ANL)

	Cost orig k$	Algorithm orig $/kg	Algorithm '84 $/kg	% of Total Mag. Cost %
Total mag. incl. tools (Sheet 1) (37.8 tonnes)	2364	62.54	105.69	
Program. mgt.; design & anal.	950			40.2
Total, magnet (no access.)	3314	87.16	148.17	
Total, accessories	586			17.7
Total mag. and access.	3900	103.17	174.36	

Note: G & A is included in above items (no fee). All costs are actual.

Table D-7 Sheet 1
Magnet Component Data Summary

Identification: AERL/CM 4 T MHD Magnet (AVCO Channel Test)

Magnet type:Rect. sad; water cooled	Year: 1978
Conductor type: Hollow copper	Escal. factor to '84: 1.47
Ampere meters: 0.226	

	Weight tonnes	Cost, Orig. k$	Algorithm orig. $/kg	Algorithm '84 $/kg	% of Total Mag. Cost %
Conductor Cu	14				
Total, coil pack	(14)	220	15.71	23.09	
Superstruct. & misc. Al.	14				
Iron frame	54				
Frame & superstr.	68	178	2.62	3.85	
Final assembly & install.	(82)	117	1.43	2.10	
Magnet subtotal	82	515	6.28	9.23	
Pack & ship	(82)	5	0.06	0.09	
Total, mag. installed	82	520	6.34	9.32	

Table D-7 Sheet 2
Magnet Component Data Summary

Identification: AERL/CM 4 T MHD Magnet (AVCO Channel Test)

	Cost orig k$	Algorithm orig $/kg	Algorithm '84 $/kg	% of Total Mag. Cost %
Total mag. installed (Sheet 1) (82 tonnes)	520	6.34	9.32	
Program mgt.	75			14.4
Design & analysis	70			13.5
Total, magnet (no access.)	665	8.11	11.92	

Note: G & A and fee are included in above items. All costs are actuak costs.

Table D-8 Sheet 1
Magnet Component Data Summary

Identification: HPDE 6.7/3.7 T MHD Magnet (dual mode)

Magnet type: Rect. sad. LN_2/water cooled
Conductor type: Hollow copper
Ampere meters: 2.7×10^8 Am

Year: 1977
Escal. factor to '84: 1.58

	Weight tonnes	Cost, Orig. k$	Algorithm orig. $/kg	Algorithm '84 $/kg	% of Total Mag. Cost %
Conductor Cu	83.5	344	4.12 (1.28 $/kAmT)	6.51 (2.02 $/kAmT)	
Coil fab	(83.5)	997	11.94	18.87	
Total	(83.5)	1341	16.06	25.37	
Assem. coil & vessel	(83.5)	229	2.74	4.33	
Total	(83.5)	1570	18.80	29.70	
Superstruct. Al. alloy	24.6	327	13.29	21.00	
Coil, struct. assembly	108.1	220	2.04	3.22	
Total cold mass	108.1	2117	19.58	30.94	
Insul. casing		212			
Iron frame	500[a]	636[a]	1.27	2.01	
Instr. piping		299			
Final assembly & install.		138			
Magnet subtotal	608.1	3402	5.59	8.84	
Mfg. engineering, tooling		188			5.5
Total, mag. incl. tool.	608.1	3590	5.90		

[a] Addition to frame already on site

Table D-8 Sheet 2
Magnet Component Data Summary

Identification: HPDE 6.7/3.7 T MHD Magnet (dual mode)

	Cost orig k$	Algorithm orig $/kg	Algorithm '84 $/kg	% of Total Mag. Cost %
Total mag. incl. tools (Sheet 1) (608.1 tonnes)	3590	5.90	9.32	
Program mgt.	167			4.7
Design & analysis	529			14.7
Total, magnet (no access.)	4286	7.05	11.14	
Power supply mod.	131			3.1
Total mag. and access.	4417	7.26	11.47	

Note: G & A and fee are included in above items. All costs are actual costs.

APPENDIX E
Cost Escalation
Data Sources

In comparing historical data on magnet costs and in using these data to predict future magnet costs, it is necessary to have data on historical escalation rates and on predicted future rates.

Since superconducting magnets are a new and developmental type of equipment and very few have been built, we must use cost escalation data developed for other equipment similar in materials and construction, but produced regularly over a period of years. Power plant equipment and chemical plant equipment fit these requirements.

Data from the following sources were reviewed and used as a basis for selecting rates considered appropriate for magnets.

"Chemical Engineering" (CE), McGraw Hill;
    Chemical plant cost index
Gilbert/Commonwealth (G/C),
    Power plant equipment cost index
Princeton Plasma Physics Laboratory (PPPL),
    Basis not specified
Boston Edison Co. (BE);
    Electric machinery and equipment

Cost escalation data from the above sources, adjusted to base year 1975, are plotted on curve sheet Fig. E-1. It should be noted that the indices agree as to general trends, but vary considerably in absolute amounts.

For use in connection with MIT's MHD magnet cost analysis, "Chemical Engineering" plant escalation rates were selected. These were intermediate between extremes shown in Figure E-1 and were quite close to the rates used by PPPL for fusion magnets. The selected rates, adjusted to base year 1975, are listed below:

Year	Index (Base 100)	Growth (%)
1975	100.0	—
1976	105.3	5.3
1977	111.9	6.3
1978	120.0	7.2
1979	130.9	9.1
1980	143.2	9.4
1981	162.8	13.7
1982	172.1	5.7
1983	173.7	0.9
1984	176.9	1.8
1985	178.3	0.8
1986	180.1	1.0 (MIT est.)

Note: The index for a given year refers to the average price level for the year, and growth rate refers to the increase since the previous year.

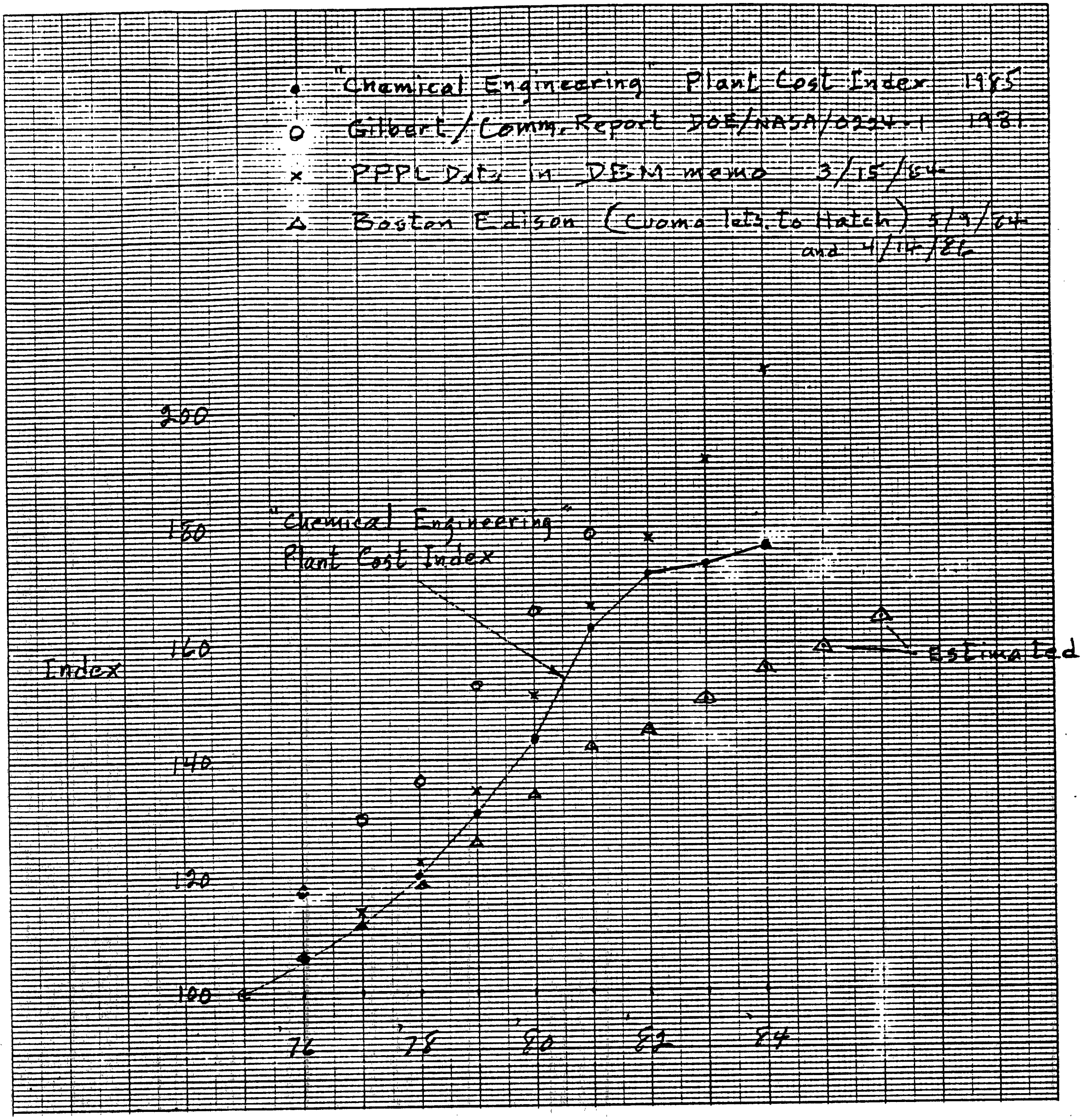

Fig. E-1
Plots of Cost Indices vs Year, 1975 to 1984

The escalation factors derived from the Chemical Engineering plant escalation rates and used in adjusting magnet system estimated cost to 1984 $ are listed below:

Year	Escalation Factor
1969	2.60
1970	2.53
1971	2.44
1972	2.35
1973	2.24
1974	1.95
1975	1.769
1976	1.680
1977	1.581
1978	1.474
1979	1.351
1980	1.235
1981	1.087
1982	1.028
1983	1.018
1984	1.000

A further discussion of sources of escalation rate data is contained below:

Princeton Plasma Physics Laboratory (PPPL)

A Fusion Magnet Costing Workshop took place at Princeton (Bldg IP, PPPL) on April 10, 1984. In preparation for that meeting, a memo dated March 15, 1984 was issued by D.B. Montgomery. Included in the memo was a table listing the cost indices for 1975 to 1984 taken from PPPL Table AII.1. These data are given below:

Year	Composite Index
1975	1.0
1976	1.068
1977	1.142
1978	1.225
1979	1.347
1980	1.514
1981	1.668
1982	1.781
1983	1.916
1984	2.076

Gilbert/Commonwealth (G/C)

The MHD-ETF conceptual design program by NASA/LeRC 1979 to 1981 resulted in the following report prepared by Gilbert/Commonwealth.

NASA/LeRc Conceptual Design Engineering Report - MHD Engineering Test Facility 200 MWe Power Plant, prepared for NASA/LeRc for DOE by Gilbert/Commonwealth, DOE/NASA/0224-1 Vol. I-V, September 1981.

The report contained data on escalation factors through 1981 for various categories of power plant equipment. The cost indices listed below were derived from G/C data for MHD topping equipment (Category 317).

Year	Index
1975	100
1976	117.8
1977	129.7
1978	136.6
1979	153.0
1980	165.7
1981	179.0

A copy of pages 3-7 of the reference report, describing cost bases and escalation factors is attached (Exhibit A).

Handy-Whitman Index

The Handy-Whitman Index referred to in Exhibit B is published by:

Whitman, Requarst & Assoc.
1304 St. Paul St.,
Baltimore, MD 21202

This publication could not be located in the MIT libraries.

Boston Edison

Boston Edison was contacted by telephone to determine what escalation factors they use in power plant estimation. Mr. Cuomo of Boston Edison supplied information in a letter of May 9, 1984 and again supplied (updated) information in April, 1986.

Cost indices derived from the most recent Boston Edison data are listed below:

Exhibit A

3.2 COSTING BASES

3.2.1 Conversion Tables for Constant Dollars

The conversion factors in Table 3-1 are used to adjust costs from their stated time frame. The factors were developed on the basis of data presented in the Handy Whitman Index; specifically, the Electric Utility Construction Index for the Plateau Region. The data covers each year of the last decade to first quarter 1981.

This information can be used in two ways: first, to take costs that originated prior to the present and escalate to a present day by multiplying the factor by the known cost (as done in this estimate effort); secondly, the data can be used to de-escalate values for comparison with other data on an earlier-year basis by dividing the present year cost by the applicable factor. The table shows separate values for each primary account. This was done since the estimate was developed on the basis of the FERC code, and Handy Whitman is available with FERC code principal accounts. The only exception in developing the table was that Handy Whitman does not have equivalent data for the 317 topping cycle equipment. In this case, the data for 314 account was used for the 317 equipment also, since it is similarly affected.

TABLE 3-1

ESCALATION FACTORS*
FOR
F.E.R.C. SUMMARY ACCOUNTS (TOTAL COST)
PLATEAU REGION

MHD
Topping
↓

YEAR	311	312	314	315	316	317	350
1970-81	2.79	2.81	2.72	2.57	2.52	2.72	2.65
1971-81	2.55	2.63	2.51	2.46	2.36	2.51	2.49
1972-81	2.35	2.42	2.24	2.25	2.20	2.24	2.31
1973-81	2.23	2.32	2.16	2.13	2.09	2.16	2.25
1974-81	2.01	2.16	2.05	1.97	1.93	2.05	2.02
1975-81	1.53	1.66	1.79	1.57	1.59	1.79	1.55
1976-81	1.52	1.52	1.52	1.46	1.51	1.52	1.43
1977-81	1.46	1.42	1.38	1.36	1.38	1.38	1.34
1978-81	1.38	1.32	1.31	1.22	1.26	1.31	1.27
1979-81	1.23	1.2	1.17	1.18	1.17	1.17	1.21
1980-81	.87	1.14	1.08	1.08	1.06	1.08	1.09

*Factor x base year amount = total value including escalation

3.2.2 Vendor Data

Vendor data refers to costs for equipment quoted by a vendor for specific component application. This has a very high degree of reliability. In this effort vendor data has been utilized in several different ways. The first of

Year	Index
1975	100
1976	106.0
1977	111.7
1978	118.5
1979	125.9
1980	134.0
1981	142.2
1982	145.1
1984	150.47
1984	155.89
1985	159.63 (est)
1986	164.53 (est)

The letter and tables received from Boston Edison are attached (Exhibit B, 4 sheets).

Chemical Engineering

Chemical Engineering, McGraw Hill, April 1986 issue contained yearly plant cost indices through 1985.

Cost indices, 1975 base year, derived from CE data are listed below:

Year	Index
1975	100
1976	105.3
1977	111.9
1978	119.9
1979	130.9
1980	143.2
1981	162.8
1982	172.1
1984	173.7
1984	176.9
1985	178.3

EPRI

A telephone call was made to Stan Vejtasa at EPRI May 4, 1984 to inquire concerning cost escalation factors used for power plant equipment. He was familiar with the Handy-Whitman Index, but did not supply any specific data. He stated that the "Chemical Engineering" Plant Cost Index was suitable for power plant equipment and was used by EPRI. He mentioned the Dept. of Commerce, Bureau of Labor Statistics "Producer Price Index."

Exhibit B Sheet 1

BOSTON EDISON COMPANY
GENERAL OFFICES 800 BOYLSTON STREET
BOSTON, MASSACHUSETTS 02199

May 9, 1984

Mr. Tim Hatch
Research Engineer
Plasma Fusion Center
Massachusetts Institute of Technology
Building NW 16, Room 160
Cambridge, MA 02139

Dear Mr. Hatch,

Attached are tables showing annual historical escalation rates of equipment costs from 1975-1983 and a forecast of equipment cost escalation from 1984-1995. The forecasted values were derived by using the TRENDLONG1283 solution of the Data Resources Incorporated long-term forecasting model.

As a measure of the inflation rate associated with the cost of magnetic systems, the implicit deflator for nonresidential equipment was used. Table 1 presents the index for each year between 1975 and 1983 together with its associated growth rate. Also shown is the compounded annual growth rate from 1975 to 1983. Table 2 shows the forecast of the implicit price deflator for nonresidential equipment from 1984 to 1995 along with annual growth rates. A compounded annual growth rate is also calculated.

If you have any questions, please feel free to call me at 424-3454.

Sincerely yours,

Robert J. Cuomo

Robert J. Cuomo
Division Head, Forecasting and
Load Research

RJC/lod

Attachment

xc: Mr. M. S. Alpert
Mr. R. D. Saunders
Mr. J. A. Whippen

Exhibit B Sheet 2

Table 1

Annual History and Growth Rate 1975-1983 Implicit Price Deflator - Nonresidential Equipment (1972=100)

Year	Index	Growth Rate (%)
1975	126.2	15.4
1976	133.8	6.0
1977	141.0	5.4
1978	149.6	6.1
1979	158.9	6.2
1980	169.1	6.4
1981	179.5	6.2
1982	183.1	2.0
1983	182.8	-0.1

Compounded Annual Growth Rate = 4.7%

Exhibit B Sheet 3

Table 2

Annual Forecast and Growth Rate 1984-1995
Implicit Price Deflator - Nonresidential Equipment
(1972=100)

Year	Index	Growth Rate (%)
1984	187.5	2.6
1985	194.3	3.6
1986	203.0	4.5
1987	213.5	5.2
1988	224.8	5.3
1989	236.9	5.4
1990	249.9	5.5
1991	264.2	5.7
1992	279.3	5.7
1993	295.1	5.7
1994	311.2	5.5
1995	327.3	5.2

Compounded Annual Growth Rate = 5.2%

Exhibit B Sheet 4
(from Cuomo, Boston Edison)

Producer Price Index

Electric Machinery and Equipment
(1967 = 100)

Year	Index	% Change
1982*	231.55	5.17
1983*	240.09	3.69
1984*	248.72	3.59
1985	254.66	2.39
1986	262.48	3.07
1987	273.53	4.21
1988	284.61	4.05
1989	295.59	3.86
1990	306.13	3.56
1991	317.67	3.77
1992	329.30	3.66
1993	341.73	3.78
1994	354.46	3.72
1995	366.36	3.36
1996	379.27	3.53
1997	392.45	3.47
1998	406.44	3.56
1999	421.69	3.75
2000	437.81	3.82
2001	454.40	3.79
2002	472.44	3.97
2003	491.06	3.94
2004	510.66	3.99
2005	533.09	4.39

* Actual

Compound Annual Growth = 3.69%
Rate 1982 - 2005

Combustion Engineering

A telephone call was made to Al Gaines, Combustion Engineering, August 30, 1983 to ask about cost indices. (Gaines and the CE Estimating Department had assisted MIT in costing the ETF MHD Magnet conceptual design in 1979-1980.) Gaines said the following sources were used for past indices:

1. Department of Labor, Bureau of Labor Statistics
   a. Employment and Earnings (supplement issued yearly), Table C2 (average hourly earnings series, by industry)
   b. Producer Prices and Price Indices, Table 4 (by industry) or Table 6
2. Periodicals such as *Steel and Iron Age*

No effort was made to obtain Dept. of Labor data because it appeared to be mainly useful where material and labor breakdown were involved. For our purposes, overall equipment prices were the primary interest.

APPENDIX F

Materials Cost Data

Costs of raw materials and of partially fabricated materials (cables, etc.) obtained during the period from 1975 to 1984 are listed in this appendix for reference purposes. Applications, sources and dates for each materials entry are provided.

Material Cost Data, Sheet 1

Material	Source of Data	Year	Cost $/lb
Copper plate	ARO/HPDE	1977	1.87
Copper, hollow conductor	MIT PFC/TARA	1982	2.40
Copper shape (channel)	Supercon Corp.	1979	2.50
Copper wire, large quan.	Supercon Corp.	1981	1.20
Superconducting wire (NbTi/Cu)	Supercon Corp.	1981	93.00
Cable, copper wire (1" OD)	Phelps Dodge Corp.	1980	1.41
Copper, base price	Phelps Dodge Corp.	1980	0.92
Al. alloy: 5083-0	Alcoa Corp.	1980	1.25
(3" plate) 6061-T651 stretch-rel.	Alcoa Corp.	1980	1.40
2219-T37 stretch-rel.	Alcoa Corp.	1980	1.90
Copper strip, full hard (0.19"×2.00")			
ETP	Anaconda Corp.	1980	1.76
OFHC	Anaconda Corp.	1980	1.90

Material Cost Data, Sheet 2

Material	Source of Data	Year	Cost $/lb
St. steel, 3" plate: 304L	Allegheny Ludlum Co.	1984	1.35
316	Allegheny Ludlum Co.	1984	1.98
Copper conductor	PLT-TF	1984	8.00
Copper conductor	TFTR-TF	1984	10.00
Superconductor, built-up, NbTi/Cu	SLAC	1984	70.91
Superconductor, built-up, NbTi/Cu	LPC/GD repeat	1984	56.82
Superconductor, built-up, NbTi/Cu	MFTF 7.8 T	1984	48.18
Superconductor, cable, NbTi/Cu	ETF 6 T (MHD) MIT	1980	42.27
Superconductor, NbTi rod 1/8"	Supercon	1979	92.00

Material Cost Data, Sheet 3

Material	Source of Data	Year	Cost
GRP-Glass polyester molded	Owen Corning Co.	1980	2.27 $/lb
Primary aluminum	*Iron Age* (McGraw Hill)	1983	76 $/gross ton
Primary copper	*Iron Age* (McGraw Hill)		80 $/gross ton
Finished steel	*Iron Age* (McGraw Hill)		26 $/gross ton
G10 (sheet)	CDIF (MIT) MIT	1980	3.00-3.50 $/lb
Steel plate, A36, 3"	*U.S. Steel Supply*, Boston	1986	0.25 $/lb
Steel, base price	*Iron Age* (McGraw Hill)	1983	0.262 $/lb
Pig iron	*Iron Age* (McGraw Hill)	1983	0.1065 $/lb
Copper, base price	*Iron Age* (McGraw Hill)	1983	0.80 $/lb
Copper wire, scrap	*Iron Age* (McGraw Hill)	1983	0.61 $/lb

APPENDIX G

Comparative Analysis of Costs of CDIF/SM and CFFF Magnets

This appendix describes a comparative cost analysis accomplished in 1982 to identify reasons for large cost differences in two MHD magnets of similar size and field strength (the CDIF/SM and the CFFF magnets). The discussion is based on information in memoranda of J.M. Tarrh (MIT) to P.G. Marston, October 20, 1980; J.M. Tarrh (MIT) to D.B. Montgomery, August 3, 1981; and A.M. Hatch (MIT) to P.G. Marston, February 20, 1982.

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Appendix G

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Comparative Analysis of Costs of CDIF/SM and CFFF Magnets

Discussion

The CDIF/SM and CFFF magnets, similar in bore size and field strength and both intended for MHD test facility service, were started in manufacture in 1979.

The CDIF/SM magnet, based on a conceptual design by MIT, was of the rectangular saddle configuration with a rectangular bore cross section. The detail design was prepared by GE and manufacture was carried out at GE to the point at which all major components were completed. The work was halted late in 1981 because of lack of funds. The total cost for the CDIF/SM (including MIT cost) was about 22 million dollars, including actual costs up to the time of the work stoppage plus estimated costs to complete.

The CFFF magnet, designed and built at ANL, was of the circular saddle configuration with a circular bore cross section. It was completed and successfully tested at ANL in 1981. The total cost according to ANL accounts was about 10 million dollars.

The major characteristics of the two magnets are summarized below:

Parameter	Units	CDIF/SM	CFFF
Peak on-axis field	T	6	6
Active field length	m	3	3
Field at start of act. len.	T	4.8	4.8
Field at end of act. len.	T	4.8	4.8
Aperture, start of act. length	m	0.78×0.98[a]	0.85 dia.
Aperture, end of act. length	m	0.98×0.98[a]	1.00 dia.
Warm bore vol., active	m	2.57	2.02
Vac. vessel overall len.	m	6.45	6.4
Vac. vessel outside dia.	m	4.11	3.66
Ampere meters, conductor	10^8Am	1.89	1.45
Weight, conductor	tonnes	35.9	48
Weight, magnet assem.	tonnes	144.3	172

[a] inside warm bore liner

A study was conducted at MIT early in 1982 to determine why the two magnets, nearly the same size, differed in cost by 12 million dollars (the CDIF/SM was more expensive by a factor of 2.2).

Conclusions reached were as follows:

1. The elements most responsible for the higher cost of CDIF/SM were the <u>business and financial practices</u> incident to performance of the work by a large industrial organization (GE) and the <u>learning</u> necessary because of limited prior experience by the GE team in design and construction of a large MHD magnet. These accounted for more than 5000 k$ of the 12,000 k$ difference, based on preliminary evaluations.
2. The differences in costs of <u>magnet components</u> (mostly subcontracted by both GE and ANL) and in costs of <u>magnet assembly</u> combine to give the CDIF/SM assembled hardware a cost roughly 2000 k$ more than that of the CFFF, or about 40% more. However, the CDIF/SM is

about 20% larger in size (volume at high field), so correcting for size, the difference becomes considerably less. It is therefore concluded that the differences in conceptual design and manufacturability between the two magnets are relatively minor factors in the overall program differences.

3. The somewhat greater component cost of the CDIF/SM magnet, as mentioned in Conclusion #2, is largely due to cost of the CDIF/SM conductor, which is almost 1500 k$ more than that of the CFFF conductor. The CDIF/SM conductor differs somewhat in configuration from the CFFF conductor and represents 30% more quantity in terms of ampere meters (although less in weight) but these differences alone cannot account for the very large difference which exists. It is concluded, therefore, that the conductor cost differential reflects mainly differences in procurement procedures (CPFF for the CDIF/SM; fixed price for the CFFF) and in source manufacturing efficiencies.

The cost elements believed to be most responsible for the cost difference between the two magnet programs are listed in Table G-I, together with explanations and estimates of the dollar differentials attributable to each.

In Table G-II component costs, assembly costs, engineering costs and other costs which make up the total program costs for the two magnets are compared, with arrows added to indicate where large differences exist.

Bar charts showing graphically the comparative costs of components of the two magnets and of other cost elements (including G & A) are presented in Figures G-1 through G-5.

Table G-I

Major Elements Responsible for Magnet Program Cost Differences - CDIF vs. CFFF

Element	Explanation	Estimated k$ Cost Difference (Excess of CDIF over CFFF)
Business practices, financial	Large industry G & A charges are higher than corresponding charges in government lab. Industry requires profit (fee).	2000
Business practices, organizational	Large industry organization tends to be more elaborate, specialized.	700
Administrative practices implicit in CPFF operation	Government prescribed system of reporting, reviews, etc. for CPFF contracts requires extra manpower.	700
Learning, particularly in engineering/design areas	The industry (GE) team was newly-formed, not experienced in large magnet design, The ANL team was highly experienced.	2000
Extra development testing needed to support new design	The CDIF magnet incorporated new features which needed developmental testing. The CFFF magnet was a scale-up of old design with mostly proven features.	1000
Materials and manufacturing	The CDIF components and estimated assembly costs exceeded those of the CFFF magnet by a significant amount (not including G & A).	2000
Slippage in CDIF program	The CDIF magnet total estimate included costs due specifically to program slippage of 3 years (stretch-out, escalation, etc.).	1200
Other	Balance of total estimated cost difference (includes differences in a number of minor elements such as special tools, accessories, etc.).	2400
Total difference (CDIF/SM vs. CFFF)	Difference between CDIF/SM estimate of 7/22/81 (including MIT costs) and CFFF estimate of 7/16/80.	12,000

Table G-II

Major Cost Items - CDIF/SM vs. CFFF

(costs in k$, line items are w/o G & A, profit)

	CDIF/SM	CFFF
Conductor	→2260	781
Structure	1716	1667
Cryostat	→1513	744
Power supply, controls, etc.	558	664
Total components	6047	3434
Winding & assembly	1507	1474
Total magnet	7554	5330
Special tools	879	350
Shop tests	346	150
Site install & test	160	150
QA & VT	→1461[1]	400
Engineering support	909	0
Program mgt.	→3210[2]	140
Design and analysis	→2904	1857
R & D	783[3]	350
Pack & ship	177	225
Miscellaneous	115	0
G & A	→2374	840
Fee	505	0
Total	21377	9792
Cryogenic system	600	578
Warm bore liner	347	0
Total	22324	10370

1 incl. 1195 MIT

2 incl. 2027 MIT

3 incl. 375 MIT

Fig. G-1
Cost - Major Components & Total
CDIF vs. CFFF

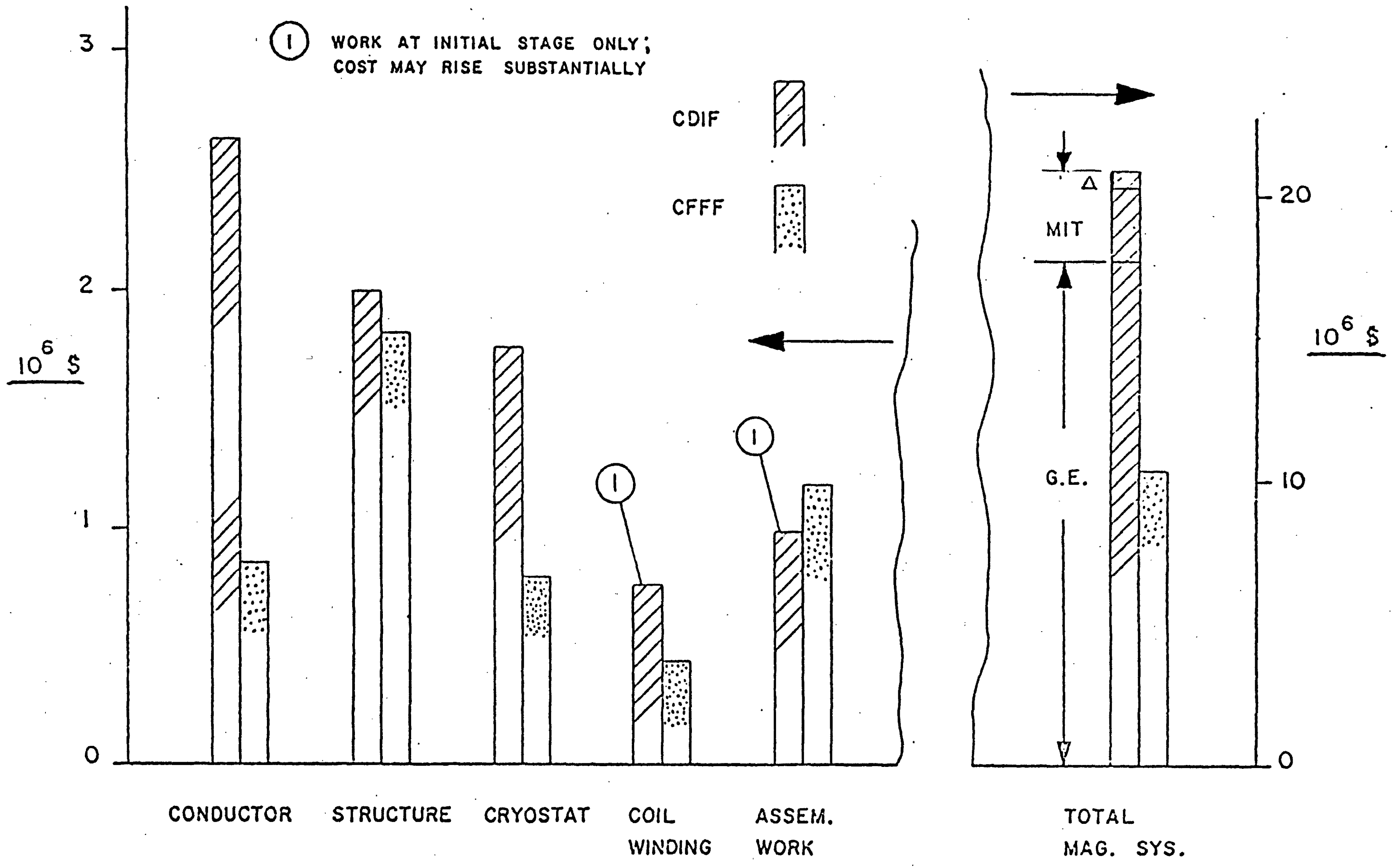


Fig. G-2
Costs - Miscellaneous
CDIF vs. CFFF

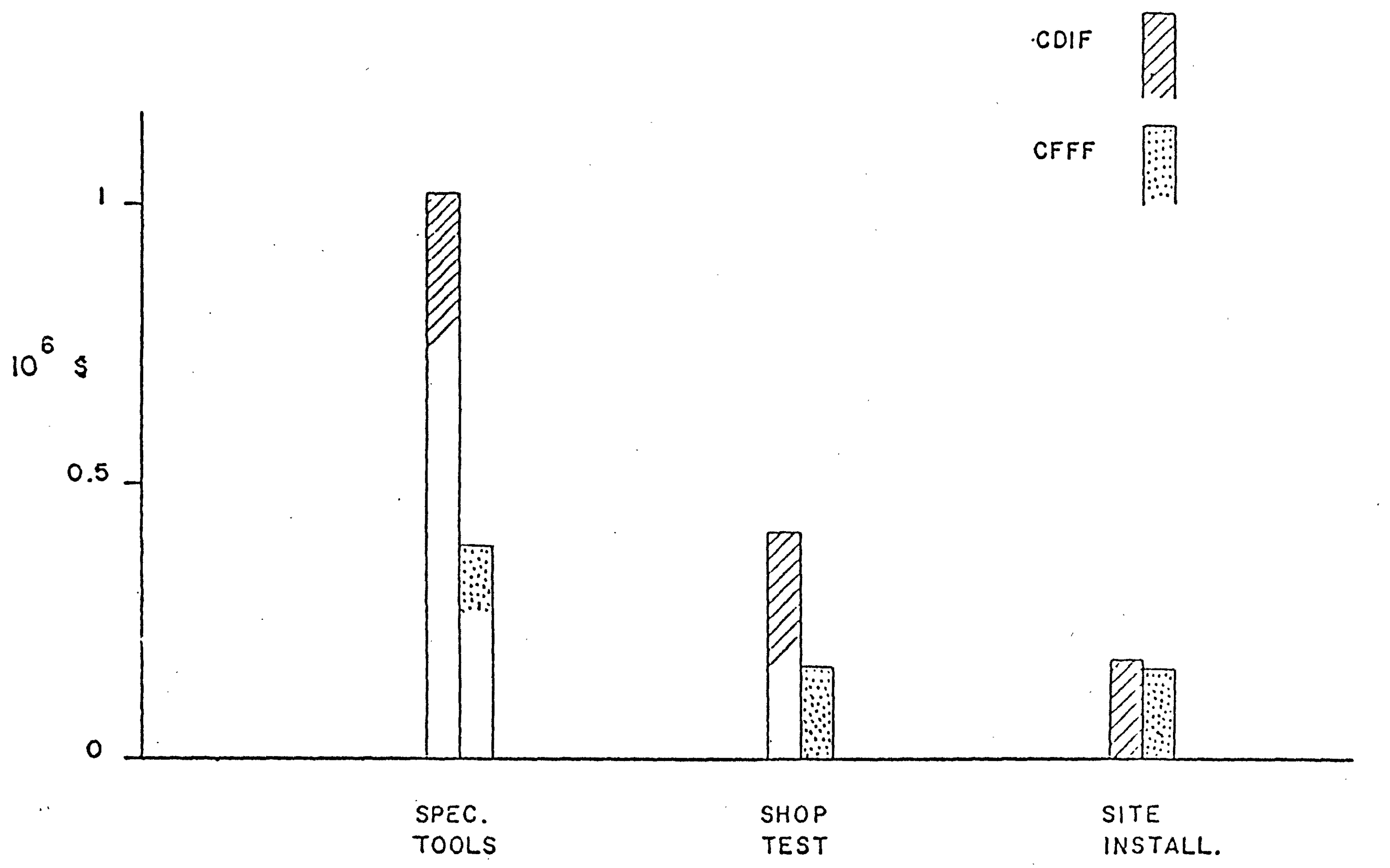


Fig. G-3
Costs - Support & Indirect
CDIF vs. CFFF

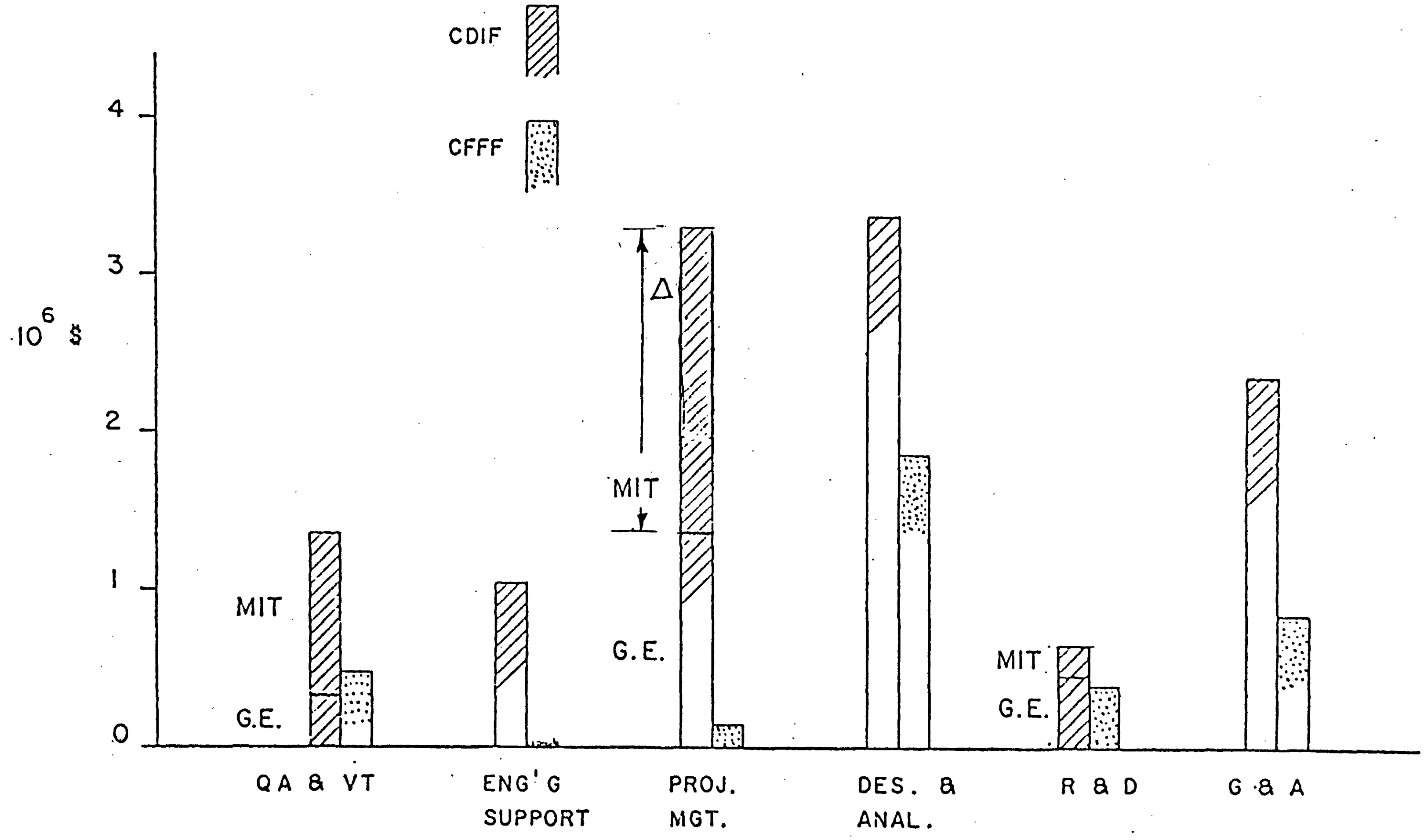


Fig. G-4
Weights
CDIF vs. CFFF

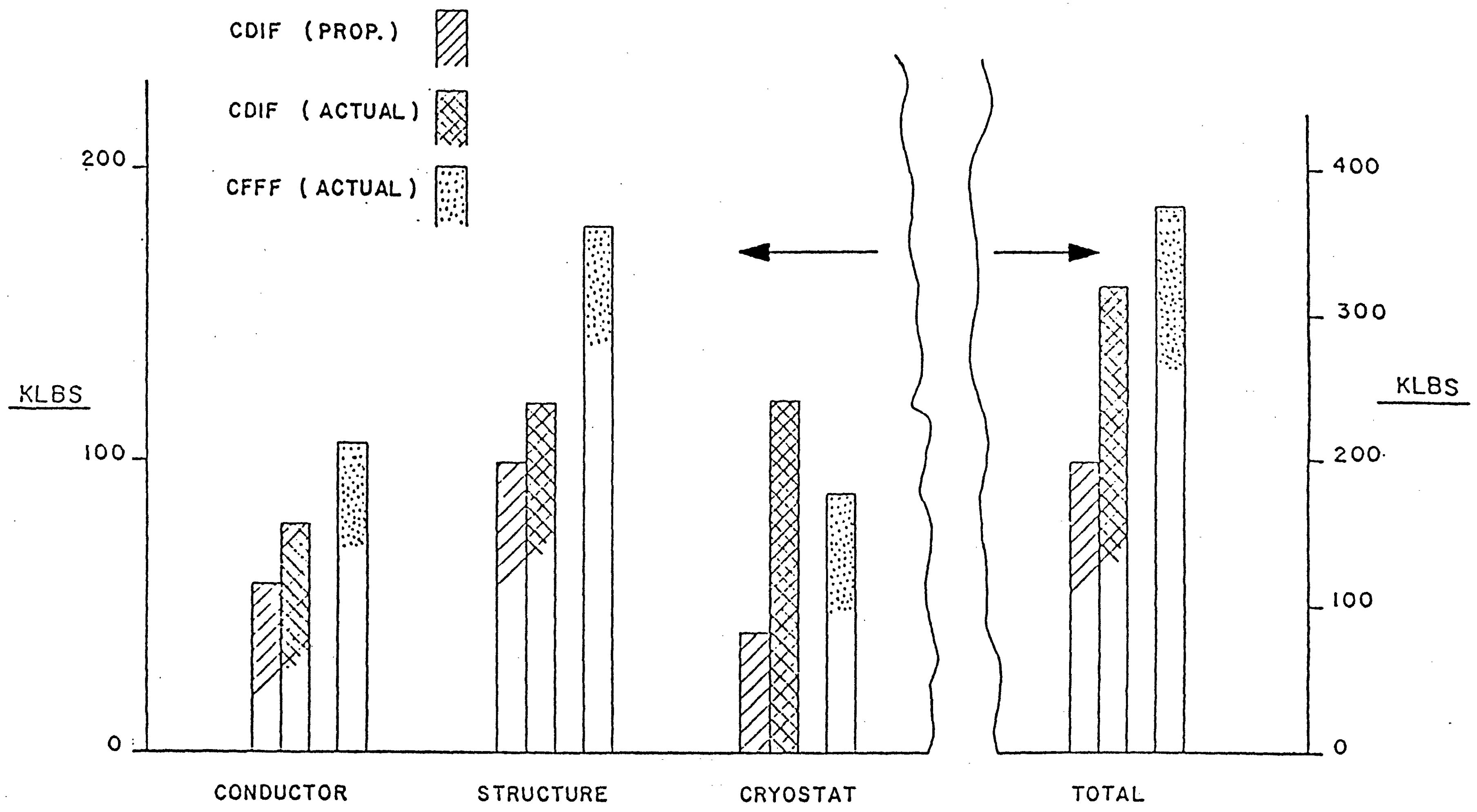
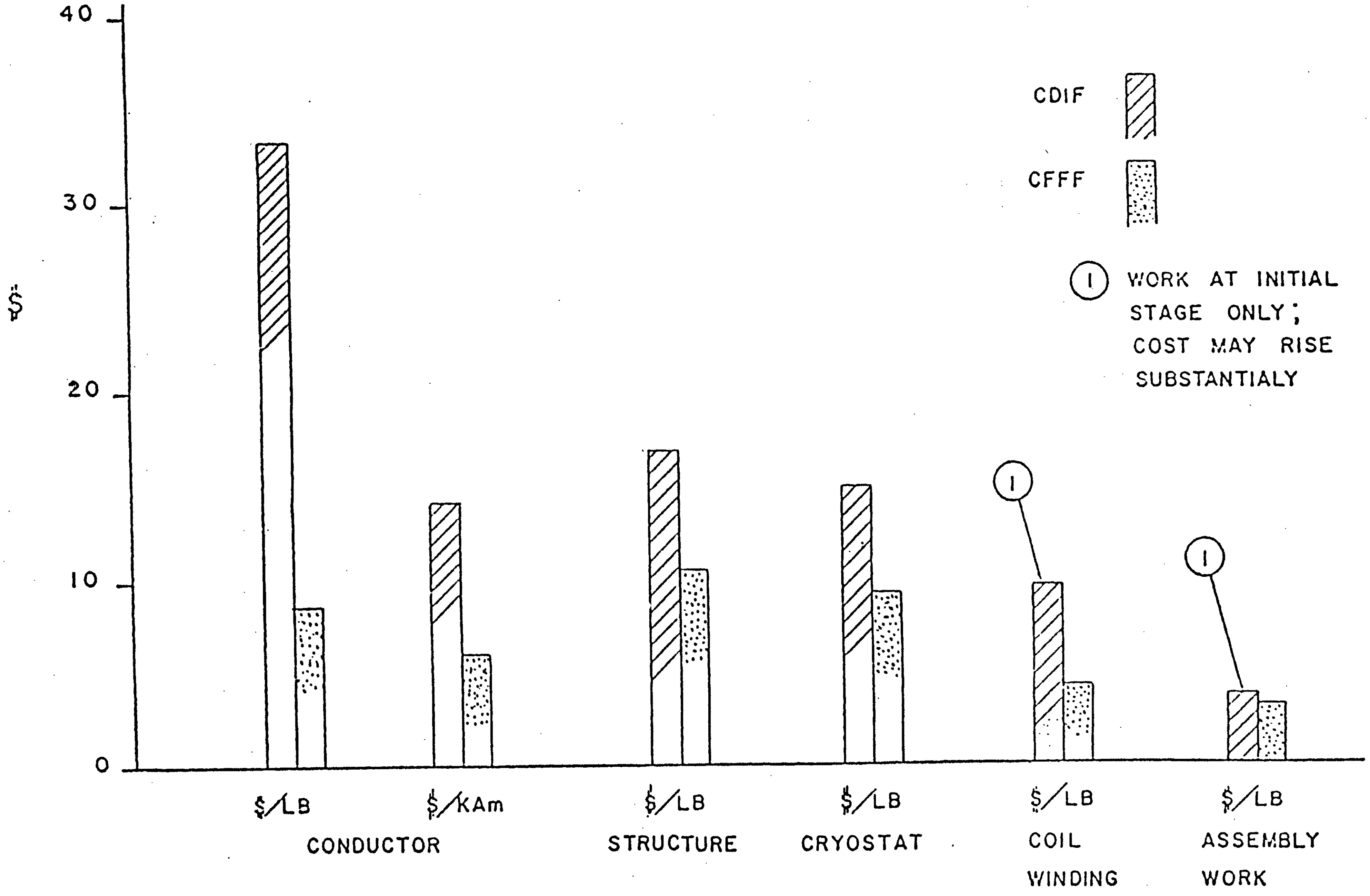


Fig. G-5
Unit Costs
CDIF vs. CFFF



APPENDIX H

Estimated Costs for Drafting

For estimating the cost of drafting necessary to make layouts, assemblies, detail drawings, diagrams, specifications, lists, etc. for a superconducting magnet system, the man-days per drawing as listed in Table H-I was used at the MIT Plasma Fusion Center. These data, based on the experience of PFC drafting personnel, are considered to be representative for good quality drawings as required for the manufacture and assembly of a relatively large one-of-a-kind superconducting magnet system. It is necessary first to estimate the number of drawings of each size (A, B, C, D, etc.) expected to be made for the particular system.

Numbers and distribution of sizes for a recent preliminary magnet system estimate at PFC were as follows:

Type	Size				
	A	B	C	D	E & R
Design layouts					10
Fabrication drawings (assemblies & dets.)	82	44	44	44	20
Diagrams & spec. drawings				24	
Part lists	60				
Tool drawings			30		(various sizes)

Table H-I

Man-Days per Drawing for Various Size Drawings

Size	Man-Days
A	0.6
B	1.3
C	2.7
D	5.6
E & R	10.4

APPENDIX J

List of Symbols and Abbreviations

Symbols

A	Ampere (electric current)
B	Magnetic field intensity, tesla
cm	Centimeter
Cu	Copper
E	Stored magnetic energy, joules
g	Gram
H	Henry (inductance)
He	Helium
I	Electric current, amperes
J	Joule
kA	Kiloampere
kg	Kilogram
kJ	Kilojoule
km	Kilometer
kV	Kilovolt
kW	Kilowatt
ℓN_2	Liquid nitrogen
ℓ	Liter
ℓ/hr	Liters per hour
ℓ_a	Active length, meters
m	Meter
MJ	Megajoule
MW	Megawatt
MWe	Megawatt, electrical
MW_t	Megawatt, thermal
N	Number of turns
Nb	Niobium
T	Tesla (magnetic field intensity)
Ti	Titanium
V	Volt
VB^2	Magnet size parameter (See Appendix B)
Zr	Zirconium
Ω	Ohm (electrical resistance)

Abbreviations

Access.	Accessories
AEP	American Electric Power Co.
AERL	Avco Everett Research Laboratory (now Everett Research Laboratory, Textron, Inc.)
AIRCO	AIRCO Corp.
ANL	Argonne National Laboratory
AVCO	AVCO Corp. (now AVCO Div., Textron Inc.)
BNL	Brookhaven National Laboratory
BL	Baseload
CASK	"CASK" configuration MHD magnet (refers to configuration of winding and substructure developed by GD)
CDIF	Component Development and Integration Facility, DOE, Butte, Montana
CFFF	Coal Fired Flow Facility, DOE, Tullahoma, TN
CEC	Combustion Engineering Corp.
CE	"Chemical Engineering", McGraw Hlll
Circ. sad.	Circular saddle coil configuration
CM	Conventional magnet
CMS	Cold mass support
DOE	United States Department of Energy
ECAS	(DOE study of commercial MHD)
ETF	Engineering Test Facility
EPRI	Electric Power Research Institute
G & A	General and administrative expense
GD	General Dynamics Corp.
GE	General Electric Corp.

Abbreviations cont.

IGT	Institute of Gas Technology
ICCS	Internally cooled cabled superconductor
LCP	Large Coil Program (fusion)
LRL	Lawrence Radiation Laboratory
LNG	Liquified natural gas
MCA	Magnetic Corp. of America
MEA	Magnetic Engineering Assoc.
MHD	Magnetohydrodynamic
MIT	Massachusetts Institute of Technology
MVU	Magnetic volume utilization
NAL	National Accelerator Laboratory (Fermi)
Pd	Power density in channel
PETC	Pittsburgh Energy Technology Center, DOE
PFC	Plasma Fusion Center, MIT
PO	Purchase order
PSPEC	Parametric Study of Potential Early Commercial MHD Power Plants (DOE/NASA sponsored)
QA	Quality assurance
Retro	Retrofit
Rect. sad.	Rectangular saddle coil configuration
SC	Superconducting
U25	U25 MHD Experimental Power Plant (USSR)
USSCMS	United States Superconducting Magnet System (used in U25 bypass loop)
West.	Westinghouse