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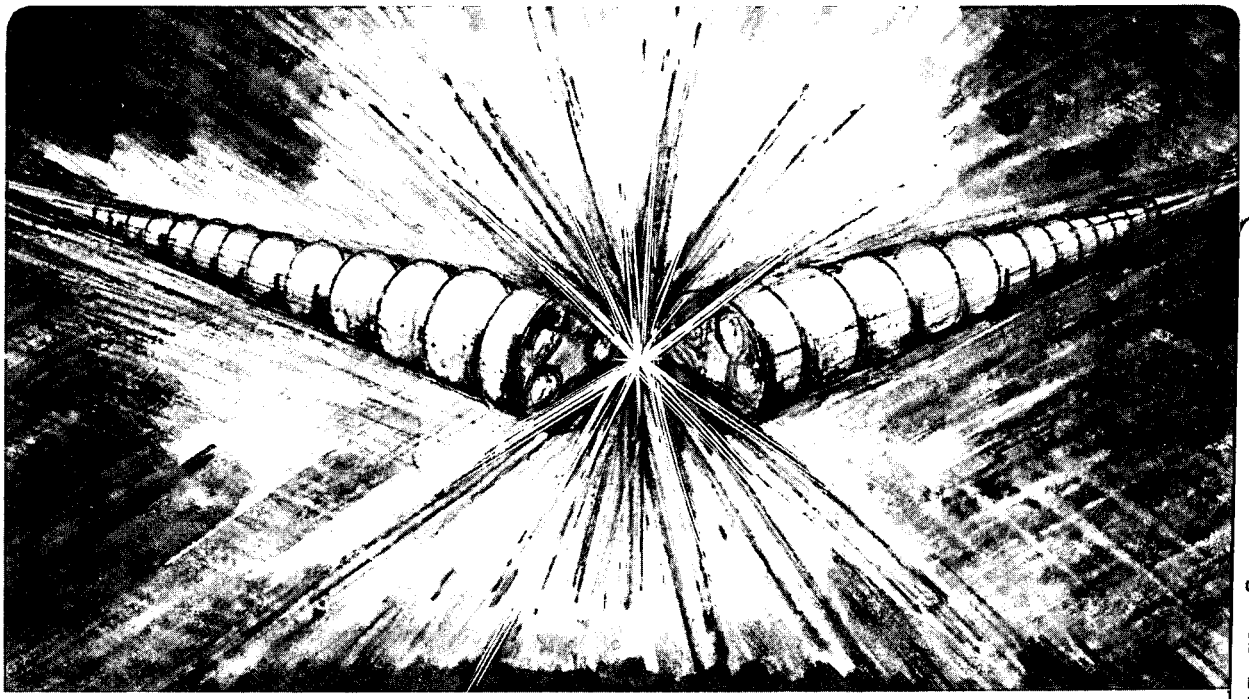

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MAGNET COSTS FOR THE ADVANCED LIGHT SOURCE

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Magnet Costs for the Advanced Light Source*

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Abstract

The Advanced Light Source (ALS) accelerator is now completed. The numerous conventional magnets required for the booster ring, the storage ring and the low and high energy transfer lines were installed during the last two years. This paper summarizes the various costs associated with the quantity fabrication of selected magnet families. These costs include the costs of prototypes, tooling, coil and core fabrication, assembly and magnetic measurements. Brief descriptions of the magnets and specialized requirements for magnetic measurements are included in order to associate the costs with the relative complexities of the various magnet systems.

I. INTRODUCTION

The ALS is a 1.5 GeV electron storage ring, optimized to take advantage of undulators and wigglers to produce synchrotron light. It is located at Lawrence Berkeley Laboratory (LBL) in the hills above the University of California at Berkeley. Construction began in 1988. All magnets had been installed by the spring of 1992 and commissioning is presently underway. The main components of the accelerator system are a full energy booster ring, with a repetition rate of 1.0 Hertz and a storage ring designed for operation at 1.5 GeV and capable of ramping to 1.9 GeV. The booster magnets were designed for possible operation at 10 Hertz.

II. MAGNET FABRICATION

All the booster ring magnet cores were assembled using 0.025 inch thick (0.6 mm) M36 silicon steel laminations with C-5 insulation to reduce the effects of eddy currents due to the time varying excitation at a future possible 10 Hertz maximum injection frequency. All storage ring magnet cores were assembled from 0.060 inch thick (1.5 mm) uninsulated low carbon steel laminations to take advantage of the economies of this fabrication technique for large numbers of DC magnets and to distribute systematic variations in steel properties uniformly around the storage ring lattice. With the lone exception of the booster dipole magnet cores, which were welded because of curved geometry, all other cores were fabricated either by gluing, or using mechanical frames combined with a modified gluing technique. It was felt that a higher quality magnet could be achieved by avoiding distortions in the core assemblies due to the thermal effects of welding.

All the ring magnet coils were vacuum potted using rigid reusable molds. The potting compound was an epoxy mixture using Tonox as a flexibilizer in order to avoid the long term development of cracks in the coil insulation. Because of the well known carcinogenic hazards of Tonox, thorough safety precautions including limitation of access to the working areas and the use of protective wear and breathing apparatus were rigidly enforced for the in-house fabrication of the coils. Hazard information and the LBL Operational Safety Procedure (OSP) were also supplied to the industrial coil vendor. These safety precautions added substantially to the cost of coil fabrication. Although the vacuum potting technique was only needed for the booster magnets due to the high voltages generated by pulsed operation, this technique was utilized for the storage ring magnets as well. High quality potting molds were needed for precise coil dimensions required for the storage ring sector chamber cutouts. Also, the economies of fabricating the large coil quantities for the storage ring magnets could easily capitalize the initial high cost of the sophisticated reusable tooling.

In addition to the coil and core fabrication, the magnet effort included the assembly of major parts, busses, interlocks, water fittings and hosing, interlock tests, measurement of electrical parameters, impulse and hipot tests of coils and the magnets. Magnetic measurements and the location of magnet fiducials for survey and alignment are included in the construction costs. Not included in the costs are engineering and design efforts and the detailed design and drafting of magnet components, assemblies and tooling. In addition, the cost of documenting fiducial data and summarizing the results of magnetic measurements and other tests are not included.

III. BOOSTER MAGNETS

The magnet fabrication for the booster ring peaked during fiscal year 1989. At this time, the average LBL construction fabrication and assembly labor rates were $36.20/hour.

A. Booster Dipole

This magnet has a curved core which follows the beam orbit. The curved geometry minimizes the stored energy, to reduce the power supply requirements for the pulsed operation. The coil design includes substantial insulation to ground for the high voltage operation at a future potential 10 Hertz operation.

Prototype Cost	109.6 K$
Production Cost	567.2 K$
Tooling Cost	102.5 K$
Number of production magnets	24+1 spare = 25
Core Weight	3940 lbs
Coil Weight	370 lbs
Magnet Weight	4310 lbs

B. Booster Quadrupole

Two different lengths of this magnet were required.

Prototype Cost	83.0 K$
Production Cost	464.5 K$
Tooling Cost	160.1 K$
Number of production magnets	2X(16+1 spare)=34
Core Weight	860 and 540 lbs
Coil Weight	65 and 50 lbs
Magnet Weight	925 and 590 lbs

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C. Booster Sextupole

The coils for this magnet were wound from solid conductor

Prototype Cost	13.5 K$
Production Cost	137.0 K$
Tooling Cost	96.3 K$
Number of production magnets	20 + 1 spare = 21
Core Weight	114 lbs
Coil Weight	18 lbs
Magnet Weight	132 lbs

IV. STORAGE RING MAGNETS

The magnet fabrication for the storage ring peaked during fiscal year 1990. At this time, the average LBL construction fabrication and assembly labor rates were $38.55/hour. The unit production cost for the storage ring magnets reflects the increased costs due to inflation and the increased complexity of the magnets fabricated for the storage ring. In general, the field quality and reproducibility requirements for the storage ring magnets were more demanding than the specifications for the booster magnets. In addition, the requirement for providing photon beam clearance and the difficulty in installing magnets along a more congested lattice than the booster ring resulted in substantially more demanding designs. The higher unit costs for the storage ring magnets due to these inflating forces was offset by the experience gained in manufacturing the booster magnets.

A. Storage Ring Dipole

The storage ring dipole magnet is a gradient magnet. Because of the high precision required for the field quality, it was decided to fabricate the core with a one piece lamination. The field quality requirement forced a wide pole and a narrow throat in the one piece yoke for the gradient geometry. As a result, the coil design required six thin pancakes which could be installed in the core through the narrow throat. Magnet measurements were tedious and costly. Hall probe measurements were made on a finely divided grid for each magnet at an equivalent excitation at 1.5 GeV storage ring operation for 100% of the magnets. In addition, Hall probe maps were required at excitations for storage ring operation at 1.0 and 1.9 GeV for approximately 20% of the magnets.

Prototype Cost	147.5 K$
Production Cost	1180.6 K$
Tooling Cost	147.3 K$
Number of production magnets	36 + 1 spare = 37
Core Weight	6380 lbs
Coil Weight	720 lbs
Magnet Weight	7100 lbs

B. Storage Ring Quadrupole

The storage ring quadrupole design was a "C" shape variant of the booster quadrupole design. Three different models (lengths) were fabricated, the QFA, the QF and QD families. The QF and QD magnet families used smaller conductor than used for the QFA in order to optimize the design for individual power supplies. The magnet measurement effort required shimming of the two magnet halves in order to reduce the sextupole error introduced by the asymmetric design.

Prototype Cost	134.1 K$
Production Cost	1054.0 K$
Tooling Cost	179.8 K$
Number of production magnets	3X(24 + 1 spare) = 75
Core Weights	2000, 1420 and 750 lbs
Coil Weights	120, 120 and 68 lbs
Magnet Weights	2120, 1540 and 818 lbs

C. Storage Ring Sextupole

This was perhaps the most complicated magnet design in the entire ALS system. The sextupole had to satisfy four functions. In addition to the sextupole windings, the magnet required coils wound to produce vertical and horizontal steering as well as a skew quadrupole field in the same yoke. As a result, the coil system included twelve separate coils with eighteen separate windings. Electrical bussing needed to be accomplished at both ends of the magnet in order to accommodate the electrical connections for the four separate magnet functions. In addition, the core was divided among three segments. Precision assembly and alignment of the three separate segments was demanding and costly. Magnet measurements included rotating coil measurements to determine the excitation and the error multipole spectrum for each magnet in all its operating modes; sextupole, horizontal steering, vertical steering and skew quadrupole.

Prototype Cost	164.0 K$
Production Cost	925.1 K$
Tooling Cost	157.7K$
Number of production magnets	48 + 1 spare = 49
Core Weight	980 lbs
Coil Weight	120 lbs
Magnet Weight	1100 lbs

V. DETAILED BREAKDOWNS

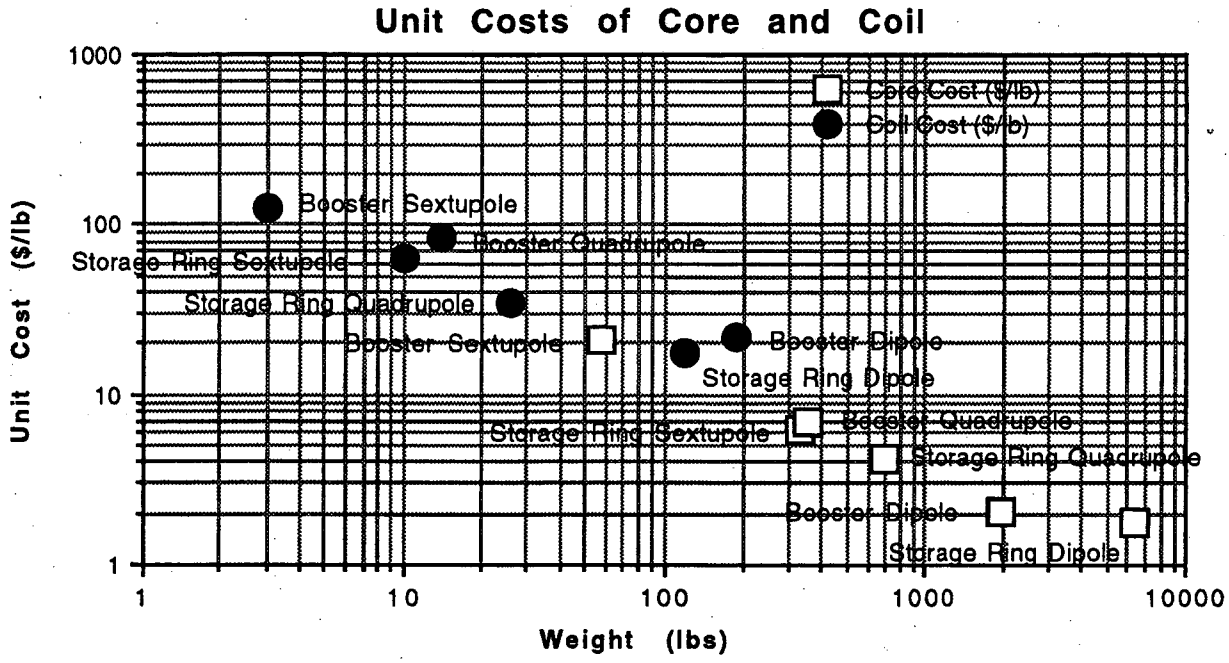
Limitations were enforced in the level to which accounting information could be broken down in this extremely large and complex construction project. Thus cost distinctions among the coil fabrication, core fabrication, assembly and magnet testing efforts were not available in the accounting structure. Countless job and purchase orders were issued for the fabrication of each magnet type. It is possible, after very tedious and time consuming effort, to obtain costs for orders in each one of the major effort categories for the fabrication of magnets and add them up in order to get the actual costs of these categories. However, it is felt that a reasonably accurate division of the various effort categories could be obtained by looking at the updated cost estimates which were required periodically throughout the project. In particular, the cost estimate after the evaluation of the prototype and before the expenditure of the production budget would be a fairly accurate projection as to the relative costs among the various effort categories. At the end of the prototype effort, a fairly accurate picture of the fabrication effort as well as the assembly and scope of the required magnet measurement effort is available.

Magnet	Core	Coil	Assy/Test
Storage Ring Dipole	35%	39%	25%
Storage Ring Quadrupole	41%	25%	34%
Storage Ring Sextupole	32%	40%	28%
Average (To be applied to the Booster Magnets)	36%	35%	29%

Applying these numbers to the actual expenditures for all the production magnets, one can develop an approximate unit cost for the coils and cores related to coil and core weights.

Magnet	Number of Magnets	Production Cost	Cost per Magnet	Total Magnet Weight (lbs)	Total Core Weight (lbs)	Total Coil Weight (lbs)
Booster Dipole	25	$567,165	$22,687	4310	3940	370
Booster Quadrupole	34	$464,511	$13,662	758	700	58
Booster Sextupole	21	$137,026	$6,525	132	114	18
Storage Ring Dipole	37	$1,180,604	$31,908	7100	6380	720
Storage Ring Quadrupole	75	$1,054,032	$14,054	1493	1390	103
Storage Ring Sextupole	49	$925,096	$18,880	1100	980	120

Magnet	No. of Core Segments	No. of Coils	Total Core Cost	Total Coil Cost	Core Segment Wt. (lbs)	Individual Coil Wt. (lbs)	Unit Core Cost ($/lb)	Unit Coil Cost ($/lb)	Assy & Test ($/mag)
Booster Dipole	2	2	$204,179	$198,508	1970	185	$2.07	$21.46	$6,579
Booster Quad	2	4	$167,224	$162,579	350	14	$7.03	$83.16	$3,962
Booster Sex	2	6	$49,329	$47,959	57	3	$20.61	$126.88	$1,892
Storage Ring Dipole	1	6	$413,211	$460,436	6380	120	$1.75	$17.28	$8,296
Storage Ring Quad	2	4	$432,153	$263,508	695	26	$4.15	$34.22	$4,778
Storage Ring Sex	3	12	$296,031	$370,038	327	10	$6.16	$62.93	$5,286



VI. SUMMARY

LBL labor rates were quoted for the period of manufacture for each magnet family. The amount of labor should not be implied from these rates. Material and vendor supplied components are included in each of the cost summaries. In addition, LBL employed lower cost contract labor during the various peaks of the fabrication and assembly period. Higher cost professional labor was required during the magnet measurement phase of the effort. Core and magnet assembly efforts were "in house". A vendor, with different labor rates, supplied most of the coil fabrication for the storage ring.

Because of all the special circumstances of manufacture, one must be cautious in the application of these summaries to future estimates. One should only use the numbers herein summarized as general guidelines.

VII. ACKNOWLEDGMENTS

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