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Summary

The selection of each dimension of a C-shaped, 18-cps alternating-gradient magnet core lamination is based upon reliability, design, and cost considerations. Cost differentials of magnet-gap height, pole-tip width, return-path widths, etc., are given. Stranded-conductor coils were found significantly more economical to operate than solid conductor coils because of the reduction in eddy-current power. Three cost minimums are discussed: the width of the flux return path, the coil conductor cross section, and the coil aspect ratio. The width of the flux-return path is emphasized and is selected slightly above the minimum cost where the magnetomotive force changes slowly.

Magnet Lamination

This report reviews considerations that led to selection of the lamination dimensions of a C-shaped gradient magnet for the guide field of an 8-GeV injection synchrotron proposed for the 200-GeV accelerator. The magnet cycles at 18 cps; its energy is stored in an inductor and capacitor resonant power-supply system.

The design is simple, and strong emphasis is placed on reliability. The magnetic field in the gap is 7120 gauss and is on the lower side of the cost optimum.[1] Sufficient steel is provided in the core to assure low magnetic and mechanical tolerances.

The gradient magnet has flat pancake coils wound with rectangular hollow copper conductor and has a core laminated with 0.025-in. AISI M-22 electrical grade steel. Other input parameters and calculated values are shown in Table I. Collins quadrupoles or other correcting elements are not included in this study.

The coil and core costs were computed by using an incremental cost expression of the form ($ = a + bx). Total cost as used in this report includes the capital cost of the magnet, power supply, cooling system, and the operating cost of electrical power.

*This work performed under the auspices of the U. S. Atomic Energy Commission.

Magnetic Field

For an 8-GeV injector synchrotron (constant $B\rho$) the cost to increase the magnetic field at the beam orbit from 7.0 to 8.0 kG (Table II) is $316 000 total cost and $219 000 in capital cost. These cost differences refer to the gradient magnet system only, not the entire synchrotron The increase in costs is due mostly to additional electrical storage required for the 13% increase in gap energy. The pole-tip width required at 8 kG is 10 in. because of the field fall-off due to saturation of the pole tip. The core vertical return path increases from 8 in. at 7 kG to 9 in. at 8 kG. The magnetic efficiency is identical for both magnets.

Magnet Gap Height

The gap height has the strongest influence on the cost of a high-repetition-rate magnet system because of the increased stored energy and ampere turns.

Some of the parameters that determine the gap height are the (1) beam shape and size, (2) beam clearance to the vacuum chamber, (3) magnet-gap profile parameter K, (4) vacuum-chamber wall thickness, (5) magnet manufacture and alignment tolerances, (6) magnet gap deflection when powered, (7) vacuum-chamber sagitta allowance, (8) vacuum-chamber manufacturing tolerance, and (9) vacuum-chamber installation allowance. The last three determine the amount of gap space allowed for the ceramic vacuum tank (Fig. 1). The magnet gap can be reduced slightly as fabrication tolerances are improved on the ceramic tank assembly as suggested by Peter Clee in Paper G-3 of these Proceedings.[2,3] Up to $230 000 in total magnet-system cost or $160 000 in magnet-system capital cost can be saved if fabrication and installation allowances of the present ceramic tank are halved and the magnet gap reduced 0.22 in. However, ceramic tank tolerances are approximately known, and to improve the knowledge of the dimensional tolerances will be expensive. Some reduction in tolerances can also be made by grinding the ceramic externally after firing, but it is the position of the inside walls that determine the beam space.

Pole-Tip Width

The pole-tip width is determined by the width of the usable high field which has a gradient-tolerance requirement of 1/2%. The 10-in. wide pole-tip width chosen for the first full-size model has a calculated useful field width 1/8 in. wider than the beam on the high-field side.

In the present study the injector-synchrotron magnet-ring lattice has both focusing (F) and defocusing (D) laminations assembled into a single FD magnet core. If the lattice were changed so that the FD magnets were separated into F magnets and D magnets, then the pole-tip width could be reduced from 10 to 9.5 in. However, separating the magnets requires 120 instead of 80 magnets and extra conductors, power supply, and power are required for 80 more coil ends. Increasing the number of coil ends increases the total cost \$90 000 and the capital cost \$50 000. More magnets also cost more because of the increased number of magnet supports and additional handling and surveying. Separating the FD magnets requires reevaluation of the ring lattice and could lead to a higher magnetic field, if the present amount of straight section is held, or to a larger ring. With separate C magnets, one can use a single lamination shape and alternate the position of the legs to obtain F or D magnets. Having one lamination reduces the die cost, but the alternate-leg arrangement increases the accelerator cost, because a wider tunnel is required. Radiation protection is not as effective with the alternate-leg arrangement as it is when all vertical legs are on the inside radius of the ring.[4] The net cost difference is not significant, and the choice of FD or F and D cores can be based on maintenance and reliability arguments.

Vertical-Leg Width

All gradient magnets are energized by the same current and must have essentially identical B-I characteristics. To assure proper tracking, the magnets are designed with a high magnetic efficiency (NI_{gap}/NI_{total}) as shown in Fig. 2. When the design point is selected on the horizontal part of the efficiency curve, variations in steel properties, the core packing factor, or core dimensions will have only a slight effect on magnet performance. Also, if all magnet units can be made to track the same by the use of more steel in the return path, then back-leg windings, their power supplies, and the extra complication of tuning many leg windings can be eliminated.

It would be desirable to eliminate the need to shuffle the steel laminations. However, because shuffling eliminates many magnetic and mechanical uncertainties at both injection and ejection, shuffling is required.

The calculated gap deflection of a defocusing magnet caused by the magnetic force is about 0.005 in. for a 6-1/2-in. vertical leg width. The focusing magnet has a deflection of about 0.007 in. and a vertical return path of 8 in. This proportionately larger deflection is because the magnet force of the focusing magnet is calculated 5 in. farther from the back leg than the defocusing magnet.

Horizontal-Leg Width

The magnet horizontal-leg width is chosen 1/2 in. less than the vertical-leg width so that the magnetomotive force (MMF) in the two horizontal legs about equals the MMF in the vertical leg. This reduction is based on SYBIL computations for nonoriented steel. These computations do not consider the magnetic permeability difference between the rolling and transverse directions. However, the effect of this anisotropy is believed to be negligible.

The steel is oriented in the lamination with the rolling direction horizontal, which is in the direction of lowest MMF. This orientation allows the flux more freedom to move laterally in the high-flux-density areas of the pole tip. The core packing factor in the pole tip is higher, because the steel is thicker (crown) at the center of the rolled strip.

Magnet Coil Window Width

A 7-in. coil window width in the core lamination is the value corresponding to the minimum total magnet cost[1] shown on Fig. 3. For this particular lattice, the coil window must be at least 6 in. wide to permit any ceramic vacuum-tank section to be removed without moving a magnet. However, a narrow coil width requires less space at the ends of the magnet and allows more straight section for other equipment. The coil window width can be reduced slightly if the coil space factor is improved by reducing the conductor-to-lamination clearance or the insulation thickness. The width can also be decreased by changing the aspect ratio or the coil total cross section. Changing the coil area raises the cost above the minimum, unless the operating life or a cost parameter is changed so as to maintain the minimum cost.

Vertical Clearance Between Coils

Vertical clearance between coils should be large enough to allow (1) the vacuum tank to be removed without removing any coil clamps, (2) vacuum-tank connections to be located between the coils at the ends of the magnets, (3) use of flat magnet coils, (4) the coils to be far enough from the gap that the vibration forces and eddy-current heating in the coil are less, and (5) the coils to be far enough from the gap so that eddy currents in the solid conductor coils will not effect the gap field. The cost effect of the vertical clearance between the coils is $33 000/in. in the range of interest.

Vertical clearance between coils can be reduced to as little as 4 in., while giving up only the ability to locate vacuum connections between the coils at the magnet end. Below a vertical height of 4 in. the vacuum tank cannot be installed without removing coil clamps or moving the magnet, and the advantages of the C magnet are lost.

Vertical spacings less than 2.9 in. between the coils requires saddle-shaped coils in order to clear the vacuum tank at the coil ends. Stranded conductors would probably be required, because the coil is now near the gap and in a higher fringe field. Saddle coils can be designed that require less straight-section space, but all saddle-coil designs require more conductor and are costly to fabricate.

Solid vs Stranded Conductor

Stranded conductors eliminate eddy-current considerations and can be wound without joints; however, they have a smaller space factor. The operating-cost differences between stranded and solid conductors are caused by eddy-current losses in the solid conductor. The eddy-current loss is computed from an average value obtained from SYBIL magnetostatic data—in this case 1.6 W/lb times the conductor weight. The 1.6 value is held constant for all cases studied, since all considered designs are nearly identical. The eddy currents can be reduced by using smaller conductors, but this increases the number of turns, which increases the magnet voltage or the number of power-supply sections.

The eddy-current loss was assumed to be zero for the stranded-coil case. However, some eddy-current losses are caused by the thin-wall copper cooling tube, which is centered in the stranded conductor in the Cornell style, or near the conductors in the Cambridge Electron Accelerator style.

The capital cost for a magnet system having solid-copper conductors is slightly less than one having stranded conductors. The stranded-conductor coil costs more than solid-conductor coil even though the coil does not contain any joints and less power supply is required for the eddy-current power. However, the lifetime total cost of the stranded-conductor magnet system is approximately $200 000 less because of the absence of eddy-current loss. The solid conductor was chosen for the magnet model because coil construction is simple and the repetition rate is only 18 cps.

Coil Packing Factor and Ground Clearance

The coil packing factor is defined as the ratio of the coil conductor area to the window area required in the lamination for the coil. The low space factor for the present solid-conductor design, 0.38, is caused by a 1/2-in. clearance between the conductor and the steel lamination on three sides of the coil. The 1/2-in. clearance to ground reduces the coil capacitance to ground, which in turn reduces the magnet leakage current. Coil insulation thickness, fabrication and installation, and thermal tolerances limit the clearance to about 1/4 in. Reducing the clearance below 1/4 in. decreases the capital costs about $35 000, but moves the conductor into a higher fringe field. A clearance of 1/2 in. between the conductor core is recommended for the first model.

Coil Aspect Ratio

The cost vs coil aspect ratio (width/height) curve is within $20 000 over the 0.8 to 3.0 aspect-ratio range studied (Table II). The minimum cost occurs when the aspect ratio is between 1.5 and 2.0, but because of the flatness of the cost curve, the aspect ratio can be selected entirely upon practical considerations. The most important consideration is the thickness of coil pancakes, which must be thin enough to pass through the magnet gap. There is also an optimum width-to-height ratio for a solid conductor that minimizes the eddy-current losses in the conductor, which in turn influences the coil aspect ratio.

Conclusion

The shape recommended for the gradient magnet model has been described. The magnet design will be based on results of the model, but some idea of the changes can be anticipated and their cost differentials evaluated. The consequences of reducing the magnet gap, the vertical distance between coils, the clearance of the coil conductor to the steel core, and use of stranded-vs solid-conductor coils have been discussed and summarized on Table II. The coil aspect ratio was found to be insensitive to cost, and the pole-tip width, the flux return path, and the coil width will probably remain the same.

Three parameters gave cost minimums: the width of the flux return path, the coil conductor total cross section, and the coil aspect ratio. The coil aspect-ratio curve is very flat and does not effect the cost significantly. The optimum amount of conductor (inverse of power dissipated) is familiar and was not covered in this report.[1] The width of the flux return was selected slightly above the minimum where the core MMF changes slowly.

The gap dimension affects the assembly of the vacuum tank; however, it does not appear that the gap can be reduced more than 0.22 in. below present levels. Vertical clearance between coils can be reduced from 6 in. to 4 in. if eddy currents in the coils do not distort the gap field, and the vertical space between the coil ends is not required. The coil clearance to ground can be reduced to 1/2 in. if it does not reduce the ability of magnet current to track within tolerance because of leakage current. The coil conductor can be changed from solid to stranded. The maximum gains possible from these changes are given in Table III, which shows that the capital cost can be reduced at the most 4.5% and the total magnet system cost 8.5%. The most significant saving is the reduction in operating cost by the use of stranded coils. The effect of design changes on maintenance costs, which are intangible and difficult to predict, should be considered along with capital costs.

Table I. Magnet parameters for the C-shaped gradient-magnet system.

Input data	
Gap magnetic field (G)	7119.
Magnetic radius (in.)	1639.77
Number of magnets	80.
Coil packing fraction	0.380
Current ratio I_{rms}/I_{max}	0.612
Vertical clearance between coils, gaps	1.770
Total machine operating life (h)	67500.
Electrical power cost ($/kWh)	0.006
Coil cost=0.278+2.250*CUWT*1.E-06 ($/lb)	4.26
Core cost=0.785+0.500*FEWT*1.E-06 ($/lb)	0.97
dc power supply ($/kW)	100.
ac power supply ($/kW)	200.
Inductor cost factor	0.16
Capacitor cost ($/J)	0.53
Air cooling system ($/kW)	374.
Water-pump power ($/kWh)	0.00186
Water-cooling system ($/kW)	160.
Water cost ($/kWh)	0.00008

Computed data	
Magnet gap (in.)	3.3971
Magnet profile (m^{-1})	4.4190
Magnet length (in.)	128.79
Total flux lines	6.38×10^9
Pole-tip avg. flux density (G)	9605.
Top leg avg. flux density (G)	12807.
Back leg avg. flux density (G)	12006.
Magnet-gap stored energy (J)	1.56×10^6
Gap peak ampere-turns	48852.
Total turns	40.
Magnet inductance (H)	2.06
Coil I^2R loss (kW)	900.
Core loss (kW)	130.
Eddy-current loss in copper conductor (kW)	222.
Magnet total power (kW)	1252.
Total inductor loss (kW)	1173.0
Capacitor ac loss (kW)	209.9
Total magnet-system loss (kW)	2634.8
Coil window width (in.)	7.0356
Fraction of copper required at coil ends	0.1635
Magnet efficiency (gap Ni/total Ni)	0.988*
Total peak ampere-turns	49406.**
Coil copper weight (lb)	138571.
Core steel weight (lb)	1660782.
Total magnet stored energy (J)	1.57×10^6
Coil copper cost (M$)	0.5898
Core steel cost (M$)	1.6154
Power-supply-system total cost (M$)	1.8674
Water-cooling-system cost (M$)	0.1795
Air-cooling-system cost (M$)	0.0488
Capital cost (M$)	4.3009
Operating cost (M$)	1.4122
Total cost (M$)	5.7131

*Sybil: 0.9877 defocus, 0.9898 focus
**Sybil: 49496 defocus, 49392 focus

Table II. Differential costs determined by the incremental cost method.

	Total	Units	Capital
Magnetic Field* ($B\varrho$ constant)	$ 316 000	$/kG	$219 000
Magnet gap height	1 080 000	$/in.	740 000
Pole tip width	200 000	$/in.	160 000
Vertical leg width	100 000	$/in.	105 000
Vertical distance between coils	33 000	$/in.	33 000
Coil packing factor	54 000	$/0.1	30 000
Coil clearance to ground	220 000	$/in.	140 000
Coil aspect ratio**	<20 000	$	0

*Reference 1 shows that a magnetic field can be found for the gradient magnets that will give a minimum injector synchrotron cost.
**Total cost less than $20 000 over range 0.8 < width/height < 3.0; capital-cost gradient essentially zero.

Table III. Maximum possible dimension changes.

	Capital cost reduction	Total cost reduction
Gap reduced 0.22 in.	$ 160 000	$ 230 000
Vertical distance between coils reduced 2 in.*	49 000	246 000
Ground clearance reduced 1/4 in.	11 000	16 000
	$ 220 000	$ 492 000
Magnet system cost	4 300 000	5 713 000
Maximum cost reduction	220 000	492 000
Minimum cost	$4 080 000	$5 221 000
Maximum reduction	4.5%	8.5%

*Coils also changed from solid conductors to stranded. The unit cost of stranded and solid conductors is assumed to be the same.

References

1. H. P. Hernandez, "Mechanical Aspects of the Injector Synchrotron," UCLRL Engineering Note M3568, May 5, 1965.

2. Peter T. Clee and H. Paul Hernandez, "A Ceramic Vacuum Chamber for a Fast-Cycling Proton Synchrotron," (Paper G-3 of these Proceedings).

3. Peter T. Clee, "Optimization of Length for Ceramic Envelopes," UCLRL Engineering Note M3773, December 28, 1966.

4. H. P. Hernandez, "C- vs H-Shaped Gradient Magnet Core Cross Section," UCLRL Engineering Note M3856, December 12, 1966.

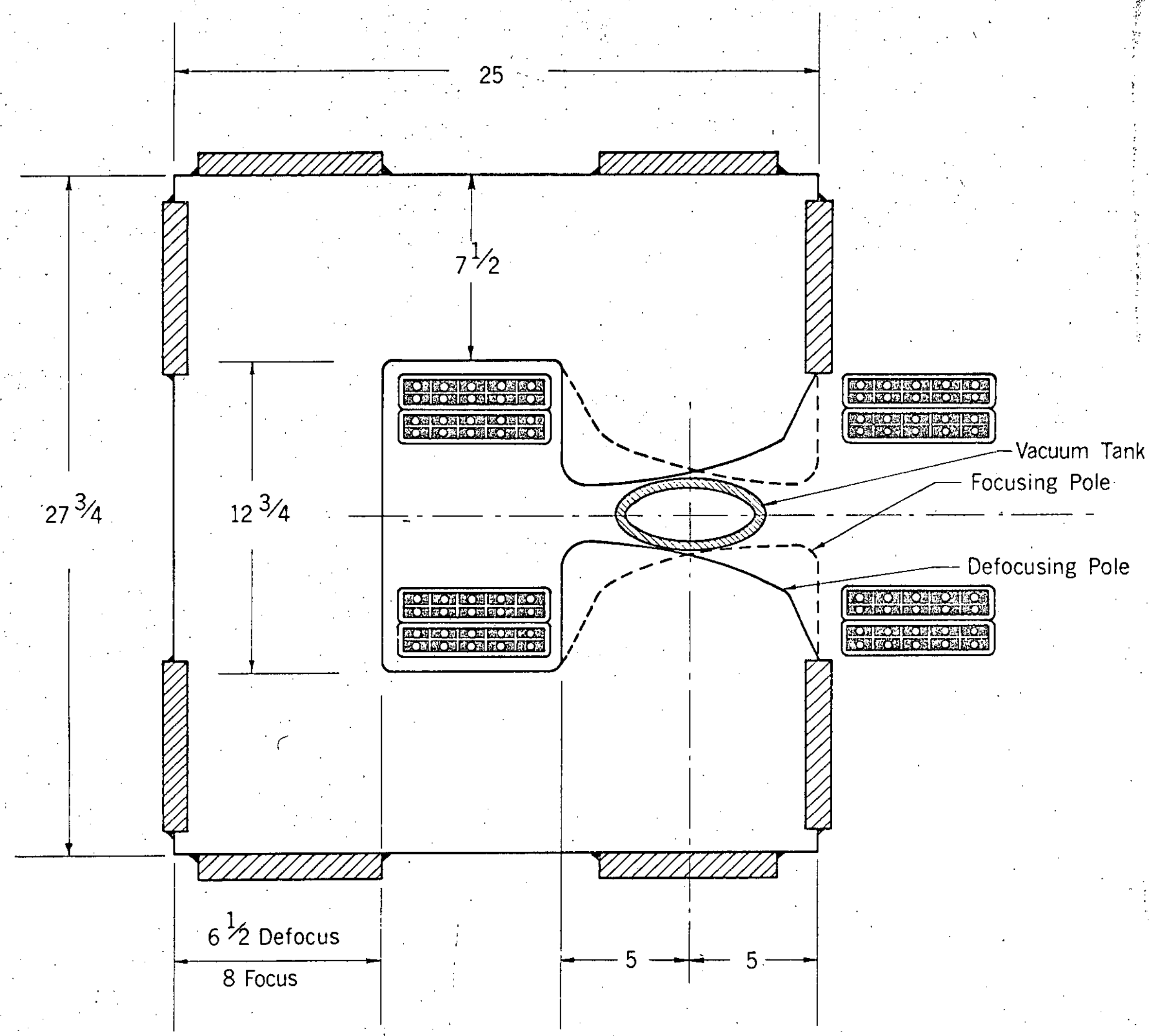
Figure Legends

Fig. 1. Gradient-magnet cross section.

Fig. 2. Effect of the vertical flux-return path width on magnet efficiency, and gradient-magnet system costs.

Fig. 3. Effect of coil width on gradient-magnet system costs.

Fig. 4. Effect of coil aspect ratio (coil width/height) on gradient-magnet system costs.



Injector Synchrotron
Gradient Magnet Cross Section

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Fig. 1

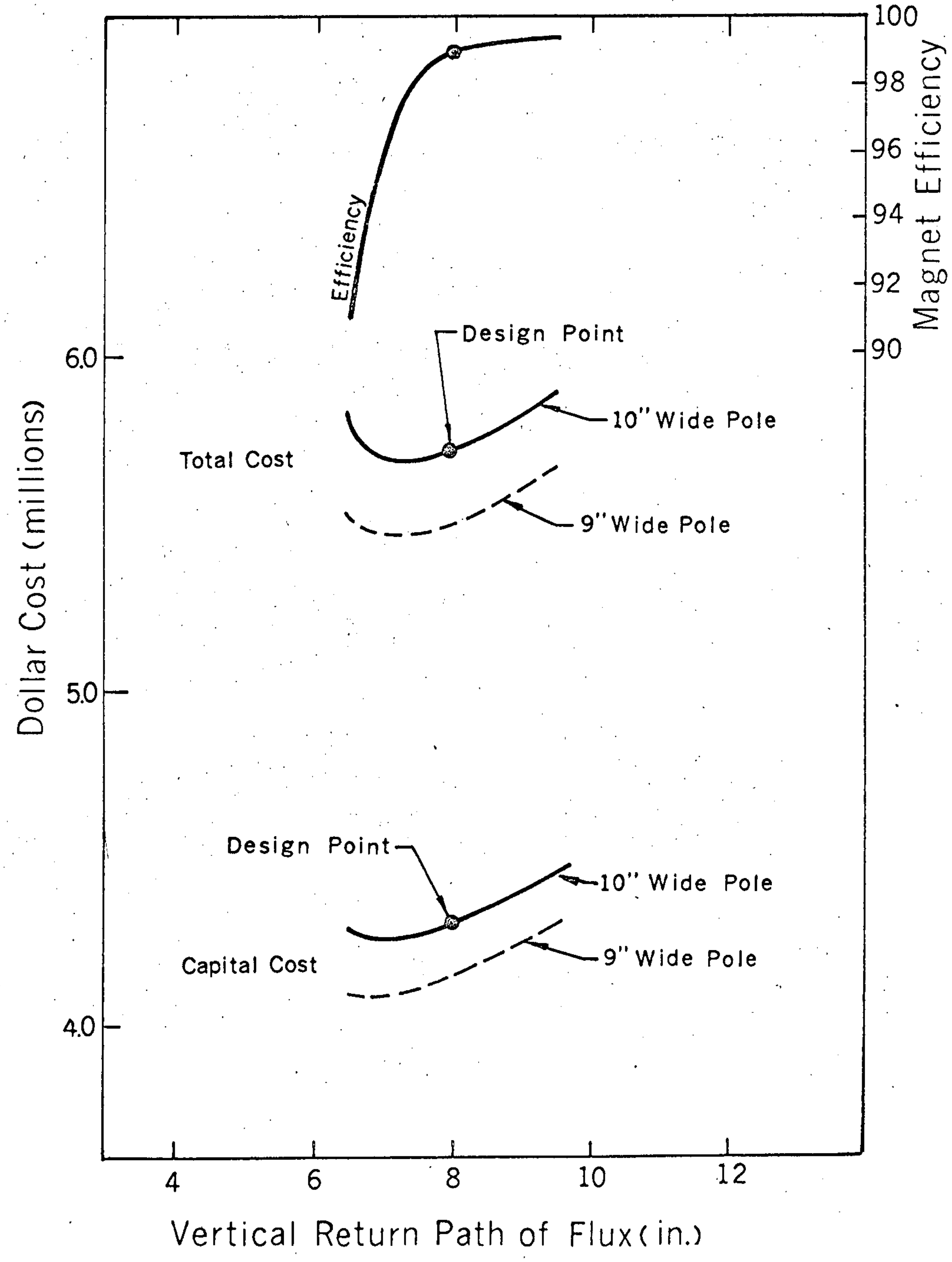

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Fig. 2

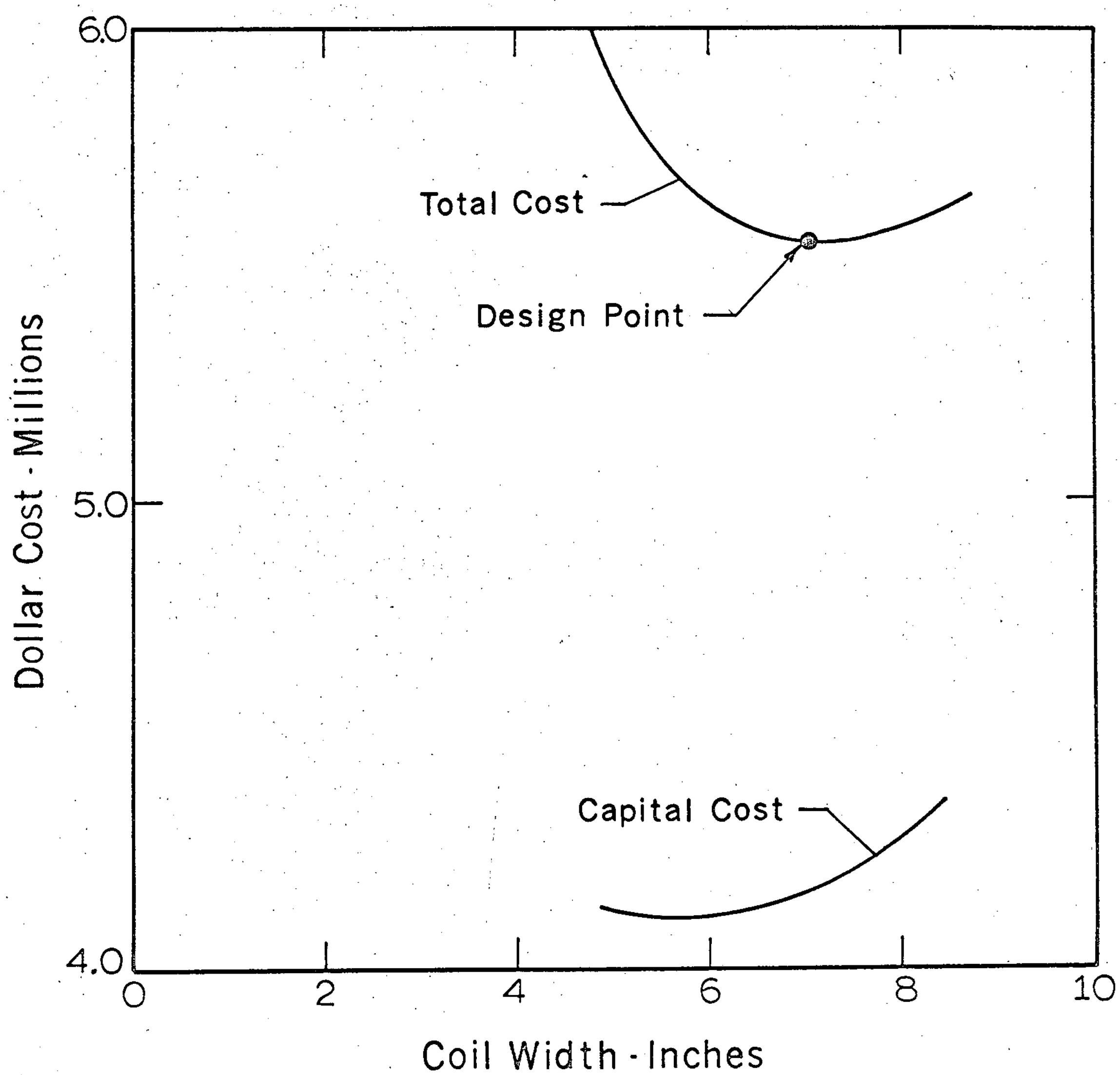

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Fig. 3

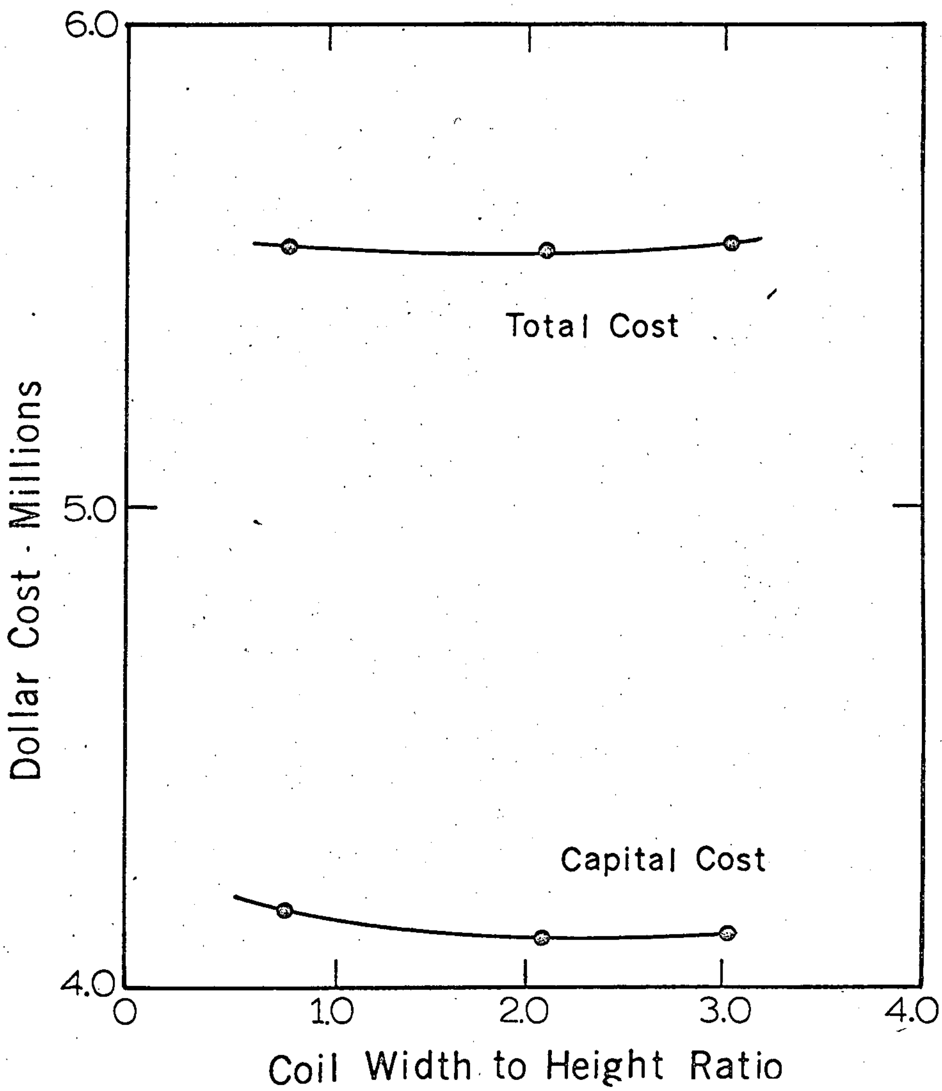

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Fig. 4