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Authors

Dols, Charles G.
Kilpatrick, Robert A.

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University of California

Ernest O. Lawrence Radiation Laboratory

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Summary

Cost studies of magnet designs for a 200-BeV synchrotron led to a novel coil design using cross sections of the conductor that differed for the inner and outer coil sides.

The primary basis for estimating costs of magnet construction was the record of the actual costs of the Brookhaven AGS magnet.

Determinations of optimum magnetic-flux densities and optimum current densities were made by minimizing the total costs of magnet cores, magnet coils, power supply, operating costs, magnet-support structure, correcting magnets, and tunnel enclosure. The studies depended significantly on the use of computer programs for predicting magnetic fields in air and in iron. Operating costs were capitalized by multiplying the cost per year by 10.

Introduction

A group at the Lawrence Radiation Laboratory in Berkeley is engaged in the design study of a 200-BeV proton synchrotron. The magnet ring for this accelerator will have a diameter of almost one mile; it includes several magnet types but this paper will focus on what is by far the most important type, representing over 90% of the total cost of the ring-magnet assembly and called the "gradient-magnet units." Figure 1 is a perspective drawing and Fig. 2 is a cross section of a gradient-magnet unit.

The field in the gradient magnets has a quadrupolar component superimposed on a unidirectional field. The unidirectional "constant" field bends the protons into a closed orbit and the quadrupolar component focuses them within the boundary of the vacuum chamber.

Although the total cost is influenced by a large number of significant variables, the relationships of these variables are relatively straightforward. The grey area in the procedure is introduced by the facts that (a) the choice of the "cost of money," i. e., the interest rate, must be somewhat arbitrary and (b) fabrication cost for a first-of-its-design accelerator cannot be estimated precisely.

The optimization of such a device proceeds logically as an iterative process in which the design parameters are rebalanced periodically as the specifications and cost data are refined.

The present synchrotron magnet is designed to meet the following specifications (Table I):

Table I. Synchrotron Specifications

Injection proton energy	8 BeV
Maximum proton energy	200 BeV
Gradient-magnet type	Open "C"
Beam intensity (protons per pulse)	3×10^{13}
No. of long straight sections	12
Free length in long straight sections	30+ meters
Pulse-repetition rate (pulses per min.)	23 to 30

The above specifications have been translated into a magnet with the following characteristics (Table II):

Table II. Magnet Parameters

No. of standard gradient-magnet units	480
Effective length of each unit	5.7 meters
No. of short gradient-magnet units	24
Effective length of each unit	1.8 meters
No. of Collins quadrupole magnets	24
Effective length of each unit	3.0 meters
Orbit field at 200 BeV	15 kG
Gradient of field at 200 BeV	475 Gcm^{-1}
Useful aperture at injection (ellipse with minor and major axes)	5×12 cm
Total weight of steel	17900 tons
Total weight of copper	1950 tons
Current density in inner conductors	1300 A in^{-2} rms
Current density in outer conductors	1000 A in^{-2} rms
Magnetic "efficiency"	0.93
Average power dissipation in gradient magnet	11.2 MW

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*Work done under auspices of U. S. Atomic Energy Commission.

Cost Estimating

Estimating the cost of a new synchrotron magnet is not an exact science. Our magnet, however, is similar in cross section and fabrication processes to the Brookhaven AGS magnet. The cost estimate of our magnet has been made by a process of comparative extrapolation from the actual costs of the AGS magnet.

We have chosen to subdivide the magnet into four areas for estimating purposes: Core, Coil, Miscellaneous unit costs, and Power and cooling requirements. Both core and coil are further divided into material and fabrication costs. For convenience, we have referred all core costs to net tonnage of steel, "NTS," all coil costs to net tonnage of copper, and all miscellaneous costs to a unit magnet.

Basic material costs for the AGS magnet are known. Our core material is to be a decarburized steel. Tentative costs have been obtained from fabricators. To the base-material cost per net ton we have added shipping costs and then multiplied this by scrap and overrun factors to arrive at a total material cost in dollars per net ton of steel. The same process was applied to the coil-material costs, but with the cost of insulation added.

From the AGS cost summary, total specific costs of the core and coil in dollars per net ton were determined. Subtracting the pertinent material costs from these gave the specific fabrication costs. The major processes in core fabrication are: shuffling the steel blanks, punching the laminations, stacking, machining, welding, and inspection. The major processes in coil fabrication are: bending and machining the conductors, assembling and brazing the joints, installing and curing the body insulation, installing and curing the ground-plane insulation, and inspecting. Within each area--core and coil--an extimated breakdown of the fabrication processes was made, so that we had estimated costs, in dollars per net ton for each of the above processes. At the same time, the miscellaneous unit costs were itemized from the summary in dollars per unit magnet. This category was separated from core and coil because the costs of the items are not direct functions of core or coil weight. All of these costs were then escalated to 1965 dollars. The AGS contracts were placed about 8 years ago. Our best estimate is that fabrication costs for this type of equipment have risen about 4% per year. Thus the escalation was for 8 years at 4%.

A comparison of significant parameters of our magnet and the AGS magnet was than made and used as the basis for extrapolating specific fabrication costs. For instance, consider the shuffling operation (probably a hand operation). Our magnet calls for half as many blanks per ton as the AGS magnet, but our blanks weight approximately twice as much. We estimate that our shuffling cost per net ton should be about 80% that of the present cost of shuffling the AGS steel. This process is too involved and inexact to warrant further discussion. Even so, we believe it to be more valid than a straight escalation.

After the process costs were estimated, they were added to the material costs to give the desired specific costs of core and coil. These plus the similarly extrapolated miscellaneous unit costs were used to determine a total estimated cost for the ring-magnet assembly.

For economic optimization, incremental costs are needed. Incremental costs differ from specific costs, previously determined, because certain items and processes remain relatively constant through small weight changes in core and coil. Tooling, number of core end plates, number of bends and braze joints--all are fixed. Our estimates of the incremental costs are:

Incremental cost of core	- $ 900 per ton
Incremental cost of coil	- $4000 per ton

Power and cooling requirements are the result of direct calculation instead of comparative extrapolation. Computer programs SIBYL and TRIM, which were used primarily to determine the pole profile, also supplied estimates of total excitation, core reluctance, and total magnetic-field energy. The total energy was used by the magnet power-supply group to assess the reactive power requirements. The total excitation, along with coil geometry and certain cooling-water parameters, was fed into another program called COILTEM that calculates factors such as the heat load, and temperatures of conductor and water.

Cost Optimizing

Optimum Flux Densities and Current Densities

Although the final selections of design features and the magnitudes of design parameters are usually influenced by "intangible" considerations, such as the high yet indeterminate value of convenient access to the vacuum chamber, nevertheless the gradient-magnet design has evolved to its present form in direct response to the results of cost studies.

When a magnet design is close to an overall optimum, the determination of optimum magnitudes of flux densities and current densities can be separated into four separate procedures:

1. Optimum flux density in the gap is determined by balancing the sum of the costs of gradient magnet, correcting magnets, and power supply (PS) against the cost of the tunnel (Table III).

2. Optimum flux densities in the iron are determined by balancing the costs of iron in the magnet, magnet support, and tunnel cross section against power-supply and cooling-system costs plus power costs.

3. Increasing the total amount of conductor in the window side of the coil increases the amount of iron core required to carry the flux around the coil side. The increased coil size reduces the average power dissipation. Minimum cost corresponds to that coil size for which an increase (or decrease) in coil and copper cost is offset by an equal decrease (or increase) in power cost.

4. Optimization of the outer coil side is done in a manner similar to Item 3. However, since an increase in the amount of copper for the outer coil side does not increase the cost of the magnet iron, the optimum size of the outer coil side is significantly greater than the inner. We find optimums at rms current densities of 1000 amperes per square inch for the outer coil conductors and 1350 amperes per square inch for the inner.

Table III lists the incremental changes in costs of tunnel, power supply, gradient magnet, and correcting lenses for a range of magnitudes of peak orbit fields. The reference field is 15 kG. By interpolation the table shows that the cost minimum corresponds to 15.7 kG. The present magnet design will operate at 15.1 kG when the proton energy is 200 BeV. The difference in total costs corresponding to this departure from optimum field level is less than 0.2% of the total costs of the magnet and tunnel system. The magnet system will be easier to operate at the lower field and will have shorter correcting magnets. On the other hand, a shorter tunnel circumference corresponding to the higher field would be helpful. Overall, the present choice of peak field seems to be a very good balance between the significant cost and convenience factors.

The study of optimum flux density in the gap was made while holding constant the conductor current density and the magnetic efficiency. The small changes in power-supply costs in that case correspond to changes in peak stored energy in the magnet. When the current densities and magnetic efficiency remain fixed the average power consumption is approximately constant.

Optimum average flux densities in iron were determined by computing the variations in total cost corresponding to variations in the cross section of the iron. The optimum pole-body contour is shown in Fig. 2. The optimum cross section of the flux return path can be stated in terms of magnetic efficiency, i. e., the ratio of mmf that would be required with iron of infinite permeability to that actually required. The optimum was found at a magnetic efficiency of 0.93.

Computer programs SIBYL and TRIM, originated by Richard Christian and Alan Winslow (respectively), were used extensively in these cost-optimization studies. Both programs include the effects of finite nonuniform iron permeability in modeling the magnetostatic behavior of two-dimensional magnets.

The determinations of optimum iron flux density and optimum current densities are sensitive to the cost of electric power. The power needed for the synchrotron magnet includes the power-supply losses, the power dissipated in the magnet windings, and the power used by the cooling system. The cooling system uses power for water pumps, heat pumps, and cooling-tower fans.

Although it is impossible to predict the exact cost of the power that will energize the synchrotron magnet many years in the future, an estimate must be made since the magnet design is rather sensitive to the cost of power. Furthermore, the estimate of the cost of power must be converted to its "present value" to put it on a basis equivalent with the capital costs.

Present Value of Power Cost

The present value of the cost of power is taken as the estimated cost of power for 10 years of operation. This basis has the support of precedent and intuitive "reasonableness." Its reasonableness can be explored (or demonstrated, depending on the point of view of the individual reader) by considering an equivalent program of costs for a "reasonable" interest rate, i. e., 6%.

Figure 3 is an illustration of a program of operating cost that has a present value equivalent to 10 times the yearly operating cost. "Time-zero" is taken as the horizontal position of the centroid of the curve of the construction expenditures. The equivalent starting time for the operating costs is time-zero plus three years and is the time corresponding to the same total cost when the full operating-expenditure level is extended backward in time. The present value of 1.0 at a time 3 years from "now" is 0.840. The present value of an annuity of 1.0 for 22 years is 12.04. Thus, with interest at 6%, the present value of the operating costs represented on Fig. 3 is $0.840 \times 12.04 = 10.1$ times the yearly operating cost.

The estimate of "innage" is 0.8, i. e., the fraction of the total time that the magnet will operate is 0.8. This corresponds to two eight-hour shifts per week for maintenance plus a total of six weeks of total shutdown per year.

It is assumed that, when the magnet is pulsing, three fourths of the time will be at full power and one fourth at one-half power. The power duty is thus $[3/4 + (1/2 \times 1/4)] \times 0.8 = 0.7$.

The total power for 10 years is thus equivalent to full power for $0.7 \times 10 \times 365 \times 24 = 61\,320$ hours.

Table III. Accelerator Cost Increments vs Peak Magnetic Field

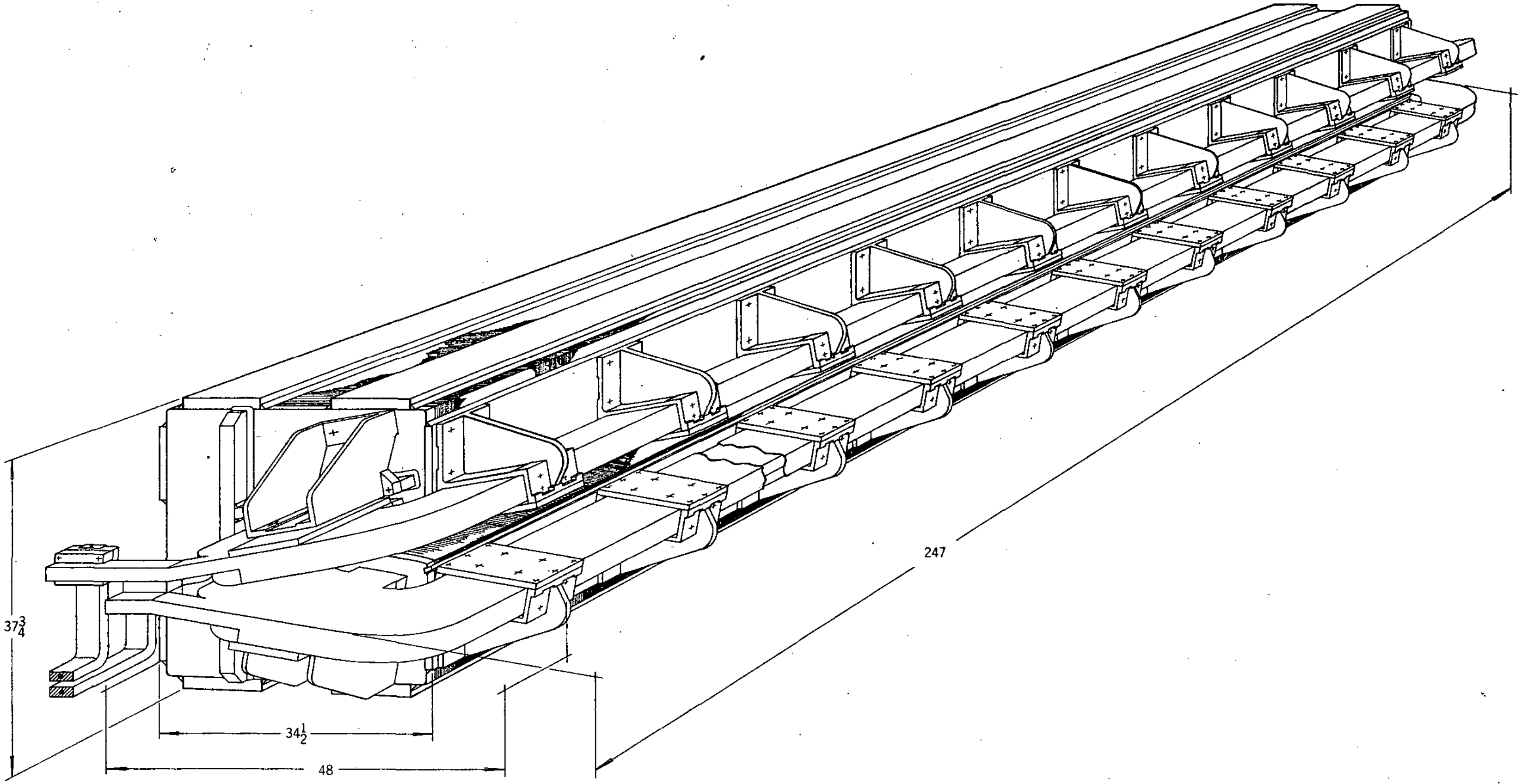
Max. orbit field, B_0 (kG)	Incremental changes in cost (thousands of dollars)				
	Tunnel and magnet support	Power supply	Magnet core	Correcting magnets	Net
14.0	+1335	- 72	-579	-250	+436
14.5	+ 642	- 36	-292	-143	+171
15.0	-	-	-	-	-
15.5	- 595	+ 36	+294	+180	- 85
16.0	-1148	+ 76	+591	+405	- 80
16.5	-1660	+108	+392	+675	+ 15

Figure Captions

Fig. 1. Gradient-magnet assembly (dimensions are in inches).

Fig. 2. Gradient-magnet cross section (dimensions are in inches).

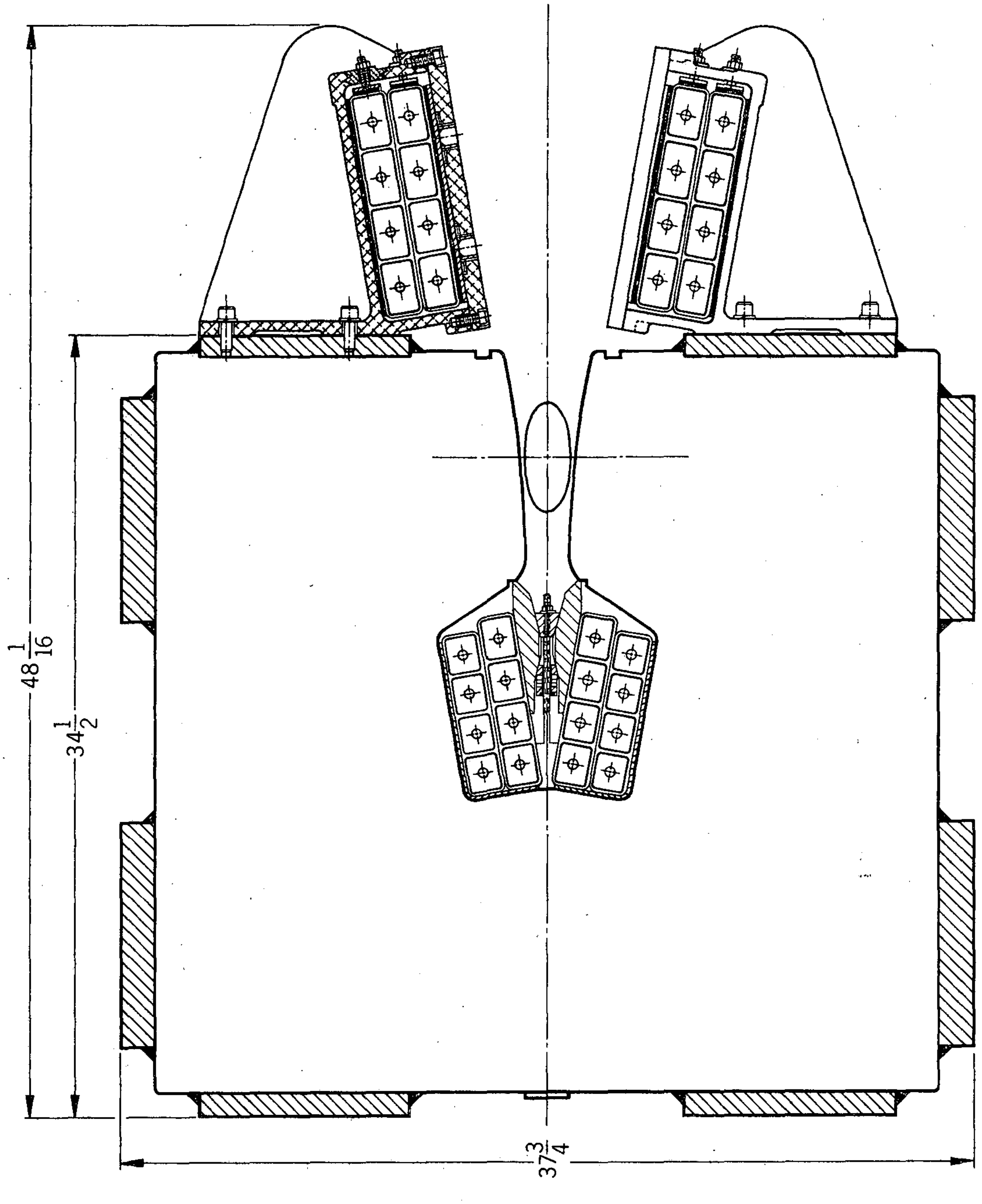
Fig. 3. As assumed expense schedule for the gradient magnets.



Gradient Magnet Assembly

MUB-5377

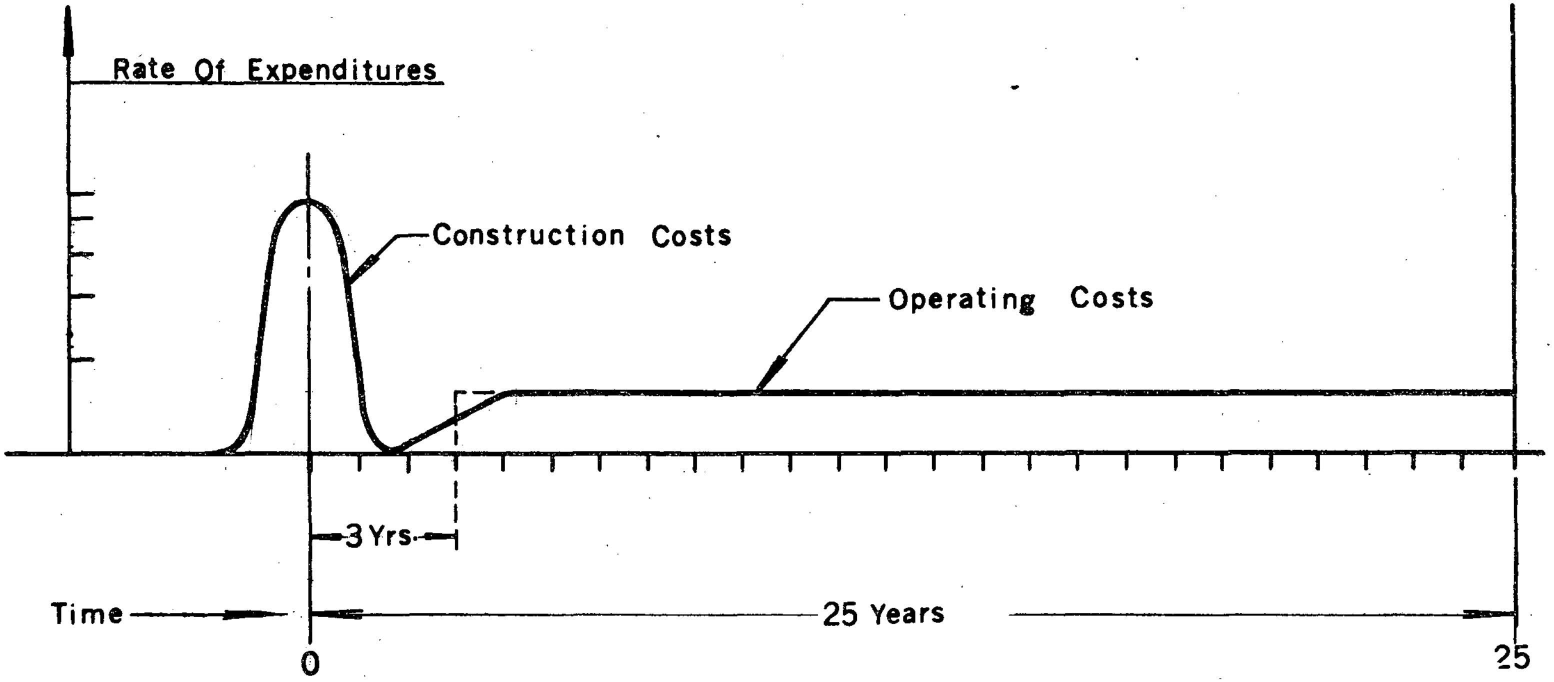
Fig. 1



Gradient Magnet Cross Section

MUB-5378

Fig. 2



An Assumed Cost Schedule

Fig. 3

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