THE ENGINEERING OF ACCELERATOR FACILITIES

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Summary

The engineering of an accelerator facility requires completion of a logical series of tasks. After confirming a need or justification, a feasibility study must be made. At this point the engineering work is usually separated into two parts - one for the accelerator proper and its associated research equipment and the other for its housing and services. For the accelerator, conceptual design leads to establishment of financial and time budgets. Systems design permits cost estimates and schedules to be made. Detail design permits bids for construction and installation to be obtained. Procurement and installation services finally lead to test and start-up. For the building, site selection and study lead to one or more conceptual designs. Preliminary design permits tentative budgets and schedules to be set. Final design leads to building contracts, course of construction services and final acceptance. The engineering costs incurred in carrying an accelerator concept through from feasibility study to an operating machine will run from a minimum of about ten percent to a maximum of about thirty-seven percent. For the accelerator site and buildings the corresponding limits are ten and thirteen percent. Thus, for an accelerator facility where the construction costs are divided approximately equally between the machine and its housing, the total engineering costs will be between ten and twenty percent of the construction costs.

Introduction

To avoid semantic difficulties it is necessary to define the meaning of the title of this paper. A brief, formal definition of the singular form, "facility" is "readiness from skill or use". In the plural form "facilities" is generally used to designate "a thing [singular] that promotes the ease of any action, operation or course of conduct such as facilities for study [or research]." However, in recent years, and perhaps with much credit due the Department of Defense, the singular form of the noun has come to mean the singular "thing" with the plural form meaning several of the singular "things."

It is in this broader sense that "accelerator facility" will be used to define the complex of accelerator, housing, utilities, services and ancillary equipment intended to aid in achieving a stated objective, be it research in physics, the production of short-lived isotopes, medical therapy or radiography. And thus "accelerator facilities" defines the general category of this class of "things."

The world-wide interest in nuclear accelerators is evident from Table I.[1]

Table I
Accelerator Installations

	Nuclear Accelerator	High-Energy Accelerator
Total population (6/66)	1800	50
Accelerator types	15	4
Total accelerator investment*	$350 million	$350 million?
Time span of comparison	35 years	20 years
Average investment/year	$10 million	$17 million?
1966 investment/year	$30 million	$50 million?
Countries with installations	40	10
Manufacturers**	30	--

*The cost of the accelerator itself is included; buildings, experimental equipment, etc. are not considered for this study.

**Only those companies that assume systems responsibility in the manufacturer of an operable accelerator are included.

It is, therefore, our intent to describe in general terms the succession of activities or tasks which must be undertaken to complete an accelerator facility. For those of you who have not lived with such a project the description may form a useful outline upon which to build a plan should you have need to do so. Also, based upon observation and experience, some remarks are proffered anent the general principles which should be borne in mind when planning and designing an accelerator facility.

Establishment of Need

The need for an accelerator facility is generally formulated by the user be he an individual or an organization. However, engineers may help the user in developing the context of use and technical and financial practicality. At this time rough rules-of-thumb serve to guide the developing concepts and alternates. Such a rule-of-thumb would be that a cyclotron of moderate energy would cost about two cents per electron volt if protons were the nucleii of prime interest and that a complete facility would be about double this amount. Similar relationships can be inferred from past experience on other types of accelerators. Figure 1 shows trends in accelerator costs - hardware only - as a function of energy for accelerators of different kinds. These curves are rough averages of data from a number of sources. Some are from manufacturer's advertised prices, some are from costs published after machines were completed but escalated from the date incurred to the present by an increment of 2% per year derived from Department of Labor, Bureau of Labor Statistics, data. Others are from construction cost estimates made for proposed machines and also updated by the aforementioned escalation factor.

Feasibility Studies

Most accelerator facilities have a degree of uniqueness -- particularly if they are planned for some field of research. The possibility of fulfilling this requirement of uniqueness may necessitate a feasibility study. Here a detailed knowledge of the state-of-the-art is required of the engineer and often a considerable degree of inventiveness. New applications for accelerators or new solutions to accelerator problems may arise from the experimental and theoretical developments occurring in existing laboratories. It is necessary, therefore, to be conversant with the programs of these laboratories. A feasibility study may be made of updating an existing accelerator -- perhaps of increasing the beam current by a new injector system or improving the extraction efficiency. Studies of space charge limits, trapping efficiencies and injector requirements might be needed in the former case and of high voltage limitations or regenerator designs in the latter case.

Analytic, graphical or computational methods or model or full scale test would all have their place. If the degree of uniqueness is so great as to require an advance in the state-of-the-art it is necessary to include in the feasibility study estimates of the duration, cost and some estimate of the attendant probability of success of the development program required. The cost of such a feasibility study may run from one-tenth percent to one percent of the construction cost of the accelerator.

Preliminary Design

At this stage in the sequence, a facility begins to assume an aura of realism. A layout of the accelerator and the equipment associated with beam utilization defines the basic geometry. In many cases, the use of beam transport systems permits consideration of a substantial number of alternates and these alternates are juggled to fit site and use requirements. As the preliminary design proceeds, equipment characteristics begin to be defined in tentative form -- many to be revised, of course -- and these characteristics permite site and building choices to be considered. For example, power requirements define substation, supply and converter ratings and heat dissipation loads. At this stage the interrelations among equipment, site, support space requirements, building design and facility use are very intimate ones and the final configuration is approached only by successive approximation. The user must work closely with the accelerator facility group in this crucial period to ensure that the desired objectives are attained. Preliminary design develops, as characteristics, sizes, weights, power requirements and the like of the major components. Again, from general cost data based upon previous experience, preliminary estimates may be made of the approximate costs of the major components. Examples of such costs are \$35. per square foot of gross light laboratory space, or \$4. per pound of copper conductor for large, epoxy-bonded, water-cooled magnet coils.

As examples, Table II[2] gives data valuable to the designer for study of alternate materials for shielding and Figure 2 shows cost trends for power supplies as related to their size and characteristics.

Table II
Cost of Shielding Materials

Materials	Weight-lbs. per cu. yd.	Dollars per cu. yard	Dollars per 1000 lbs.
Earth backfill	3240	\$ 1.50	\$ .46
Compacted backfill	3645	3.50	.96
Gravel	3375	8.00	2.73
Slurry concrete	3915	30.00	7.65
Normal concrete	4050	60.00	14.81
Heavy concrete	5400	120.00	22.22
Normal concrete blocks	4050	150.00	37.04
Heavy concrete blocks	6750	400.00	59.26
Steel	13230	3,500.00	265.15

A word of caution should be uttered regarding the use of these generalized data. Bids on a given item may show a spread by a factor of two or more. This spread may reflect the bidder's anxiety for the job or a bidder's naivete. These examples are intended to show the type of data needed to make preliminary estimates of cost.

By the time the preliminary design is completed, estimates of the facility cost can be in hand. This cost is based upon the estimated costs of machine and equipment components and upon the space, utilities and support equipment needed. Two important intangibles must be introduced at this point in the estimating sequence. The first is the category of "miscellaneous." Miscellaneous covers a very real set of items; namely, those which are related to the major components but not included therein and which cannot be identified at this time. The more detailed the preliminary design, the smaller the miscellaneous category. At first, the miscellaneous category may be some 25% but as knowledge of the facility grows the miscellaneous may become as low as 10%. The second intangible is the "contingency." Contingencies recognize at least three kinds of hazards. The first is the underestimate of the cost of making the minor advance in the state-of-the-art -- the perfectly obvious improvement or application of known principles which just does not quite work the way it should the first time. The second is the perfectly obvious improvement which should be incorporated -- the one which will only cost one percent more but increase the usefulness of the facility by an order of magnitude but which had not been the basis of the original estimate. And the third is the strike, the hurricane, the change in the international situation or anything that is unexpected and of course costly. A contingency allowance may be of the order of 15% but again is a matter of judgement. The miscellaneous allowance is first applied to the estimated hardware components and then the contingency is applied to the sum. Engineering costs are next applied to the second sum. Thus if total engineering costs of 35% were used the final cost would be estimated at almost exactly double the estimate of the major components. Hence, beware! Contingencies are difficult to explain to the auditors because they are so sensitive to the abilities, enthusiasms and experience of the protagonists.

The allowances for miscellany and contingencies need not be so great for the building as for the accelerator and its support equipment. This in part is due to the much greater experience extant in the field. However, a very real hazard exists in the insistence at a later date, after funds have been released, that there is just not enough space and some areas must be increased.

Probably the major pitfall that must be guarded against when making the preliminary cost estimate is the subvert intent to use the "foot-in-the-door" technique. The assumption is often made that bargain basement projects will be bought blindly and once trapped the funding agency will perforce continue support until the project is completed.

Once the scope of the project has been established and preliminary estimates of capital costs have been made, the architectural, engineering and administrative costs can be estimated. Architectural fees are based upon building costs and are covered by an explicit fee structure. These include the engineering costs related to the building. For accelerators and experimental equipment, the engineering costs will run to 30 to 35 percent of the total cost -- or about half the shop time and materials costs -- with direct overhead being included in both categories.

Administrative costs will depend upon the structure of the organization doing the work. Probably the best way to estimate the expense is to cost out the real or proposed administrative organization and establish an overhead burden rate.

Intimately associated with the cost of the accelerator facility is the schedule for doing the work. The estimates of engineering, fabrication and assembly costs will give a measure of the effort involved. Building completion dates will fix the time at which equipment installation may begin. Manpower limitations or material or equipment delivery dates may well set the schedule. To aid in planning and visualization, a simplified critical path chart is often manually constructed.

The Preliminary Engineering Report, presenting the preliminary design of the facility and its components, the related cost estimates, proposed funding requirements, construction schedule and manning tables, is the produce of this phase. The justification along with the Preliminary Engineering Report will then be presented to the funding agency for final decision, in the expectation of obtaining the necessary approvals and financial support.

Typically the cost of the preliminary design for the facility will run some one percent of the construction cost. The Atomic Energy Commission designates this work Title I Services and the Department of Navy identifies the result of this work as a Preliminary Engineering Report. Such work is intended to answer all pertinent questions.

Design and Construction

After funds have been allocated, work on the project begins in depth. Rather than describing all of the detail involved in the engineering of an accelerator facility reference will be made to the categories of effort.

Project Organization

Some mention should be made at this point about project organization. Much depends upon the size of the project in relation to the size and type of user's group. At one extreme would be a hospital or medical research foundation buying a Van de Graaff accelerator or an electron linear accelerator. The accelerator would be purchased on a fixed price basis from the manufacturer. Installation criteria, including shielding requirements, and instruction manuals would be furnished by the manufacturer under terms of the contract. The user would probably employ an architect-engineer firm to design the accomodations based upon the user's need and the accelerator criteria. The accelerator manufacturer would be responsible for the proper installation of the accelerator and would train the user's operating crew. After the accelerator had met the contract specification it would be put under warranty -- usually for one year. The manufacturer might offer to assume responsibility for maintenance, and even operation, under a follow-on service contract.

At the other extreme is a project such as the 200 GeV proton synchrotron facility which would be starting from scratch to take some eight years for construction. During this period the organization and staffing of this facility as a National Laboratory must also be undertaken. The magnitude and time involved warrant a planned transition from a construction-oriented organization to a research-oriented organization. Of course, many persons making a valuable contribution during the construction period would also be valuable in the research organization but not necessarily in the same capacity nor should the organizational format be a rigid one. Even research objectives and techniques will have changed during this long interval.

Work Organization

All of the information submitted in the Preliminary Engineering Report is reviewed and confirmed or revised. Budgets and schedules are spelled out in greater detail and responsibilities are assigned to the members of the working organization. It is important to set up a computerized version of a critical path chart, such as PERT-cost, so that each person carrying an assigned responsibility will have a weekly accounting of costs and schedules and slack time for his job. Input to the computer should include estimates of effort and time to completion of each job as well as accounting input. Unless the two inputs are kept separate the fallacy arises that the fraction of budgeted funds spent represents the fraction of job completion. Suddenly someone finds that he is the bottleneck on the critical path, that 90% of his budget is spent and that the job is only half completed. Runaway costs and schedule delays result from the delayed recognition of critical problem areas. Project success depends upon management competence as well as upon technical excellence.

Design Responsibility

The design function is popularly believed to be perhaps the only responsibility the engineer assumes. Somewhat more broadly, the responsibility is to assure that an item of hardware, be it component, assembly or subsystem perform its intended function. Thus to drawings must be added specifications. Bids must be evaluated before contracts are awarded. Vendors may require qualification and the successful bidder may need advice or assistance. Completed items must be inspected and tested for compliance with specification before acceptance. This responsibility often falls upon the engineer, especially if the item is custom built.

For accelerator facilities designed for a routine task, such as medical therapy, a fairly permanent and well-defined set of requirements can be postulated. This permits a specific design to be developed to meet these requirements. The layout of the facility can be studied in detail so as to obtain minimum capital cost and superior operating qualities. Accelerators for process applications are another example. Shielding for conveyor lines could be studied in depth to obtain optimum product flow with minimum cost and good access for service.

The opposite extreme is an accelerator facility intended for high energy physics research. The accelerator itself would be highly developmental in nature and the development effort would be an integral part of the program. Such development effort is difficult to budget and schedule. Break-throughs are unpredictable and nature uncooperative.

Design for Flexibility

The research program, for which the accelerator facility is a tool, is itself unpredictable by definition. The objective, therefore, is to provide the maximum flexibility. Not much can be done to provide for future upgrading of the accelerator proper. For accelerators employing magnetic fields little can be done to increase the energy at a later date as the initial design will be based upon field strengths difficult to exceed. Opportunity may be inherent for increasing beam current -- and many machines have benefitted by such upgrading -- but such improvement usually results from the installation of updated components.

Accomodating Change. The greatest liklihood of future change lies with the ancillary research instruments. The design and development of such instruments is independent of the accelerator facility but their use is not. Hence, the goal in the design of the accelerator facility should be one of accomodating change. Maturation of a facility is synonymous with physical growth and increasing complexity. Therefore three basic considerations must ever be in mind during design. The first is to so site the facility as to permit the growth of any specific function or addition of functions not initially defined. By maintaining large, level, clear areas around the facility future additions can be placed in proper juxtaposition. Thus the control room or counting area can be expanded. Laboratory space can be added around new beam transport paths. Supporting office and shop space can be increased. Too many examples exist of installations where necessary additions can be made only with heroic effort and at great expense.

Providing Non-specific Space. The second consideration is to always make the space provided within the buildings as non-specific as practicable. This consideration is of course related to the first. The main power supplies might be expanded or relocated but would never become unnecessary. However, office space might become light laboratory space or shop space become an experimental or developmental area.

Providing Service Flexibility. The third consideration is to establish a system for service access to and for interconnections among different categories of space. A scrambled maze of signal, power and communication cables and water lines spread over the floor of an experimental area is neither safe nor efficient. Conversely, to run all the necessary services in buried conduit is both expensive and inflexible. There are probably as many solutions to this problem as there are installations. For multistory, light laboratory and office space the alternates are well known. They take such forms as vertical shafts within the building or on the outside, horizontal corridors within the building plan, interconnected between floors, or alternate partial or full height stories giving access through floor or ceiling to any point within the planform of the usable area. Accelerator areas, experimental halls and havey shops, on the other hand, often use trenches or tunnels for access because of the heavy floor loads due to shielding, large magnets, machinery or accelerator. The major problem encountered is the interference resulting at intersections of the service runs. A frequent solution is to use vertical separation although this may not avoid the intersections becoming blocked for the personnel access needed for installation, modification or inspection and service. Service and utilities areas beneath the equipment area usually are offset laterally because of radiation shielding requirements and the cost of the structure necessary to support the heavily loaded floors above. Tunnels and access passages to basement service areas should always be carried to points outside the building exterior. This permits supplies and equipment for installation in these areas to be brought in without interfering with work within the building during construction, provides access when openings within the building are prohibited, and makes for easy extension when the facility is to be expanded.

Design and Construction Service Costs

The final design of the facility results in sets of drawings and accompanying specification often called bid packages. In the case of the site, buildings and services it is normal practice to award a general contract and the successful bidder is responsible for the selection and performance of the subcontractors. The fee for the architect-engineer services for this part of the facility will be six to eight percent of the corresponding construction costs. If review of the contractors and subcontractors shop drawings and technical supervision are also provided an additional expense of one to two percent of the construction cost is incurred.

The final design of the accelerator and associated equipment is carried to a much finer degree of detail than the buildings. Thus the bid packages are prepared for components and subsystems and generally include shop drawings. The responsibility rests with the project staff and much more effort is invested. The detail design cost thus runs anywhere from five to twenty percent of the equipment construction cost. Procurement and installation services are usually also provided by the project staff which implies an additional three to ten percent of the construction costs. The lower fees would be incurred for the procurement and installation of a major component, such as a power supply, bought on a competitive bid basis from a major supplier where the item was in commercial production, or very similar to such, and the supplier made the necessary shop drawings, supervised the installation and supplied the operation and maintenance manuals.

Test and Start-up

It is general practice to schedule building completion ahead of the arrival of the main accelerator components to provide working space, crane and power for assembly and test of these components. Subsystems are assembled and tested, RF and magnetic field measurements are made and start-up of the entire facility is attempted. This is a trying period and, hopefully, a short one. Any changes made at this time delay the acceptance date and are costly. Earlier component and sub-assembly testing helps to avoid delays at the end of construction and are important to have been planned and conducted. Engineering effort during test and start-up will cost from one to five percent of the construction cost and will be, at least in part, a measure of engineering success.

Conclusions

Engineering functions are inherent in every phase of effort in providing an accelerator facility between the time the desire is expressed and the facility is in use. Whether the engineering functions are provided by an equipment manufacturer, a contract firm or the user's staff -- or a mixture of such elements -- matters little insofar as overall cost is concerned assuming, however, equal managerial and technical competence and equally efficient organizations. The only major variable will be the number of units -- component, subsystem or system -- over which the engineering costs can be distributed.

References

(1) Burrill, E. Alfred, "The World-Wide Usefulness of Particle Accelerators," Technical Meeting No. 9B, NUCLEX 66.

(2) Mackinlay, Ian, "Flexibility in Accelerator Housings", IEEE Transactions on Nuclear Science, Vol NS 12, No. 3, June, 1965.

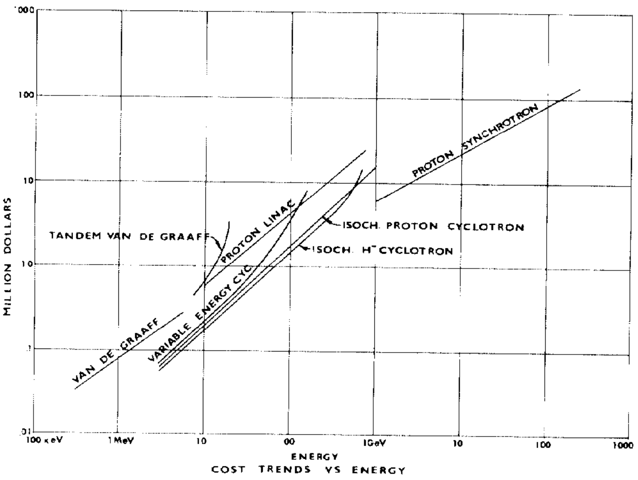

Fig. 1. Accelerator cost trends as a function of energy.

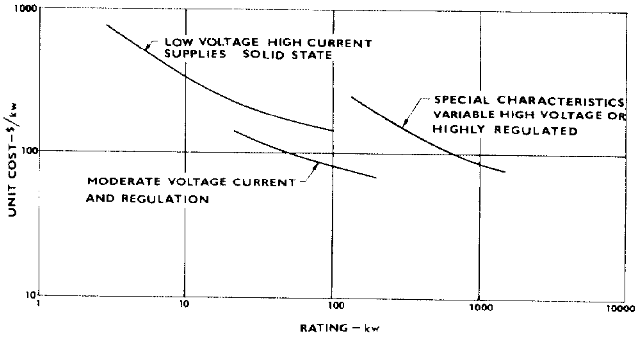

Fig. 2. D. C. Power supply cost trends as a function of power rating.