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ABSTRACT

Actual costs are presented for the Berkeley 88-inch cyclotron. Tables show occupational rates, cost summary, design costs, cost by major categories, detailed cost breakdown, and unit costs. Graphs show laboratory effort versus time.

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After one or two polite inquiries of a technical nature, the first question, put I think rather indelicately, to a group proposing a new accelerator is: "How much will it cost?" and the next is: "How many people will it take?", with its important corollary: "Where do you think you are going to get them?".

Unfortunately these questions are always asked (and must be answered) during the initial chaos before the main parameters, let alone the detailed design, have been established. It is difficult enough to estimate the cost of an item even after all the working drawings are prepared. At our Laboratory each engineer must estimate the man-hours for each job for which he is responsible, before the drawings go to the shop. The average of all mechanical engineering jobs for the past three years showed that the actual work exceeded the estimated work by about 20%. I mention this only to indicate that it is hard enough to make estimates with all the information at hand; much more so, of course, in the vague early stages of a project.

Various methods exist for making accelerator cost estimates. One of these is the "factor method." This involves choosing a price which sounds reasonable, and then selecting a factor by which to multiply it—because you know perfectly well that you can never build anything for a reasonable price. The success of this method obviously depends upon the selection of the proper factor. Some authorities use 2 or 3, others insist that e or π are more rational. Another method used at our Laboratory with success by W. Dexter, a well-known expert in this field, involves the use of a Table of Random Numbers.

† Work done under the auspices of the U.S. Atomic Energy Commission.

†† On leave at Rutherford High Energy Laboratory, Harwell, England.

The principal method used on the Berkeley 88-inch cyclotron was the comparison method, in which the cost of a new article is deduced by comparing it with that of an old article, making due allowance for changes in design and for changes in cost between the dates of manufacture.

The total cost of an accelerator or component built at a laboratory may be expressed as follows;

TOTAL COST = DESIGN COST + LAB SHOP COST + COST OF PURCHASES.

$$C_T = C_D + C_S + C_P . \qquad (1)$$

Pay rates and overhead charges for both design and shop change with time. Also, the cost of purchased items increases due to inflation. Let

R_D = old design rate (\$/hr),

R'_D= new design rate (\$/hr),

R_S = old shop rate (\$/hr),

R'_S= new shop rate (\$/hr),

R_P = old price index (relative cost of purchased items),

R'_P = new price index (relative cost of purchased items),

C = old cost,

$C' = \frac{R'}{R} C$ = new cost.

Then from (1),

$$C'_T = \frac{R'_D}{R_D} C_D + \frac{R'_S}{R_S} C_S + \frac{R'_P}{R_P} C_P . \qquad (2)$$

It turns out that at Berkeley the design cost, the laboratory shop cost, and the cost of purchases are roughly equal for an accelerator or typical component; that is,

$$C_D = C_S = C_P = 1/3\ C_T.$$

So eq. (2) may be written

$$C'_T = 1/3\ C_T \left(\frac{R'_D}{R_D} + \frac{R'_S}{R_S} + \frac{R'_P}{R_P}\right) \, .$$

The cost of the Berkeley 88-inch cyclotron was based largely on the cost of the Livermore 90-inch cyclotron completed in 1955. The two machines are, of course, of entirely different types, so the cost comparison was made not as one lump sum but by major components, allowing for changes in design and for changes in cost, according to eq. (3).

Electrical cost estimates were made by W. Dexter and B. Smith, and building estimates by T. Myhrer and R. West (all at Lawrence Radiation Laboratory). We feel very fortunate that the final cost of the machine is within 2% of the initial estimate, including preliminary studies. The final cost of the building exceeded the initial cost estimate by 37%. This, however, was not due to faulty estimating but is rather the result of the carefully considered decision to greatly increase the size of the building over that originally contemplated. As initially planned the building net area was 17 000 ft^2; the final net area is 33 000 ft^2. The unit cost ($\$/ft^2$) was actually lower in the final building than in the original estimate.

To make this paper as useful as possible to anyone else involved in making cost estimates, we will present the cost figures on the Berkeley 88-inch cyclotron. These figures can then be used as a base case for cost estimating on other accelerators, making appropriate changes for differences in design and for changing costs as indicated by eq. (2). Fortunately this machine is a very clean-cut typical example of accelerator construction at Berkeley. This machine experienced all the usual kinds of contingencies: the "accident" type of contingency, such as the dropping of one of the main-coil pancakes when a crane cable snapped; the "external" type of contingency, as exemplified by the steel strike which held up magnet delivery; and the "technical" contingency, such as the midstream decision to increase the proton energy. Furthermore, while Berkeley makes no claim to being a Gem of Efficiency, we can say that the figures presented here honestly include all costs.

It is, of course, recognized that institutions differ very much in their cost accounting procedures. Methods of charging overhead vary considerably. Some make no charges for professional salaries and other technical help. As seen from eq. (2), this means that for two institutions designing and building identical machines, the costs could vary as much as 3 to 1.

It is, then, essential to present at the outset the actual rates of charges on our machine for different kinds of occupations. These are shown in table 1. Rates shown are averages for the different occupations, including overhead. The design was started early in 1958 and is considered essentially complete as of May 1, 1962. The rates shown in table 1 are for October 1960. This data represents the approximate "center of gravity" of the total-effort curve shown in fig. 1. When the occupational rates were plotted for the last ten years, various sudden changes could be seen, reflecting changes in accounting procedure. Smoothing out these bumps indicates that these rates, when used for predicting future costs, should be increased linearly with time at about 4 to 5% per year. Similarly, the cost of materials and building costs also show a linear increase with time at 4 to 5% per year. These latter two items were checked by plotting the Metals Index published by the U. S. Bureau of Labor Statistics, and the Cost of Industrial Buildings in San Francisco published in the Architectural Record.

The latest available actual cost figures on our machine are as of February 28, 1962. At that time many of the subaccounts were closed out. Remaining costs, which are relatively minor, were extrapolated from cost curves to April 16, at which time the project will change from a construction to an operations status.

It is convenient to present cyclotron costs in various ways. First let us look at the cost summary shown in table 2. "Total Accelerator Cost" is only for the accelerator proper, and does not include external beam-handling equipment, such as quadrupoles and switching magnet. This cost does include the main-vault shielding for the cyclotron, but does not include shielding for the experimental caves. No experimental equipment is included. "Preliminary Studies" is shown as a separate item; it includes theoretical work, model magnet studies, rf model studies, and ion-source development—amounting to \$380 000 total. This was a so-called "operations" account whereas the other costs shown are on a "construction" account. Operations accounts carry a higher overhead than construction accounts. To be consistent with the other numbers shown in the various tables, the amount for Preliminary Studies is adjusted to \$250 000 to allow for this difference in accounting procedure

Other tables show a variety of costs for our machine:

Table 3 shows a breakdown of accelerator design costs,

Table 4 shows accelerator costs by major categories,

Table 5 shows building and site costs by major categories,

Table 6 shows a detailed breakdown of accelerator costs,

Table 7 shows some miscellaneous unit costs.

In applying the unit costs of table 7, considerable discretion must be used. For instance, in the case of the main coils this unit cost should only be applied to coils of similar size and construction.

The manpower requirements are shown in the self-explantory curves in fig. 1. It should be noted that these curves apply only to laboratory personnel and do not include people on outside contracts.

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Fig. 1. Manpower requirements for the Berkeley 88-inch cyclotron (Laboratory personnel only).

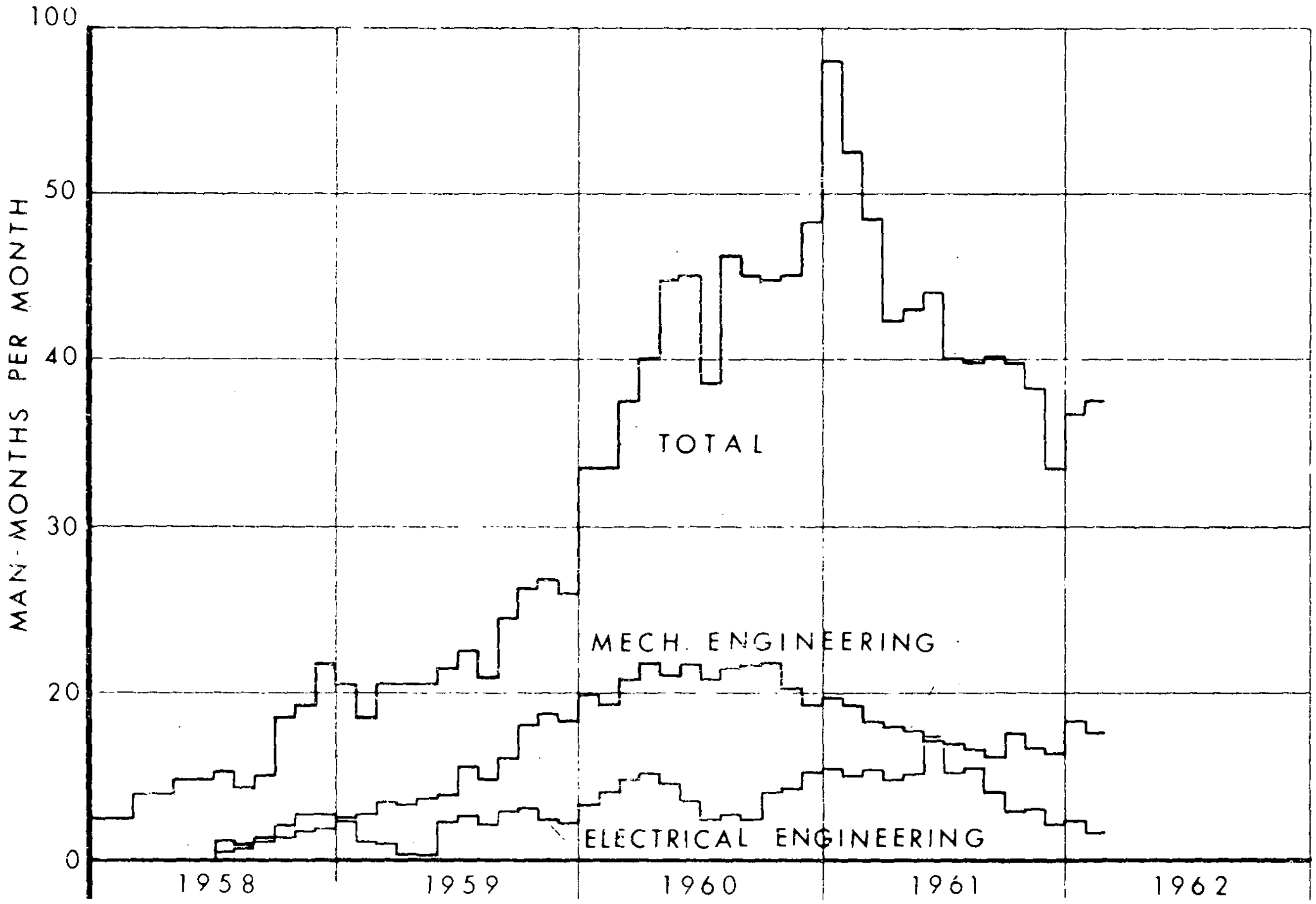

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Fig. 1

TABLE 1

Berkeley occupational rates for October 1960*

(as charged against the 88-inch cyclotron)

	($/hr)
Carpenters, painters	4.90
Electricians, plumbers	5.60
Mechanical shops	5.25
Engineering	5.75

*These rates include overhead. When using these rates for predicting future costs, it is suggested that they be increased linearly with time at 4 to 5% per year.

TABLE 2
Cost summary

Accelerator		
Construction	$1 990 000	
Design	1 210 000	
Preliminary studies	250 000*	
Total accelerator cost		$ 3 450 000**
Building and site		
Construction	$1 500 000	
Design	150 000	
Total building and site cost		$1 650 000
Total project cost		$5 100 000

*Preliminary Studies cost is $250 000 if charged as "construction" account, $380 000 as "operations" account. (Shown here as construction account to be consistent with other numbers.)

**This is only for the accelerator proper. Does not include external beam equipment, experimental apparatus, or experimental caves.

TABLE 3

Accelerator design costs

Project adminstration	$ 74 000
Theoretical group	100 000
Magnet test group	133 000
Mechanical engineering	633 000
Electrical engineering	270 000
Total design costs	$1 210 000

TABLE 4

Accelerator costs: major categories

General	
Project administration	$ 74 000
Theoretical group	100 000
Magnet test group	133 000
Preliminary studies	250 000
Major components (including engineering)	
Magnet	489 000
Magnet power supplies	259 000
Magnet-measuring equipment	81 000
rf system	709 000
Vacuum system	208 000
Dee tank	61 000
Ion source	125 000
Probes	65 000
Deflector	170 000
Water distribution system	29 000
Shielding	450 000
Controls, instruments, and miscellaneous electrical	247 000
Total accelerator cost	$3 450 000

TABLE 5

Building and site costs: major categories

Architect and engineers fees, site	$ 9 000
Site preparation	36 000
Architect and engineers fees, building	144 000
Building construction	1 150 000
Equipment	121 000
Crane	68 000
Electrical utilities to site	83 000
Mechanical utilities to site	31 000
Site fencing	8 000
Total building and site costs	$1 650 000

TABLE 6

Accelerator costs: detailed cost breakdown

<u>General</u>	
Project administration	$ 74 000
Theoretical group	100 000
Magnet test group	133 000
Preliminary studies	250 000
<u>Components, mechanical costs (including engineering)</u>	
Magnet, miscellaneous	33 000
Magnet main coils	106 000
Magnet trim coils	174 000
Magnet core	142 000
Magnet pole tips	134 000
Magnet-measuring equipment	67 000
rf system, miscellaneous	40 000
Oscillator	52 000
Dee	41 000
Dee stem	36 000
Panels	199 000
Resonator tank	81 000
Transmission lines	49 000
Pre-exciter oscillator	5 000
Vacuum system	188 000
Dee tank	61 000
Deflector	150 000
Ion source	105 000
Probes	40 000

TABLE 6 (continued)

Water distribution system	29 000
Shielding	450 000
Components, electrical costs (including engineering)	
Magnet power supply	71 000
Magnet trim-coil power supplies	188 000
Magnet-measuring equipment	14 000
rf power supply	102 000
rf oscillator	62 000
rf model (part only)	22 000
rf instruments	10 000
Pre-exciter oscillator	10 000
Vacuum system	20 000
Deflector power supply	20 000
Ion source power supply	20 000
Auxiliary power supply	25 000
Controls, instrumentation	215 000
Beam phase detector	10 000
Phase probe	15 000
Servo equipment	7 000
Total accelerator cost	$3 450 000

TABLE 7

Some miscellaneous unit costs

Magnet core, installed (excluding engineering)	
275 tons @ $135 000	$490/ton
Main coils, installed (excluding engineering)	
10 tons @ $ 98 000	$9 800/ton
Concrete shielding blocks, installed (excluding engineering and doors)	
1 900 yd^3 $230 000	$121/$yd^3$
Building (excluding design, equipment, crane)	
33 000 ft^2 (net) @ $1 150 000	$35/$ft^2$
Magnetic-amplifier power supplies* (including installation and 0.01% regulator)	
25 kW @ $9 500	$380/kW
50 kW @ $11 500	$230/kW
100 kW @ $17 000	$170/kW
200 kW @ $26 000	$130/kW
500 kW @ $50 000	$100/kW

*From W. Dexter (Lawrence Radiation Laboratory)