SSCL-293

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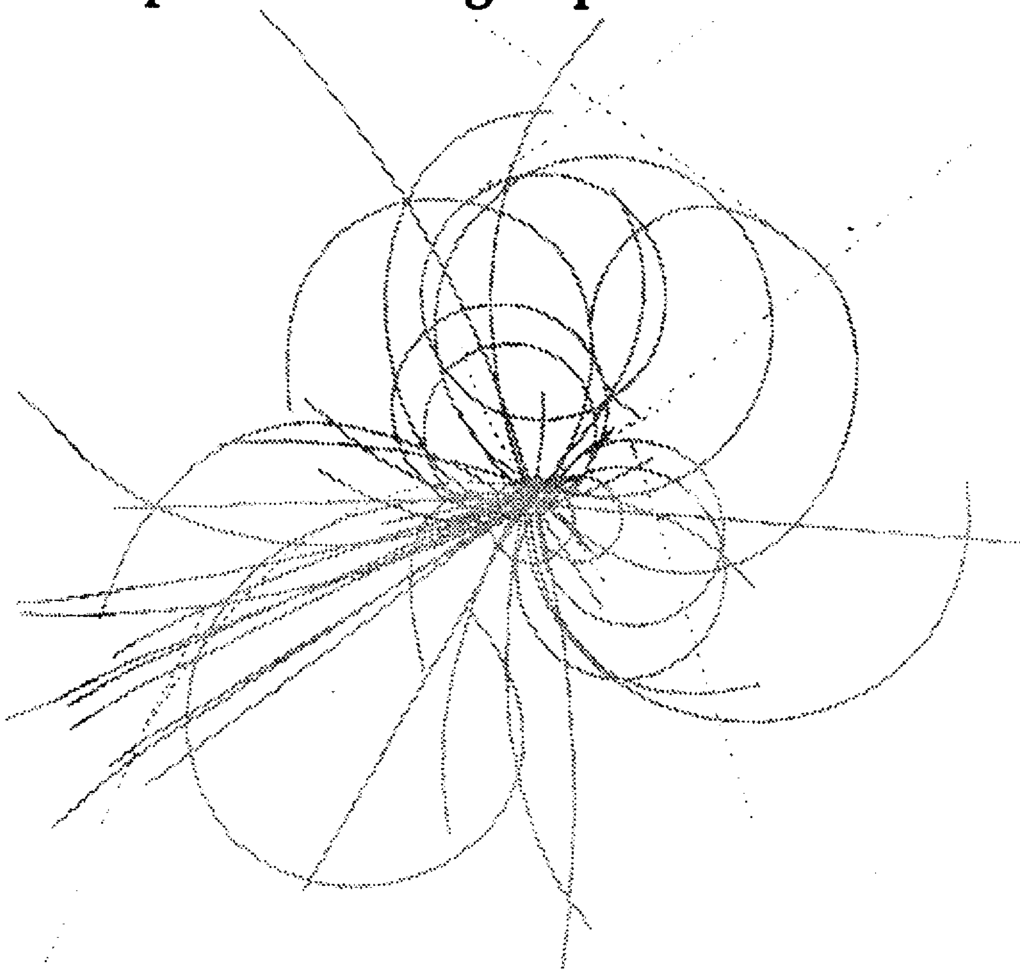
Superconducting Super Collider Laboratory



Schedule Analysis Data Package
Final Report 05-30-90

Martin Marietta Co.

May 1990

SSCL–293

SCHEDULE ANALYSIS DATA PACKAGE
FINAL REPORT 05-30-90

MMAC

Superconducting Super Collider Laboratory*
Physic Research Division
2550 Beckleymeade Avenue
Dallas, Texas 75237

May 1990

This is a companion document prepared by Martin Marietta Co.
This document is incomplete without additional information contained in SSCL-N-729.

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1.0 INTRODUCTION TO COST ANALYSIS

The objective of the cost portion of this study is to determine the design and manufacturing costs for two alternative calorimeter technologies, liquid argon calorimetry (LAC) and scintillating spaghetti calorimetry (SPACAL). Research and Development (R&D), Engineering, Design and Integration (EDI), and Materials and Services (M&S) estimates have been completed for each alternative. Included in this report are the ground rules and assumptions used, the cost estimating approach and methodology, summary of the cost estimates, funding profiles, and a cost risk analysis.

From the detector modeling work performed on EMPACT under separate funding, a baseline configuration was chosen for both alternatives to perform the cost analysis. Other valuable information defined was the manufacturing processes and labor/machine requirements for designing and building the two calorimeters. Tooling and assembly processes were included due to their affect on overall detector costs. Figures 1 and 2 are isometric drawings of the two calorimeter configurations chosen for this study.

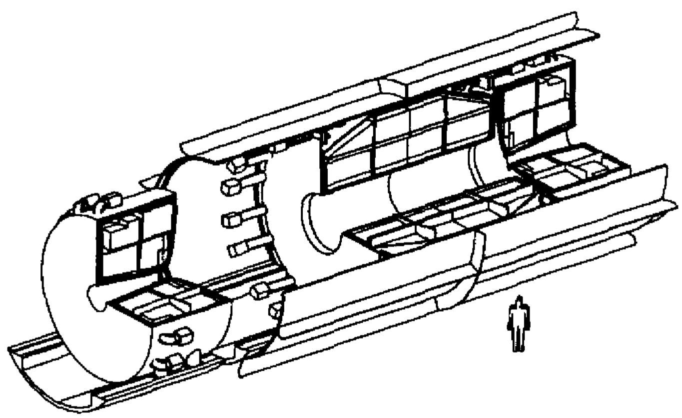


Figure 1 - LAC Baseline Configuration

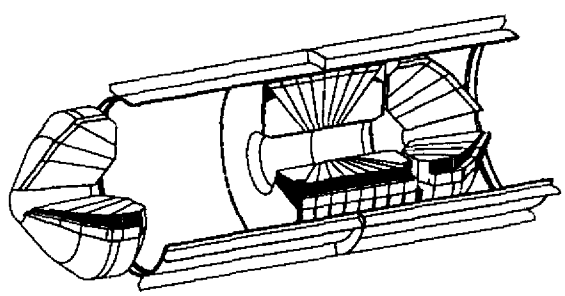


Figure 2 - SPACAL Baseline Configuration

2.0 GROUND RULES AND ASSUMPTIONS

This section contains the Ground Rules and Assumptions used for estimating the costs.

1. All costs are reported in 1990 as thousands of dollars.

2. Estimate includes Research and Development (R&D), Engineering, Design and Inspection (EDI), Material and Fabrication (MFG) costs, Cryogenic Services for LAC, and front end electronics costs.

3. Cost estimates include all labor and materials, except for physicists salaries.

4. The following methods were used to develop the cost estimates:
   - engineering bottoms-up
   - industrial engineering and manufacturing analysis
   - parametrics and factors
   - historical detector costs
   - vendor quotes for materials

5. Costs are reported by program phase (R&D, EDI, and MFG) and program element in a Work Breakdown Structure (WBS) format.

6. R&D includes trade studies, R&D test, prototype test, test support, and material and fabrication to support the R&D program.

7. EDI includes modeling and preliminary design, design analysis, engineering support, test engineering, systems engineering, logistics engineering, safety/quality engineering administration and other technical services (e.g. program management, planning, computers, travel). Upon completion of the EDI phase drawings, they are submitted to begin the procurement process.

8. Manufacturing includes labor and material costs required for assembling the calorimeter, performing tests, and installing the calorimeter into the detector underground. Also included are facilities and equipment required.

9. Costs include the Central and End Cap Calorimeters only. Forward Calorimeters have not been included.

10. Differences in Installation and Operations costs between the two options was found to be negligible and therefore are not included.

11. Drawing sheet count for EDI assumes Computer Aided Engineering applications.

12. Engineering parametric estimates are based on Martin Marietta experience on past programs.

13. R&D estimate includes R&D proposals submitted from outside sources along with additional work identified by Martin Marietta.

14. Component level R&D costs have not been included (e.g. R&D for fiber to withstand radiation levels for 10 years). It has been assumed that these items will be available. R&D includes the effort for assuring the technology will perform within the requirements of the selected calorimeter configurations and can be designed and built.

15. Uranium costs have been included for LAC.

16. Labor rates are fully burdened with Overhead, G&A, and fee.

17. Module and Tower procurement assumes use of highly automated processes.

18. Modules and Towers will be assembled off-site with the Central Barrels and End Caps being assembled in above ground facilities near the experimental hall.

3.0 COST ANALYSIS

3.1 Detector Descriptions

Figures 3 and 4 is a quarter section illustration of the modules and super ring arrangements for the LAC and SPACAL . Further information on the design of the two calorimeters can be referenced in the "Status of EMPACT Liquid Argon Calorimeter Engineering Design," EMPACT Note 218 (1990) and "Status of EMPACT SPACAL Calorimeter Engineering Design," EMPACT Note 219 (1990).

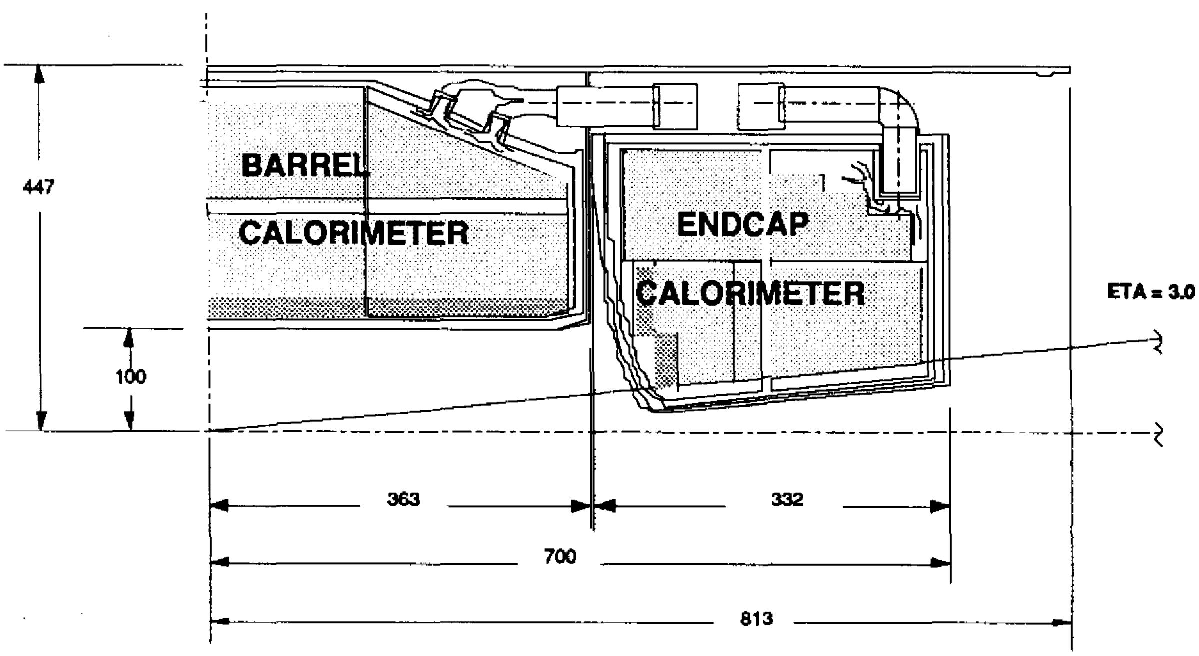


Figure 3. LAC Cross-Sectional View

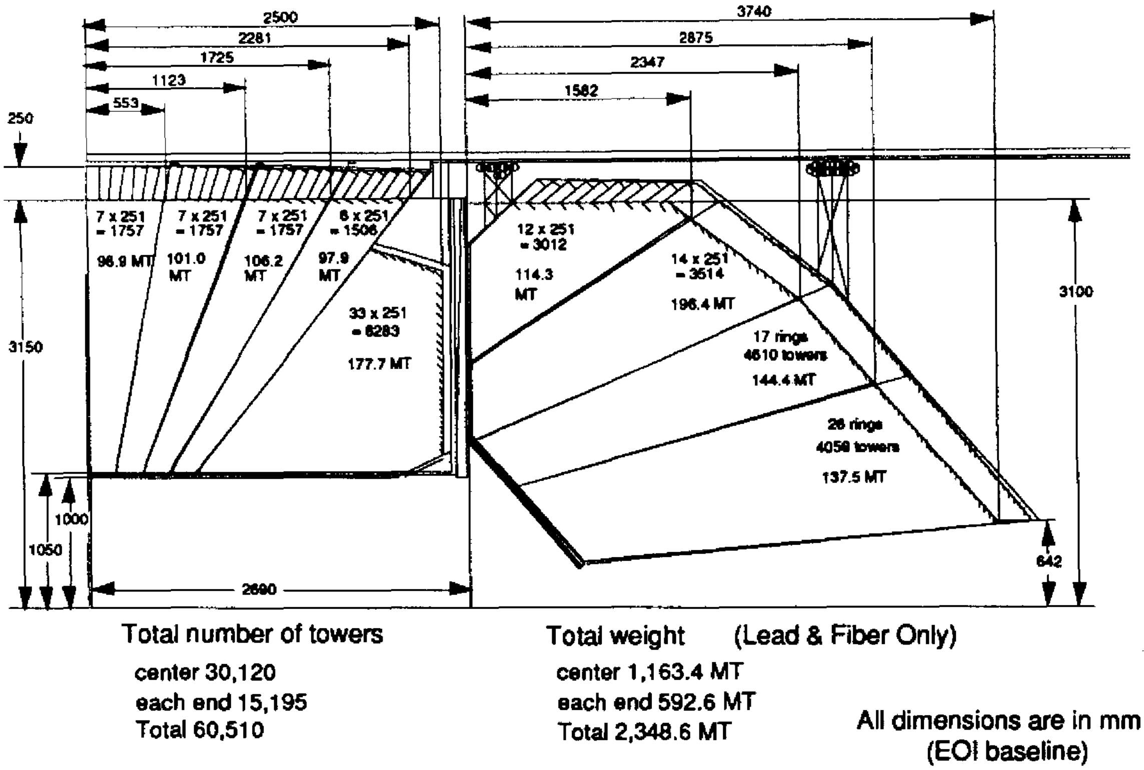


Figure 4. SPACAL Cross-Sectional View

3.2 Cost Methodology

3.2.1 R&D Cost Methodology

This section describes the methodology used to estimate the calorimeter system costs. Estimates were generated in three phases for both options. The first estimate generated was the R&D estimate for both LAC and SPACAL.

Our approach to the cost analysis for R&D and EDI is included in Figure 5. Experts in engineering, manufacturing, and industrial engineering were used to define a baseline concept and estimate, the effort required to design and assemble the various subsystems. The cost tables included in the appendix outline the elements of each calorimeter which have been estimated.

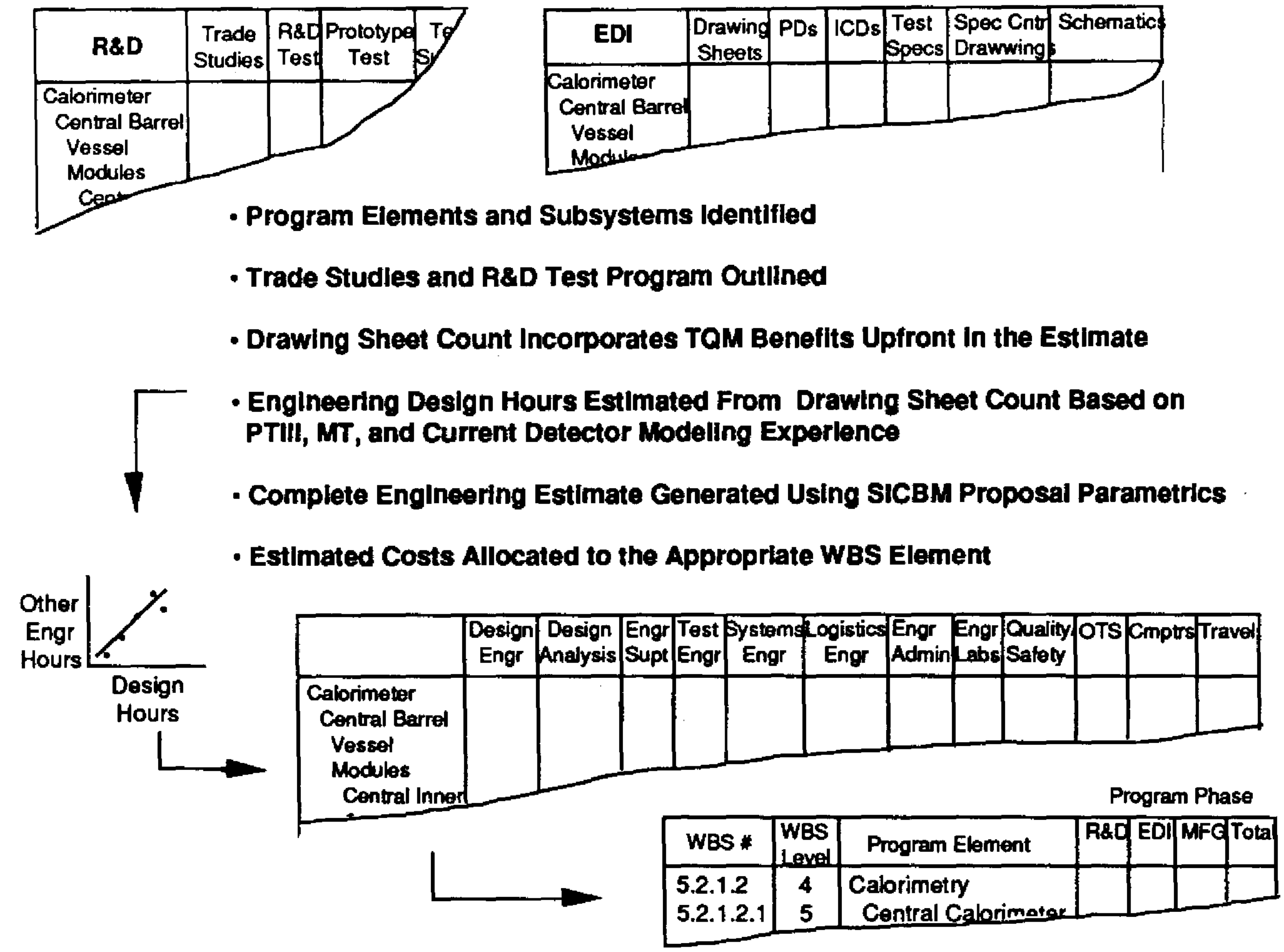


Figure 5. R&D and EDI Cost Analysis Approach

Tables 1 and 2 which follow, outline the R&D tasks to be performed for LAC and SPACAL, respectively. The rows represent the detector subsystems and requirements to be studied and the columns represent the resources required to perform the study. R&D includes Trade Studies, R&D Test, Prototype Test, and Test Support activities to be performed during this phase. Material and Fabrication costs are for prototype units built to support R&D Test and to verify that the design will meet the physics performance required. The computer costs are for CAE work stations required to do modeling and analysis. Project management includes effort to perform planning, contracts administration, procurement, finance, and project management and administration.

Engineering Bottoms-Up (manmonths)	Trades	R&D Test	Prototype Test	Test Support	Total Labor (manmonths)	Material & Fabrication ($K)	CAE Work Stations
Module Resolution & Response							
Module R&D Facilities							
Test Beams							
Test Fixtures							
Cryostat							
Data Acquisition System							
Stack Options							
Metalized Plastic Sheets							
Brite Pads							
Pb Stacks							
Other Tile Development							
Cryogenics							
Electrode Structure							
Electronics							
Simulation Code							
Test Design							
Test Support							
Engineering, Design, & Integr.							
Hermeticity/Containment							
Argon Boiling/Electronics Cooling							
Radiation Hardness							
Sensor Position Tolerances							
Materials Compatibility & Testing							
Materials Engineering							
Feed-Thrus							

Table 1. LAC R&D Estimate Format

Engineering Bottoms-Up (manmonths)	Trades	R&D Test	Prototype Test	Materials Test	Test Support	Total Labor (MM)	Material & Fabrication ($K)	CAE Work Stations
Tolerance Studies								
Tower Shape & Construction								
Gap & Tolerance Allocation								
Lead Fabrication								
Fiber Fabrication								
Mirrored Fabrication Studies								
Non-Mirrored Fabrication Studies								
Shape Control								
Interface Fitting Definition								
Super Ring Construction								
Segment Definition								
Support Concepts								
Interface Definition								
Subscale Test Evaluation								
Bonding Techniques								
Tolerance Allocation								

Table 2. SPACAL R&D Estimate Format

3.2.2 EDI Cost Methodology

The EDI estimate was developed using a combination of Bottoms-up estimates and Cost Estimating Relationships (CERs). The CERs were developed from historical data for performing the various engineering activities. The number of drawing sheets required to begin development of each calorimeter and hours per drawing sheet were used as the independent variables for the CERs. From the CERs, estimated manhours for each of the engineering functions required were calculated. These manhours were then allocated to the specific tasks. This CER estimating method minimizes the use of "engineering judgment."

The Cost Estimating Relationships (CERs) is a statistical tool that enables the estimator to predict the amount of one cost element if the value of another cost element is known. CER's were developed from past Martin Marietta programs. Data was collected from large scale engineering programs which utilized a similar engineering process that would be used to design a calorimeter.

Computer Aided Engineering was assumed to be used extensively in both designs which results in a cost savings over past engineering practices. These savings were factored into the estimate by reducing the drawing counts and hours per drawing required. An example of these savings can be seen in the design of the modules. A module consists of many layers of uranium plates and G-10 boards. A drawing could be developed for just one layer and a computer program written to generate drawings for each additional projected module.

Table A-1 and Table A-2 in the appendix outline the EDI tasks to be performed for LAC and SPACAL, respectively. The rows represent the detector subsystems to be designed and the columns represent the design engineering activities to be performed.

Design Engineering includes mechanical and electrical design effort for the design documentation, drawing development, and design maintenance and support effort. Tables A-1 and A-2 were used as input sheets for the designers to identify the drawing counts. Following is a list of definitions for each of the design engineering activities:

Drawing Sheets - consist of the dimensioned drawing for the hardware, including a parts list, Procurement Drawings (PDs) - specifications for hardware which will be designed and developed by an outside source, Interface Control Drawings (ICDs) - include the mechanical interfaces and requirements between hardware elements, Layout Drawings - illustrate how the individual subsystems are laid out into a final assembly, Test Specifications - requirements that the hardware must meet during testing, and Design reviews - meetings for presentation and reviews of the designs.

From the inputs developed by the designers, engineering design hours were computed. This included hours for preparing drawings, developing parts lists and specifications, quality reviews, drawing changes, and supervision.

The total engineering design hours were then used as inputs to calculate the total EDI hours required. Other engineering activities, in addition to design engineering, includes design analysis, engineering support, test engineering, systems engineering, logistics, engineering administration, engineering labs, and quality engineering and safety. Parametrics were used to estimate these other engineering functions based on the engineering design hours generated. The following list defines each of the additional engineering functions required during the EDI phase.

Design Analysis - Analysis includes hours to perform stress, dynamics, thermal, and analytical mechanical analyses. Analysis is performed only as required for designs which are new or being revised and require analytical work to verify that all requirements have been met. Analysis effort has shown to be a direct function of the design engineering performed.

Engineering Support - Support hours include effort for Materials Engineering (Parts/Materials/Processes), Computer Aided Engineering, and Checking and Release. The support effort occurs when design activity is being performed. Support hours can be estimated with a high degree of confidence using design hours as a base.

Test Engineering - Test Engineering is the effort associated with test requirements, development of detailed test plans/procedures, test conduct, and test operations. For test activity directly related to hardware, it has been shown that this effort correlates very well to the effort required to design the hardware.

Systems Engineering - Systems Engineering includes the following tasks: Reliability, Human Factors, Electromagnetic Control, Mass Properties, Survivability, and Systems Integration. Systems Engineering directly corresponds to the output generated by the design, analysis, and their supporting functions.

Logistics - Logistics includes Logistics Engineering, Integration and Support, Spares and Maintainability.

Engineering Administration - Engineering Administration is the effort involved in developing and maintaining Engineering Plans at the job unit level that integrate with manufacturing and project schedules. Change Administration, Human Resource Planning for all engineering labor, and database administration are some examples.

Engineering Labs - Engineering Labs include mechanical, power, thermal, test operations, engineering prototypes and development labs, electronics labs, and parts evaluation labs to support engineering.

Quality Engineering/Safety - Quality engineering includes engineering effort for fabrication, packaging, and shipping. Safety includes all engineering labor to ensure that current safety standards and requirements are met. Quality and Safety effort is required both as a result of the basic engineering function and as a result of manufacturing processes.

After calculating the engineering hours, other program related costs were factored in to complete the EDI cost estimate. These other costs include Other Technical Services, Travel, and Computers. The definitions for each of these is as follows:

Other Technical Services (OTS) - OTS includes effort to perform planning, contracts administration, procurement, finance, and project management and administration. There is a very good relationship between all of the OTS support performed on a program and the onsite Engineering, Fabrication, Quality, Test and Tooling performed on a program.

Travel Dollars - Travel includes the cost for all travel required during the program. Travel was derived using Engineering and OTS labor hours as the base.

Computer Dollars - Computer costs were estimated discretely by identifying the number of CAE workstations required to do the design. Computer labor dollars were added to account for the effort performed by the Data Center for support of the total program.

3.2.3 Manufacturing Cost Methodology

Manufacturing costs were derived form historical factors, vendor estimates, parametrics, and bottoms-up estimates generated by manufacturing and industrial engineering. Estimates were developed for both LAC and SPACAL. These estimates include materials and services costs by unit. For higher cost items such as the LAC modules, cryogenic services and assembly, the SPACAL tower assemblies, and super ring assemblies, more detailed information was developed.

Tables A-9 and A-10 in the Appendix are the formats used to develop the manufacturing estimate. From the baseline, design specifications were developed for each of the hardware elements to use as a basis for estimating. The methodology column indicates the source where the $/unit numbers were derived. Figures 3 and 4 and "Status of EMPACT Liquid Argon Calorimeter Engineering Design," EMPACT Note 218 (1990) and "Status of EMPACT SPACAL Calorimeter Engineering Design," EMPACT Note 219 (1990) illustrate the major hardware elements for the two calorimeters. This should be used as a reference for identifying the components which have been estimated.

3.3 Cost Estimates

The following sections summarize the results of the cost analysis.

3.3.1 Cost Summaries

The cost analysis effort defines the R&D, EDI, and Manufacturing costs for the LAC and the SPACAL. Table 3 summarizes the cost results for the two calorimeters.

This summary includes R&D, EDI, Calorimeter manufacturing, Cryogenic Services, and Front-End Electronics. These five areas differ in cost based on the calorimeter technology chosen and their impacts on the total detector cost . Other detector elements such as tracking, muon detection systems, data acquisition, installation, and operations costs differences were assumed to be negligible. There is a considerable difference in the front-end electronics cost between LAC and SPACAL. LAC consists of 300,000 channels compared to 60,000 channels for SPACAL. There is also a difference in the facility equipment costs because of the cryogenic services required for the LAC. Overall, the SPACAL was estimated to be $35 million or 16% higher than the LAC.

	R&D	EDI	MFG	Services	Electronics	TOTAL
LAC	$7 M	$29M	$98 M	$4 M	$79 M	$217 M
SpaCal	$4 M	$34M	$154 M		$60 M	$252 M

Table 3. - Calorimeter Cost Summary

Figure 6 is a Pareto analysis performed which shows the high cost items in the two options. Table 4 summarizes the differences in manufacturing costs which includes material costs and assembly labor, services, and electronics.

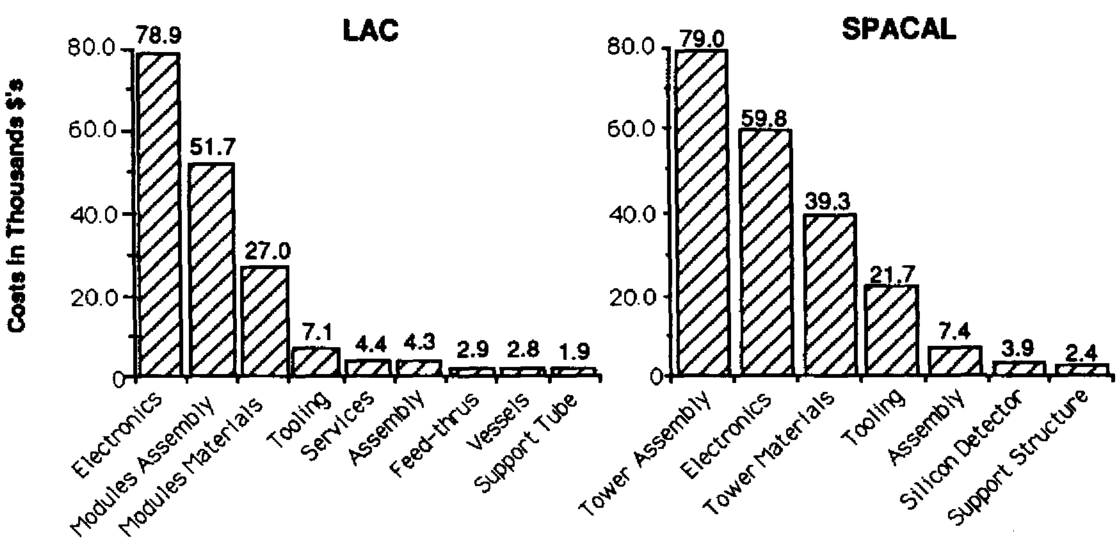


Figure 6. Pareto Analysis

LAC MANUFACTURING COSTS ($K)

	Central	End Cap	Total
Uranium	$10,930	$7,701	$18,631
G-10 Boards	$2,102	$1,471	$3,573
Structure	$2,867	$2,018	$4,885
TOTAL MATERIALS	$15,899	$11,190	$27,089
Module Assembly	$28,551	$23,159	$51,709
Calorimeter Assembly	$1,672	$2,648	$4,320
Vessels/Support Struct			$4,685
Tooling/Test Eq.			$7,127
Services			$7,293
TOTAL CALORIMETER			$102,223
Electronics			$78,844
TOTAL DETECTOR IMPACT			$181,067

SPACAL MANUFACTURING COSTS ($K)

	Central	End Cap	Total
Lead	$4,810	$4,900	$9,710
Fiber	$7,260	$5,838	$13,098
Glue	$1,600	$1,630	$3,230
Photomultipliers	$6,024	$6,078	$12,102
Tower End Fittings	$578	$583	$1,162
TOTAL MATERIALS	$20,272	$19,030	$39,302
Tower Assembly	$39,307	$39,659	$78,966
Calorimeter Assembly	$4,327	$3,080	$7,407
Support Structure			$2,396
Tooling/Test Eq.			$21,743
Silicon Detector			$3,865
TOTAL CALORIMETER			$153,678
Electronics			$59,765
TOTAL DETECTOR IMPACT			$213,443

Table 4. Manufacturing Costs Comparison

3.3.2 R&D Costs

The R&D cost for LAC is estimated to be $7.0 million compared to $4.7 million for SPACAL. Tables A-3 and A-4 in the appendix include a detailed breakdown of the R&D program estimates for LAC and SPACAL, respectively. The labor portion includes the effort for trade studies, R&D test, prototype test, and test support required during the R&D phase for each applicable calorimeter subsystem. Computers have been included because extensive modeling will be done to support the trade study analysis. Material and fabrication is required for those items where tests will be performed.

R&D is higher for the LAC because of the stringent operating conditions due to the cryogenic temperatures. The Module Resolution and Response cost of $3.3 million was derived from R&D proposals written to date. This is also true for the $1.2 million for prototype construction of the SPACAL.

3.3.3 EDI Costs

The EDI cost for LAC is estimated to be $28.8 million compared to $34.1 million for SPACAL. This estimate was developed by engineers who outlined the drawings, interface control documents, test specifications, specification control drawings, schematics, and design reviews required for each subsystem before the hardware can be procured. The difference in cost is largely due to the design of 60,000 tower assemblies for the SPACAL compared to less than 500 modules for the LAC.

Using parametrics based on historical Martin Marietta programs, and adjusting appropriately to meet the calorimeter design requirements, the number of engineering design hours required was determined as explained in the methodology section. Tables A-5 and A-6 in the appendix include the estimate of the number of drawing sheets required to design the calorimeter. Table A-7 and A-8 include the engineering design hours estimated to perform the various EDI activities required for LAC and SPACAL, respectively. Each of these engineering areas are represented by the columns. The last column represents the total EDI cost which includes other technical services (program management, planning, etc.), travel, other direct costs, computers and computer support. A definition of each type of drawing and engineering activity was given in Section 3.2, EDI Cost Methodology.

3.3.4 Manufacturing Costs

3.3.4.1 Materials and Services Cost Summary

The manufacturing cost for LAC is estimated to be $98.5 compared to $153.7 million for SPACAL, not including front-end electronics costs and cryogenic services. The SPACAL estimate is driven by the assembly time for the 60,510 towers. Tables A-9 and A-10 in the appendix include the detailed manufacturing estimates for LAC and SPACAL, respectively. This estimate was developed from inputs from manufacturing, industrial engineering, modeling, vendor quotes, historical costs, and parametrics. The table includes the unit measure (e.g. lbs) and number of units estimated (e.g. 200,000 lbs). The quantity column is the number of subsystem elements estimated (e.g. 32 feed-throughs). The material type (e.g. Al) and $/unit ($7.76/lb) are used to estimate material costs. In the case of labor, manufacturing touch hours are used to estimate labor costs ($/hr). The methodology column includes the source of the estimate.

3.3.4.2 LAC Modules Detailed Cost Analysis

Baseline Configuration

The major elements of the liquid argon calorimeter are the modules. They also make up 80% of the calorimeter cost , thus an in depth cost analysis was performed for this reason. This was accomplished by developing a bottoms-up estimate with assistance from the Manufacturing and Industrial Engineering departments.

The first step was to develop a baseline design to use for the estimate. Figure 7 shows how the modules are arranged within the central barrel and end caps. Figure 8 is an illustration of one module showing the structure which is used to hold the layers of uranium plates. Figure 9 shows how the uranium plates, liquid argon spaces, and G-10 boards are layered.

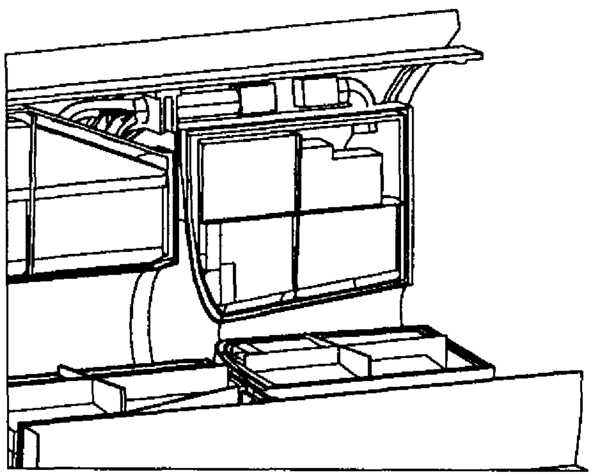


Figure 7. LAC Module Arrangements

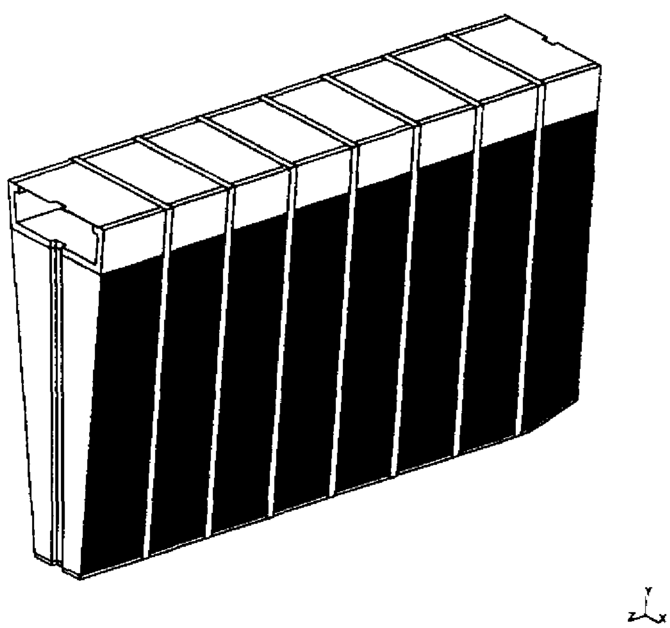


Figure 8. LAC Module Design

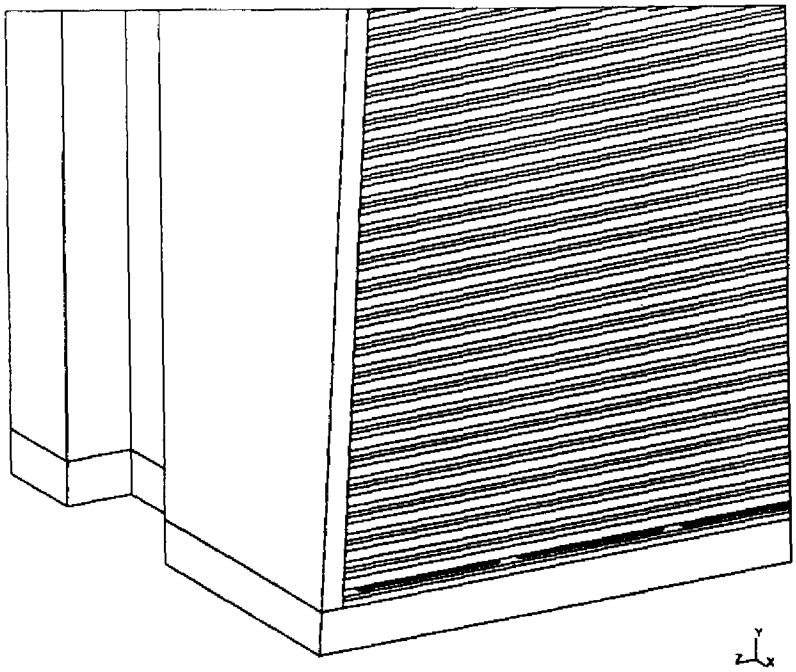


Figure 9. LAC Module Layers

Material Costs

Next, the specifications for the 6 different modules within the central barrel, 2 EM and 4 hadronic were developed. The same was done for the 6 types of modules in the end caps. The total weight of Uranium, the number of uranium plates, and the number of G-10 boards was derived for each module. A cost of $3.50 per pound was used for the uranium plates which was developed by a Depleted Uranium vendor. An estimate of $60.61 per G-10 board was developed by the manufacturing engineering department. As shown in Table 5, the total Uranium cost for the Central Barrel is $10.9 million and the total G-10 board cost is $2.1 million. Similarly for the End Caps, the total Uranium cost is $7.7 million and $1.5 million for the G-10 boards.

MATERIAL COSTS

EM Modules	Thickness (mm)	Density (g/cm3)	Qty/Module	Weight/Module (kg)	% of Total Weight
Uranium Plates	3	18.95	24	833	88.3%
Liquid Argon	2	1.4		41	4.3%
G-10 Boards	1.14	1.7	24	28	3.0%
Liquid Argon	2	1.4		41	4.3%
			Total Weight	943 kg	
Hadronic Modules					
Uranium Plates	3.325	18.95	133	5502	93.3%
Liquid Argon	2	1.4		245	4.1%
G-10 Boards	1	1.7	133	148	2.5%
Uranium Plates	3.325				
G-10 Boards	1				
Liquid Argon	2				
			Total Weight	5895 kg	

CENTRAL	Total Module Weight (kg)	Uranium Weight (kg)	G-10 Weight (kg)	# of Uranium Plates	# of G-10 Boards	Uranium Cost ($K)	G-10 Board Cost ($K)
1 - End Outer	4527	4225	114	102	102	$33	$6
2 - End Inner	5895	5502	148	133	133	$42	$8
3 - Central Outer	7060	6589	178	159	159	$51	$10
4 - Central Inner	4631	4322	117	104	104	$33	$6
5 - EM End	943	833	28	24	24	$6	$1
6 - EM Central	751	663	23	19	19	$5	$1
TOTAL	23,806	22,134	608	542	542	$171	$33
# modules: 64							
Total Central Material Costs	1,523,606	1,416,580	38,900	34,686	34,686	**$10,930**	**$2,102**
kg/plate: 40.8		$60.61 per G-10 board					
cm3/plate: 2,155		given thickness of 3.325mm and width of 33.65cm					
length (cm): 193		$3.50 /lb quoted for Uranium Plates					

END CAP	Total Module Weight (kg)	Uranium Weight (kg)	G-10 Weight (kg)	# of Uranium Plates	# of G-10 Boards	Uranium Cost ($K)	G-10 Board Cost ($K)
1 - End Outer	3881	3622	98	88	88	$28	$5
2 - End Inner	3456	3226	87	78	78	$25	$5
3 - Forward Outer	6412	5984	161	145	145	$46	$9
4 - Forward Inner	2447	2284	62	55	55	$18	$3
5 - EM Outer	375	331	11	10	10	$3	$1
6 - EM Inner	167	147	5	4	4	$1	$0
TOTAL	16,738	15,595	424	379	379	$120	$23
# modules: 64							
Total End Cap Material Costs	1,071,203	998,051	27,145	24,266	24,266	**$7,701**	**$1,471**
kg/plate: 41.1							
cm3/plate: 2,170							
length (cm): 194		given thickness of :.325mm and width of 33.65cm					

Table 5. LAC Modules Material Costs

The remaining material costs consist of the structure which holds the module together as shown in Figure 8. The cost for this steel structure was estimated to be 22% of the Uranium and G-10 Board Cost based on historical calorimeter data. This resulted in a total structure cost of $2.9 million for the Central Barrel and $2.0 million for the two End Caps.

Assembly Cost

An assembly cost was developed based on an Industrial Engineering estimate.
Table 6 below outlines the 10 steps which are required to assemble one Central Barrel module. For each step, the set-up time, run time, and quantity was entered into the Industrial Engineering Standards Computer model. There were six different runs generated per central barrel and end cap, due to the different quantities of uranium sheets, G-10 boards, and structure required for each. The output of assembly labor hours/module for each configuration is shown in Table A-11 of the appendix.

	CENTRAL CALORIMETER	I - End Outer			
Step	Part Name	Set-Up	Run	Qty	Total Time (Hours)
1	Channel				
2	Plate				
3	Strongback				
4	End Cap				
5	Uranium Sheets				
6	Bridge				
7	Bond G10/U				
8	Strap				
9	Spacer				
10	Segment Assy				
	TOTAL LABOR/MODULE				

Table 6. LAC Module Assembly Steps

Cost Summary

Table 7 summarizes the costs for the modules. The assembly labor hours/module was multiplied by the number of modules to generate a total touch labor hour number of 85,013 hours for the Central Barrel and 62,587 hours for both End Caps. Manufacturing Support, Quality Engineering, and Inspection were added resulting in total manufacturing hours of 414,981 for the Central Barrel and 336,625 for both End Caps. Manufacturing Labor hours were then converted to dollars with factory tooling, program management, freight and material, adding to give a total cost of $44.4 million for the Central Barrel and $34.3 million for both End Caps.

CENTRAL CALORIMETER SUMMARY	Touch Hours Per Module	# of Modules	(90% learning) Total Touch Labor Hrs	END CAP CALORIMETER SUMMARY	Touch Hours Per Module	# of Modules	(90% learning) Total Touch Labor Hrs
1 - End Outer	464	64	15,794	1 - End Outer	405	64	13,787
2 - End Inner	589	64	20,047	2 - End Inner	367	64	12,466
3 - Central Outer	696	64	23,665	3 - Forward Outer	637	64	21,651
4 - Central Inner	474	64	16,117	4 - Forward Inner	274	64	9,331
5 - EM End	148	64	5,032	5 - EM Outer	89	64	3,041
6 - EM Central	128	64	4,357	6 - EM Inner	68	64	2,310
TOTAL			85,013	TOTAL			62,587
MANUFACTURING SUPPORT			255,191	MANUFACTURING SUPPORT			214,208
QUALITY ENGR/INSPECTION			74,778	QUALITY ENGR/INSPECTION			59,830
TOTAL MFG LABOR HOURS			414,981	TOTAL MFG LABOR			336,625
MFG LABOR COST ($K)			$19,919	MFG LABOR COST ($K)			$16,158
FACTORY TOOLING ($K)			$4,980	FACTORY TOOLING ($K)			$4,039
PROGRAM MANAGEMENT ($K)			$3,436	PROG MGMT			$2,787
FREIGHT ($K)			$215	FREIGHT			$175
MATERIAL ($K)			$15,900	MATERIAL ($K)			$11,189
Uranium			$10,930	Uranium			$7,701
G-10 Boards			$2,102	G-10 Boards			$1,471
Structure			$2,867	Structure			$2,018
TOTAL CENTRAL MODULES			$44,450	TOTAL END CAP MODULES			$34,349

Table 7. LAC Modules Cost Summary

3.3.4.3 LAC Assembly Cost Analysis

A bottoms-up estimate was developed by manufacturing engineering for the assembly of the Central Barrel and End Cap into its final configuration before moving it into the underground hall. "Status of EMPACT Liquid Argon Calorimeter Engineering Design," EMPACT Note 218 (1990), contains illustrations of the above ground assembly process.

The estimate was generated by manloading the individual assembly steps identified in the Master Schedule shown in the Schedule Analysis. Included in the assembly estimate are the number of persons required and the duration of each task performed. Table 8 on the following page summarizes the hours for assembly. The Central Barrel requires 37,164 hours and each End Cap requires 29,421 hours for assembly.

END CAP	Persons	Duration (months)	Manhours
Set up Mandrel	4	0.2	130
Build Ar Vessel Subassy	3	1	489
Weld Washer	3	0.5	245
Weld Half Mid-Cylinder	3	0.5	245
Weld Flat Portion Ar Headwall	3	0.5	245
Well Inner Cylinder	3	0.5	245
Weld Rear Ar Headwall	3	0.5	245
Calorimeter Monolith Assy	5	1	815
Position Cable Support Tool	4	0.2	130
Innner Hadronic Modules (2)	3	1	489
Frwd Monolithic EM Rings (2)	3	1	489
Install Monolith Vessel Subassy	4	0.5	326
Weld Mid-Cylinder Segments	3	1	489
Mount Outer Hadronic Modules	3	1	489
Weld Ar Vessel Outer Shell	3	1	489
Well Elliptical Head	3	1	489
Support End Cap	2	1	326
Remove Mandrel	4	0.2	130
Mount on Rotation/Insertion Tool	4	0.2	130
Position Inner Vac Assy	4	0.5	326
Position Rear Headwall Assy	4	0.5	326
Weld Outer Vac Shell/Ellip Hd	3	1	489
Weld to Rear Headwall	3	1	489
Weld Stanction Vac Jackets	3	1	489
Roll Transfer to Vac Shell	4	0.5	326
TOTAL TOUCH HOURS			9079
MFG SUPPORT			11803
INSPECTION			3555
ENGINEERING			2054
PROJECT MANAGEMENT			2930
TOTAL ASSY HOURS			29421

CENTRAL BARREL	Persons	Duration (months)	Manhours
Set up Mandrel	4	0.5	326
Install Calorimeter Modules	7	1	1141
Install Cable Support Tool	2	0.2	65
Route Cables	2	2	652
Install Ar Outer Shell	3	1	489
Move to Cradle	4	0.2	130
Install in Outer Vac Shell	3	1	489
Cylindrical Supt Beams Placed	4	1	652
Install Pinned Radial Links	2	0.5	163
Alignment	2	2	652
Weld Inner Vac Shell	3	1	489
Weld Endcap Vac Shells	3	1	489
Install Feed-Throughs	2	2	652
Test	3	10	4890
TOTAL TOUCH HOURS			11280
MFG SUPPORT			14663
INSPECTION			4399
ENGINEERING			2433
PROJECT MANAGEMENT			4389
TOTAL ASSY HOURS			37164

Table 8. LAC Assembly Hours

3.3.4.4 LAC Cryogenic Services Cost Analysis

The Cryogenic Services System consists of the liquid argon plant and cooling system for the calorimeter. The layout of the system is illustrated in "Status of EMPACT Liquid Argon Calorimeter Engineering Design," EMPACT Note 218 (1990). The following systems have been identified to be included in the cost estimate:

1. Local (at level) Argon storage
2. Remote liquid Nitrogen storage
3. Vacuum pumps
4. Liquid Nitrogen conditioner
5. Liquid Nitrogen valves and automatic controls
6. Local Argon reference pressure Dewar
7. Control system for Argon "over pressure" regulation
8. Boiler for the vaporization of excess liquid Nitrogen
9. Boiler to vaporize Argon
10. Instrument and valve controller

Table A-12 in the appendix summarizes the cryogenic components, specifications, quantities, and costs for each of the elements in the system. The total cost for cryogenics services is estimated to be $3.7 million.

3.3.4.5 LAC Tooling Requirements

"Status of EMPACT Liquid Argon Calorimeter Engineering Design," EMPACT Note 218 (1990) should be referenced for the tooling requirements. The cost for tooling is included in Table A-9 of the appendix. This estimate was developed from historical detector tooling costs as a function of total calorimeter hardware cost. A factor was used due to the lack of tooling design specifications such as weight which may be used to estimate tooling costs.

3.3.4.6 SPACAL Tower Assembly Cost Analysis

Baseline Configuration

The major elements of the scintillating fiber calorimeter are the tower assemblies. They make up 77% of the calorimeter cost. A similar estimate, as completed for the LAC modules, was developed for the assembly of the towers. This was accomplished by developing a bottoms-up estimate with assistance from the Manufacturing and Industrial engineering departments.

The first step was to develop a baseline design to use for the estimate. Figure 2 is a view of the SPACAL showing how the towers are arranged into the ten super-rings in the central barrel and four super-rings in each of the end caps. Figure 10 is an illustration of an individual tower showing the layers of lead and fiber with the photomultiplier tube and tower fittings at the end.

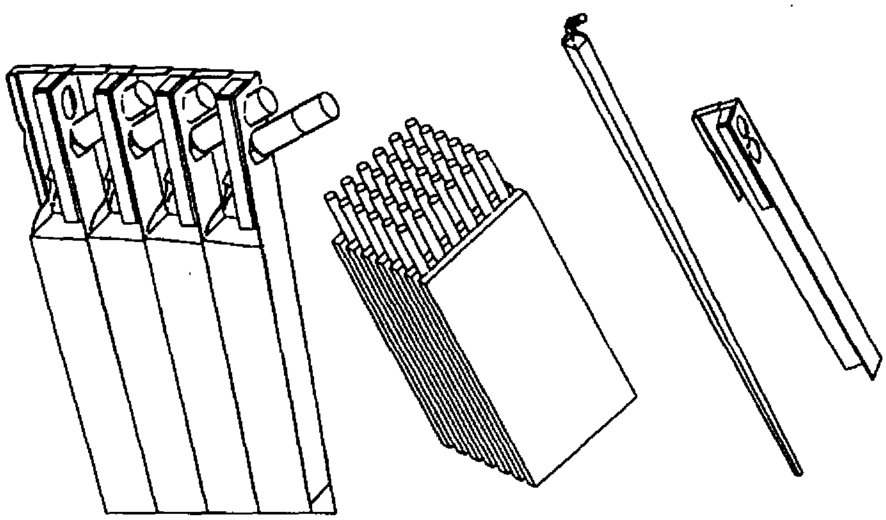


Figure 10. Tower Assembly Illustration

Material Costs

Next, the specifications for the 5 different super rings within the central barrel were developed. The same was done for the four super rings in the end caps. The total weight of lead, glue, and tower end fittings, the kilometers of fiber, and the number of photomultiplier tubes was derived for each super ring. A cost of $1.70 per pound for rolled sheets of lead, $0.30 per meter of fiber, $200 per photomultiplier tube, $213 per gallon for glue, and $20 per pound for tower end fittings were used which were obtained from vendor estimates. Table 9 below summarizes the total material costs for the SPACAL tower assemblies.

MATERIAL COSTS ($K)	Central	End Cap	Total
Lead	$4,810	$4,900	$9,710
Fiber	$7,260	$5,838	$13,098
Glue	$1,600	$1,630	$3,230
Photomultipliers	$6,024	$6,078	$12,102
Tower End Fittings	$578	$583	$1,162
TOTAL MATERIALS	$20,272	$19,030	$39,302

Table 9. SPACAL Tower Material Costs

Assembly Cost

An assembly cost was developed with assistance from industrial engineering. Table 10 outlines the 20 steps which are required to assemble one tower. For each step the set-up time, run time, and quantity was entered into the Industrial Engineering Standards Computer model. The total assembly labor hours, including support, per tower was estimated to be 29.2 hours.

SpaCal TOWER ASSEMBLY		Set-Up	Run	Qty	Total Time (Hours)	Total Time per Module (Hours)
1	Shear Grooved Lead Sheet to Size	167.20	0.48	855000	410,567	6.6
2	N/C Punch Lead Blank Profile	309.70	0.33	855000	282,460	4.6
3	Resize Grooves at One (Outer) End	16.30	0.33	855000	282,166	4.6
4	Ultrasonic Clean	0.20	0.11	855000	94,050	1.5
5	Rack Lead Details	47.50	0.04	855000	34,248	0.6
6	Bond Layup: Robotic System	112.10	0.02	47500	1,062	0.0
7	Remove Tower Layup from Fixture/Pallet	0.00	0.01	47500	475	0.0
8	Form Twist & Arc in Tower	123.50	0.1	47500	4,874	0.1
9	Bond/Cure/Protective Boot	0.00	0.58	47500	27,550	0.4
10	Machine the Two Tapered Surfaces & Small	323.00	4.1	47500	195,073	3.1
11	Bundle Fibers and Trim	0.48	0.08	17500	1,400	0.0
12	Wet Sand/Polish Fiber Ends	0.39	0.04	17500	700	0.0
13	Turn the Acrylic Cookie to Dimension	0.85	0.1	47500	4,751	0.1
14	Epoxy Pot Lens to Fiber Ends	0.90	0.36	47500	17,101	0.3
15	Inspect Tower for Fiber Function	0.59	0.04	47500	1,901	0.0
16	Assemble Photo Multiplier to Tower	0.83	0.23	47500	10,926	0.2
17	N/C Punch Profile of Tower Extension	193.80	0.14	47500	6,844	0.1
18	Break Bend Blank	229.90	0.15	47500	7,355	0.1
19	Bond Tower Extension to Tower	171.00	0.36	47500	17,271	0.3
20	Load in Storage Shipping Container	0.00	0.19	47500	9,025	0.1
TOTAL LABOR/TOWER					1,409,798	22.7

SpaCal Tower Assembly	Hours	avg hrs/tower	Costs ($K)
Total Touch Hours	1,409,798	22.7	63,441
Mfg Support	86,237	1.4	3,881
Inspection	63,441	1.0	2,855
Sust Engr	36,655	0.6	1,649
Prog Mgmt	215,478	3.5	9,696
TOTAL	1,811,609	29	78,966

Table 10. SPACAL Tower Assembly Hours

Cost Summary

Table 11 summarizes the costs for the towers for each super ring. The assembly labor hours/tower was multiplied by the number of towers and labor rate to generate a total cost of $59.6 million dollars for the Central Barrel and $58.7 million dollars for both End Caps.

	Central	End Cap	Total
Lead	$4,810	$4,900	$9,710
Fiber	$7,260	$5,838	$13,098
Glue	$1,600	$1,630	$3,230
Photomultipliers	$6,024	$6,078	$12,102
Tower End Fittings	$578	$583	$1,162
TOTAL MATERIALS	$20,272	$19,030	$39,302
Tower Assembly	$39,307	$39,659	$78,966
TOTAL TOWER COST	**$59,579**	**$58,689**	**$118,267**
Calorimeter Assembly	$4,327	$3,080	$7,407
Support Structure			$2,396
Tooling/Test Eq.			$21,743
Silicon Detector			$3,865
TOTAL CALORIMETER			$153,678
Electronics			$59,765
TOTAL DETECTOR IMPACT			$213,443

Table 11. SPACAL Towers Cost Summary

3.3.4.7 SPACAL Super Ring Assembly Cost Analysis

A bottoms-up estimate was developed by manufacturing engineers for the assembly of the Central Barrel and End Cap into its final configuration before moving it into the underground hall. "Status of EMPACT SPACAL Calorimeter Engineering Design," EMPACT Note 219 (1990), contains an illustration of the assembly process. The estimate was generated by manloading the individual assembly steps identified in the Master Schedule shown in the Schedule Analysis. Included in this estimate, as shown in Table 12, are the number of persons required and the duration of each task to be performed. The Central Barrel requires 96,027 hours and each End Cap requires 30,541 hours for assembly.

END CAP	Persons	Duration (months)	Manhours
Weld Assemble Support Can	2	0.3	98
Turn Can to Eng Dimension	1	0.5	82
Drill Flange Mounting Holes	1	0.2	33
Cut/Roll Details Barrel Ends/8	2	0.25	82
Load Spt Can On Assy Tool	3	0.1	49
Machine Length/Cord	1	0.5	82
Install Formed Rubber Dams	2	0.1	33
Load Wiring Harness	1	0.6	98
Weld Assemble Barrel End	2	0.3	98
Load/Connect Tower Assys	3	0.6	293
Space Towers	1	0.3	49
Turn ID/OD Configurations	1	0.25	41
Epoxy/Vacuum/Cure	2	0.3	98
Position Cable Support Tool	3	0.1	49
Turn To Eng Dimensions	1	0.4	65
Drill/Tap holes for Cal Mount	1	0.75	122
Cover/Store For Next Assy Ops	1	0.1	16
Drill holes for Roller Ways	1	1	163
Load Barrel End on Cradles	3	0.25	122
Weld Assemble Inboard Outer	2	0.3	98
Machine Way Support Fittings	2	3.5	1141
Turn Can to Eng Dimensions	1	0.5	82
Drill Holes for Roller Ways	1	0.8	130
Assem Spt Fitting/Ways on Barrel	3	0.3	147
Drill Flang Mounting Holes	1	0.2	33
Weld Assemble Barrel End	2	0.6	196
Drill/Tap Holes for Cal Mount	1	0.3	49
Weld End to Central Barrel	2	1.6	522
Load Spt Can on Assy Tool	3	0.1	49
Cut/Roll Details Barrel Ends/8	2	0.3	98
Load Harness	1	0.7	114
Locate Formed Rubber Dams	2	0.2	65
Machine Length/Cord	1	0.5	82
Load Tower Assys	3	0.7	342
Mount on Rotation Insert Tool	3	0.1	49
Space Towers	1	0.4	65
Epoxy/Vaccum/Cure	2	0.4	130
Turn to Eng Dimensions	1	0.5	82
Turn ID/OD Configuration	1	0.6	98
Cover/Store for Next Ops	1	0.1	16
Weld Assemble Spt Can	2	0.3	98
Turn Spt Can to Dimensions	1	0.5	82
Load Barrel End on Cradles	3	0.1	49
Load on Assy Tool	3	0.1	49
Locate Formed Rubber Dams	2	0.2	65
Install Layer Wiring Harness	1	0.8	130
Locate/Connect Towers	3	0.8	391
Space Towers	1	0.4	65
Epoxy/Vacuum/Cure	2	0.4	130
Position Cable Support Tool	3	0.1	49
Turn to Eng Dimensions	1	0.4	65
Cover/Store for Next Assy	1	0.1	16
Weld Assemble Support Can	2	0.3	98
Turn to Eng Dimensions	1	0.5	82
Drill Flange Mounting Holes	1	0.2	33
Load Spt Can on Assy Tool	3	0.1	49
Locate Formed Rubber Dams	2	0.3	98
Install Layer Wiring Harness	2	0.7	228
Locate/Connect Tower Assys	3	1.2	587
Space Towers	2	0.3	98
Epoxy/Vacuum/Cure	2	0.7	228
Turn to Eng Dimensions	1	0.5	82
Attach Inboard to Inner	4	0.5	326
Attach Outboard to Inboard	4	0.5	326
Attach Outer to Outboard	4	0.5	326
Assemble Roller Spt/Rollers	5	0.5	408
Mount on Rotation Insert Tool	3	0.1	49
TOTAL TOUCH HOURS			9462
MFG SUPPORT			12224
INSPECTION			3705
ENGINEERING			2121
PROJECT MANAGEMENT			3029
TOTAL ASSY HOURS			30541

CENTRAL BARREL	Persons	Duration (months)	Manhours
Weld Assemble Support Can	16	0.25	652
Fab Layer Wiring Harness	16	6	15648
Weld Assemble Support Tube	2	0.3	98
Turn Spt Can to Dimensions	1	0.5	82
Load Harness in Spt Can	1	1.3	212
Install Cable Support Tool	3	0.1	49
Drill Flange Holes	1	0.2	33
Cut/Roll Cent Barrel Details/8	2	0.25	82
Turn Lose Flang to Dimensions	1	0.1	16
Load Spt ring Assy on Ring Tool	3	0.1	49
Load Formed Rubber Seal	2	0.1	33
Machine Details	1	0.5	82
Bond Lead Sheet to Tube	4	0.2	130
Mill Mounting Holes Lose Flang	1	0.1	16
Load/Connect Tower Assys (300)	3	1.3	636
Space/Fix Tower Assys	1	0.6	98
Weld Assemble Central Barrel	2	0.4	130
Bond Silicone Tiles to Lead	4	6.4	4173
Epoxy/Vacuum/Cure Assys	2	1.3	424
Turn Super Ring Exposed Surface	6	0.4	391
Turn ID/OD Dimensions	1	0.25	41
Attach Insertion Tool	3	0.8	391
Drill Support Ring Holes	1	1	163
Insert/Attach Ring to Barrel	4	1	652
Mill Mounting Holes Tube Flang	1	0.2	33
Load on Assy Cradles	3	0.25	122
Weld Assemble Support Can	2	0.3	98
Turn Spt Can to Dimensions	1	0.5	82
Drill Flang Holes	1	0.2	33
Load Spt Ring Assy on Ringtool	3	0.2	98
Load Harness in Spt Can	1	0.4	65
Load Formed Rubber Seal	2	0.2	65
Load/Connect Tower Assys (300)	6	1.2	1174
Space/Fix Tower Assys	1	0.4	65
Epoxy/Vacuum/Cure Assys (8)	2	0.8	261
Turn Ring Exposed Structure	1	0.8	130
Attach Insertion Tool	3	0.6	293
Weld Assembly Support Can	2	0.3	98
Turn to Dimensions	1	0.5	82
Drill Washer Holes	1	0.2	33
Drill Flang Holes	1	0.2	33
Load Spt Can on Assy Tool	3	0.1	49
Assemble Bonding Retainer Ring	2	0.1	33
Load Harness in Spt Can	1	0.6	98
Install Formed Rubber Rings	2	0.3	98
Load/Connect Tower Assys	3	3.6	1760
Space/Fix Tower Assys	1	0.6	98
Epoxy/Vacuum/Cure Assy	2	1.2	391
Turn Ring Exposed Surface	1	1	163
Attach Insertion Tool	3	0.2	98
Insert/attach to Barrel	3	0.2	98
Insert/Bolt Tube/Cent Barrel	4	1	652
Attach/Weld Spt Tube Adaptor	4	0.5	326
Install Rosetts Inside Tube	2	0.3	98
Finish Support Tube	3	0.2	98
TOTAL TOUCH HOURS			31100
MFG SUPPORT			38293
INSPECTION			12179
ENGINEERING			5366
PROJECT MANAGEMENT			9089
TOTAL ASSY HOURS			96027

Table 12. SPACAL Assembly Hours

3.3.4.8 SPACAL Silicon Detector Cost Analysis

A bottoms-up estimate was also developed for the Silicon detector. The silicon detector lines the inside of the calorimeter. It consists of a layer of silicon diodes, preamps, electronics, and lead. Table 13 summarizes the costs for the silicon detector. Its estimated cost is $3.9 million.

	Unit Measure	# Units	Qty	$/unit	Total Mfg Cost ($K)
Silicon Detector					3,865
Silicon Diodes	cm2	416000	1	2	832
Preamps	each	416000	1	2.5	1,040
Electronics	channels	15000	1	10	150
Lead	lbs	8000	1	1.5	12
Assembly	%	0.9			1,831

Table 13. Silicon Detector Costs

3.3.4.9 SPACAL Tooling Requirements

"Status of EMPACT SPACAL Calorimeter Engineering Design," EMPACT Note 219 (1990) should be referenced for the tooling requirements. The cost for tooling is included in Table A-10 of the Appendix. This estimate was developed from historical detector tooling costs as a function of total calorimeter hardware cost for the LAC calorimeter. The factor was then scaled up based on the total tooling count for the SPACAL as shown in the Technical Note. This tooling count factor was used due to the lack of tooling design specifications, such as weight, for estimating tooling costs.

3.4 Funding Profiles

A funding profile for the LAC and SPACAL is shown in Figure 11. It shows the funding requirements for R&D, EDI, Manufacturing, Services, and Electronics. The funding requirements have been generated in six-month intervals. The funding spreads follow the schedules outlined in the Schedule Analysis and were obtained from the work performed on EMPACT.

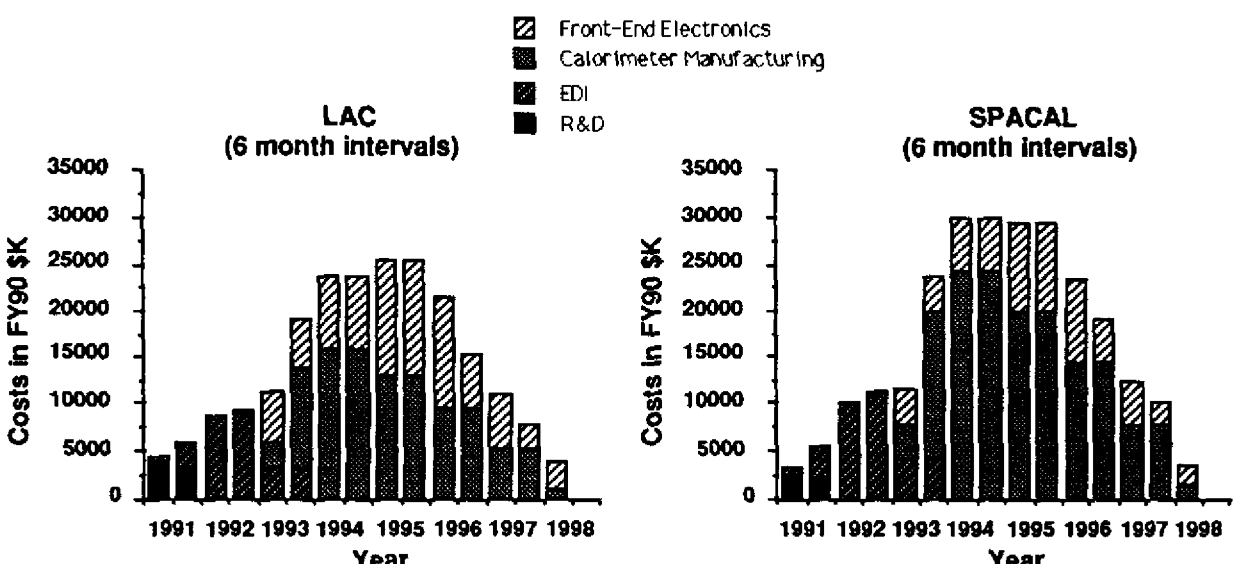


Figure 11. Funding Profiles

4.0 COST RISK ANALYSIS

This section discusses the risk definitions and implications associated with the two detectors. Risk Analysis is a method for measuring the uncertainty that is inherent in the prediction of a future event. Only cost risk has been considered in this analysis.

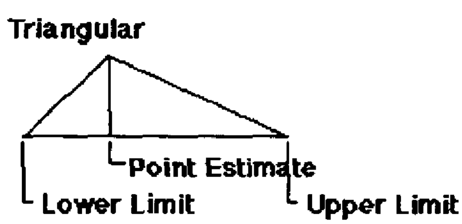
Risk analysis, when treated as a statistical process, aids management decision making by allowing potential hazards to be assessed. Cost Risk Analysis should be used as an integral part of the decision process because it allows for more informed decisions to be made as the costs of various alternatives and the associated variations in the cost can be considered. Point cost estimates do not reflect uncertainty introduced by limited cost information, omitted factors, biased estimates and changes in technical parameters.

Risk analysis addresses the factors which influence point estimates. Point estimates are developed based on the cost methodology described in the previous sections. Point estimates are negatively influenced by cost increases such as late requirements, test failures, redesign, customer directed changes, time constraints, and budget reductions. Optimistic point estimates assume everything goes "green light", product improvement is smoothly implemented, designers use innovative cost savings techniques, and the problem is defined precisely the first time. The actual cost for a given program should lie somewhere between these two extremes. The risk analysis approach seeks to define a "best" risk adjusted cost estimate.

Cost estimating risk reflects the uncertainty in the baseline cost methodology. All technical, performance, and schedule parameters are held constant so that only the uncertainty in the cost estimating process is addressed. Cost estimating uncertainties arise from incertitudes inherent in the cost estimating relationships (CERs), omitted factors, limited design information, biased estimates, and inadequacy of the CERs and complexity factors to simulate the system. An example of cost risk is the material cost estimate for fiber. These risks can be reduced by the use of improved cost estimating methodology as it is further developed.

The risk analysis process involves the following steps:

1. Develop Cost estimates
2. Identify the cost risks for each WBS element.
3. Determine upper and lower ranges for cost and technical risk for the individual WBS elements.
4. Determine the appropriate distribution function for the probability of each element (due to early stage of the program design data, triangular probability functions were used for all elements).



5. Perform a Monte Carlo simulation to determine the cumulative probability distribution.

The upper and lower values of the range define a probability function to be used in the analysis of the cost risk for a WBS element. The triangular distribution function is considered to contain +/- 3 sigma (standard deviations) or 99.9% of all the possibilities of the individual costs.

The risk simulation is performed by independently varying the cost of each of the WBS elements and summing these elements to arrive at a single trial value which represents one of the possibilities of cost. This process is repeated a number of times (1,000 simulatins was used) and a statistical analysis of the results is performed. This statistical approach allows assessment of the cost impacts of each WBS element and provides visibility into high cost and high risk areas.

The results of the analysis and simulation is shown in Table 14 and Figure 12. Table 14 shows the total R&D, EDI, Manufacturing, and Electronics Cost risk for the two detectors. Estimates have been included for 20%, 50%, and 80% confidence in meeting these costs. Figure 12 contains the cumulative probability curves. As the designs become more mature these curves will shift to the left showing a greater certainty in the cost estimates. For example, in these early stages of detector designs, the nominal estimate represents a confidence of 20%, but as the program matures, this confidence will increase. Tables A-13 and A-14 in the appendix contain the detailed risk assessment ranges for the LAC and SPACAL for each of the WBS elements.

		Probability (success/failure)				
Alternative	Nominal	0/100	20/80	50/50	70/30	100/0
LAC	$217M	$187M	$217M	$221M	$224M	$260M
SPACAL	$252M	$221M	$253M	$257M	$260M	$299M

Table 14. Cost Risk Summary

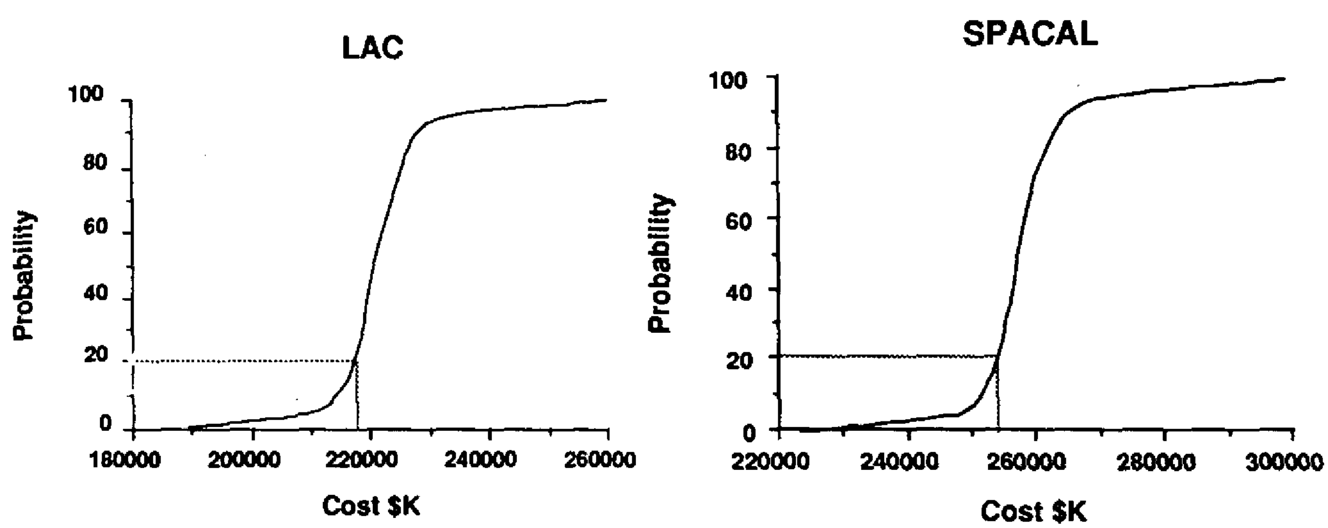


Figure 12. Cumulative Probability Distribution

APPENDIX

Table A-1. LAC EDI Estimate Format

Engineering Bottoms-Up	# of Drawing Sheets	# of PDs	# of ICDs	# of Test Specs	# of Layout Dwgs	# of Design Reviews	Design Engr	Design Analysis	Engr Support	Test Engr	Systems Engr	Logistics Engr	Engr Admin	Engr Labs	Quality/ Safety
Liquid Argon Calorimeter EDI															
Central Barrel															
Central Barrel Vessels															
Argon Vessel support															
Feed-thrus															
Vacuum/Support Tube															
Cooling Coils															
Cooling Piping															
Insulation															
Support Tube Support															
Module Designs															
Central inner															
Central outer															
End inner															
End outer															
Cabling															
Assembly & Test															
Tooling															
Test Equipment															
Endcap															
Endcap Vessels															
Feed-thrus															
Vacuum/Argon Support															
Cooling Coils															
Cooling Piping															
Insulation															
Module Designs															
Forward inner															
Forward outer															
End inner															
End outer															
Cabling															
Assembly & Test															
Tooling															
Test Equipment															
Forward Calorimeter															
Below Ground Cryogenics															
Argon System															
System Design															
Low head tankage															
High Head tankage															
Fill, Transfer, Cooling															
Spill Management															
Nitrogen System															
Low head tankage															
High Head tankage															
Fill and Transfer															
Spill Management															
Exhaust Fans															
Control System															
Control Room															
Above Ground Cryogenics															
Instrumentation															
Facilities T&H															
Calorimeter Installation															

Table A-2. SPACAL EDI Estimate Format

Engineering Bottoms-Up	# of Drawing Sheets	# of PDs	# of ICDs	# of Test Specs	# of Layout Dwgs	# of Design Reviews	Design Engr	Design Analysis	Engr Support	Test Engr	Systems Engr	Logistics Engr	Engr Admin	Engr Labs	Quality/ Safety
Spaghetti Calorimeter EDI															
Test Article															
Central Calorimeter Installation															
Super Ring Installation															
Super Ring Assembly															
Tower Assembly															
Central Tower Assembly															
Lead Details															
Fiber Details															
End Fittings															
Light Pipe															
Optical Fiber															
Photomultiplier Installation															
Cable Installation															
Support Structure															
Inner Tension Liner															
End Cap Calorimeter Installation															
End Cap Installation															
End Cap assembly															
Super Ring															
Super Ring Assembly															
Tower Assembly															
End Cap Tower Assembly															
Lead Details															
Fiber Details															
End Fittings															
Light Pipe															
Photomultiplier Installation															
Cable Installation															
Sub Structure															
External Structure															
Calorimeter Installation															
Forward Calorimeter															
T & H Equipment															

Table A-3. LAC R&D Cost Estimate

PROGRAM ELEMENT	Total R&D Cost (FY1990 $K)
Liquid Argon Calorimeter (LAC)	7023
Research & Development	5139
Module Resolution & Response	3387
Module R&D Facilities	677
Test Beams	0
Test Fixtures	41
Cryostat	521
Data Acquisition System	115
Stack Options	471
Metalized Plastic Sheets	4
Brite Pads	0
Pb Stacks	281
Other Tile Development	185
Cryogenics	117
Electrode Structure	268
Electronics	902
Simulation Code	240
Test Design	29
Test Support	73
Engineering, Design, & Integr.	609
Hermeticity/Containment	120
Argon Boiling/Electronics Cooling	500
Radiation Hardness	88
Sensor Position Tolerances	300
Materials Compatibility & Testing	250
Feed-thrus	494
Project Managment	528
Computers	1264
Travel	92

Table A-4. SPACAL Cost Estimate

WBS ELEMENT	Total R&D Cost (FY1990 $K)
Scintillating Fiber Calorimeter	4678
Research & Development	3390
Prototype Construction	1230
Labor, Travel & Contingency	680
Fiber	275
Lead	200
Photomultipliers and Readout	75
Tolerance Studies	500
Tower Shape & Construction	1100
Gap & Tolerance Allocation	60
Lead Fabrication	120
Fiber Fabrication	120
Mirrored Fabrication Studies	90
Non-Mirrored Fabrication Studies	90
Shape Control	60
Interface Fitting Definition	560
Super Ring Construction	560
Segment Definition	60
Support Concepts	120
Interface Definition	60
Subscale Test Evaluation	50
Wiring & Cabling	0
Bonding Techniques	230
Tolerance Allocation	40
Project Managment	397
Data Management	0
Computers	821
Travel	70

Table A-5. LAC EDI Drawing Sheet Estimate

Engineering Bottoms-Up	# of Drawing Sheets	# of PDs	Drawing Complexity Factor	# of ICDs	# of Test Specs	# of Layout Dwgs	# of Schematics	# of Design Reviews	Prototype Effort (M/M)
Liquid Argon Calorimeter EDI	956	13	26	42	70	91	0	39	152
Central Barrel	348	0	12	18	26	25	0	15	86
Central Barrel Trades			1.0						
Central Barrel Vessels	16		1.0		2	3		1	
Argon Vessel support	6		1.0			2		1	
Feed-thrus	12		1.0		3	2		1	
Vacuum/Support Tube	8		1.0	3				1	
Cooling Coils	20		1.0		1	3		1	
Cooling Piping	8		1.0	3	2	2		1	
Insulation	4		1.0					1	
Support Tube Support	4		1.0	1		4		1	
Module Designs	114	0		0	8	4	0	4	86
Module Design Trades			1.0						6
Central inner	90		0.3		2	1		1	40
Central outer	8		1.0		2	1		1	
End inner	8		1.0		2	1		1	40
End outer	8		1.0		2	1		1	
Cabling	54		1.0	3		5			
Assembly & Test	65		1.0	8	4			1	
Tooling	30		1.0		6			1	
Test Equipment	7							1	
Endcap	474	0	9	15	26	23	0	13	66
Endcap Vessels	32		1.0		2	3		1	
Feed-thrus	18		1.0		3	2		1	
Vacuum/Argon Support	36		1.0	2		2		1	
Cooling Coils	20		1.0		1	2		1	
Cooling Piping	8		1.0	2	2	1		1	
Insulation	4		1.0					1	
Module Designs	220	0		0	8	8	0	4	40
Forward inner	90		0.3		2	2		1	40
Forward outer	90		0.3		2	2		1	
End inner	20		1.0		2	2		1	
End outer	20		1.0		2	2		1	
Cabling	54		1.0	3		5			
Assembly & Test	55		1.0	8	4			1	
Tooling	20		1.0		6			1	
Test Equipment	7							1	
Forward Calorimeter	74		1.0	2	6			4	
Below Ground Cryogenics	29	7		5	8	21	0	3	0
Trades			1.0						
Argon System	13	1		3	3	9	0	0	0
System Design	5		1.0	2	1	4			
Low head tankage	1		1.0			1			
High Head tankage	1		1.0			1			
Fill, Transfer, Cooling System	4		1.0	1	1	1			

Table A-5. LAC EDI Drawing Sheet Estimate

Engineering Bottoms-Up	# of Drawing Sheets	# of PDs	Drawing Complexity Factor	# of ICDs	# of Test Specs	# of Layout Dwgs	# of Schematics	# of Design Reviews	Prototype Effort (M/M)
Spill Management	2	1	1.0		1	2			
Nitrogen System	6	3		2	2	5	0	0	0
Low head tankage		1	1.0			1			
High Head tankage		1	1.0			1			
Fill and Transfer System	4		1.0	1	1	1			
Spill Management	2	1	1.0	1	1	2			
Exhaust Fans	1	1	1.0		1	1		1	
Control System	8	2	1.0		2	3		1	
Control Room	1		1.0			3		1	
Above Ground Cryogenics Specs	2	6	1.0	2	2	3		1	
Instrumentation	4		1.0		2	8		1	
Facilities T&H	15		1.0			11		1	
Calorimeter Installation	10		1.0					1	

Table A-6. SPACAL Drawing Sheet Estimate

Engineering Bottoms-Up	# of Drawing Sheets	# of PDs	Layouts	# of ICDs	# of Test Specs	# of Parts List Sheets	# of Schematics	# of Design Reviews
Spaghetti Calorimeter Full-Scale Design	1318	8	50	14	28	834	12	29
Test Article	128				2	79		1
Central Calorimeter Installation	492	4	20	6	10	316	6	11
Super Ring Installation	20					4		1
Super Ring Assembly	120					60		1
Tower Assembly	302	2				242		6
Central Tower Assembly	120					60		1
Lead Details	60					60		1
Fiber Details	60					60		1
End Fittings	60					60		1
Light Pipe		2						1
Optical Fiber	2					2		1
Photomultiplier Installation	12					2		1
Cable Installation	12	2				3		
Support Structure	20					3		1
Inner Tension Liner	6					2		1
End Cap Calorimeter Installation	537	4	20	6	10	358	6	11
End Cap Installation	6					2	6	1
End Cap assembly	12					3		1
Super Ring	507	4				351		8
Super Ring Assembly	138					69		1
Tower Assembly	345	2				276		5
End Cap Tower Assembly	138					69		1
Lead Details	69					69		1
Fiber Details	69					69		1
End Fittings	69					69		1
Light Pipe		2						1
Photomultiplier Installation	6					1		1
Cable Installation	12	2				3		
Sub Structure	6					2		1
External Structure	12					2		1
Calorimeter Installation	9					3		1
Forward Calorimeter	74			2	6			4
T & H Equipment	78		10			78		1

Table A-7. LAC EDI Cost Estimate

Engineering Bottoms-Up	ENGINEERING												TOTAL ($K)
	Design Engr	Design Analysis	Engr Support	Test Engr	Systems Engr	Logistics Engr	Engr Admin	Engr Labs	Quality/ Safety	TOTAL ENGR HRS	TOTAL MM	TOTAL ($K)	w/ OTS, travel and computers
Liquid Argon Calorimeter EDI	119,688	43,633	36,442	34,888	38,152	17,381	9,966	17,807	34,062	321,688	1,974	21,596	28,784
Central Barrel	47,285	17,238	14,397	13,783	15,073	6,866	3,937	7,035	13,457	123,906	760	8,532	11,372
Central Barrel Trades	0	0	0	0	0	0	0	0	0	0	0	0	0
Central Barrel Vessels	2,005	731	610	584	639	291	167	298	571	5,897	36	362	482
Argon Vessel support	818	298	249	238	261	119	68	122	233	2,405	15	148	197
Feed-thrus	1,670	609	509	487	532	243	139	249	475	4,913	30	301	402
Vacuum/Support Tube	809	295	246	236	258	118	67	120	230	2,381	15	146	195
Cooling Coils	2,221	810	676	647	708	322	185	330	632	6,531	40	401	534
Cooling Piping	1,283	468	391	374	409	186	107	191	365	3,772	23	231	308
Insulation	413	151	126	120	132	60	34	61	118	1,215	7	75	99
Support Tube Support	910	332	277	265	290	132	76	135	259	2,677	16	164	219
Module Designs	22,252	8,112	6,775	6,486	7,093	3,231	1,853	3,311	6,333	65,447	402	4,015	5,351
Module Design Trades	978	357	298	285	312	142	81	146	278	2,876	18	176	235
Central inner	11,452	4,175	3,487	3,338	3,651	1,663	954	1,704	3,259	33,683	207	2,066	2,754
Central outer	1,101	401	335	321	351	160	92	164	313	3,237	20	199	265
End inner	7,621	2,778	2,320	2,221	2,429	1,107	635	1,134	2,169	22,413	138	1,375	1,833
End outer	1,101	401	335	321	351	160	92	164	313	3,237	20	199	265
Cabling	5,156	1,880	1,570	1,503	1,644	749	429	767	1,467	15,165	93	930	1,240
Assembly & Test	6,133	2,236	1,867	1,788	1,955	891	511	912	1,745	18,038	111	1,107	1,475
Tooling	3,285	1,197	1,000	957	1,047	477	273	489	935	9,660	59	593	790
Test Equipment	330	120	100	96	105	48	27	49	94	970	6	60	79
Endcap	46,823	17,070	14,256	13,648	14,926	6,799	3,899	6,966	13,325	122,547	752	8,449	11,261
Endcap Vessels	3,338	1,217	1,016	973	1,064	485	278	497	950	9,817	60	602	803
Feed-thrus	2,170	791	661	633	692	315	181	323	618	6,383	39	392	522
Vacuum/Argon Support	3,359	1,224	1,023	979	1,071	488	280	500	956	9,879	61	606	808
Cooling Coils	2,102	766	640	613	670	305	175	313	598	6,181	38	379	505
Cooling Piping	1,143	417	348	333	364	166	95	170	325	3,361	21	206	275
Insulation	413	151	126	120	132	60	34	61	118	1,215	7	75	99
Module Designs	21,061	7,678	6,413	6,139	6,714	3,058	1,754	3,133	5,994	61,944	380	3,800	5,065
Forward inner	11,571	4,218	3,523	3,373	3,689	1,680	963	1,722	3,293	34,033	209	2,088	2,783
Forward outer	5,051	1,842	1,538	1,472	1,610	734	421	752	1,438	14,857	91	911	1,215
End inner	2,219	809	676	647	707	322	185	330	632	6,527	40	400	534
End outer	2,219	809	676	647	707	322	185	330	632	6,527	40	400	534
Cabling	5,156	1,880	1,570	1,503	1,644	749	429	767	1,467	15,165	93	930	1,240
Assembly & Test	5,300	1,932	1,614	1,545	1,689	770	441	788	1,508	15,588	96	956	1,275
Tooling	2,452	894	746	715	781	356	204	365	698	7,210	44	442	590
Test Equipment	330	120	100	96	105	48	27	49	94	970	6	60	79
Forward Calorimeter	7,232	2,636	2,202	2,108	2,305	1,050	602	1,076	2,058	21,270	130	1,305	1,739
Below Ground Cryogenic Services	9,493	3,461	2,890	2,767	3,026	1,379	790	1,412	2,702	27,921	171	1,713	2,283
Trades	0	0	0	0	0	0	0	0	0	0	0	0	0
Argon System	3,040	1,108	926	886	969	441	253	452	865	8,941	55	549	731
System Design	1,052	384	320	307	335	153	88	157	299	3,094	19	190	253
Low head tankage	202	74	62	59	64	29	17	30	58	595	4	37	49
High Head tankage	202	74	62	59	64	29	17	30	58	595	4	37	49
Fill, Transfer, Cooling Sys	591	215	180	172	188	86	49	88	168	1,738	11	107	142

Table A-7. LAC EDI Cost Estimate

Engineering Bottoms-Up	ENGINEERING												TOTAL ($K)
	Design Engr	Design Analysis	Engr Support	Test Engr	Systems Engr	Logistics Engr	Engr Admin	Engr Labs	Quality/ Safety	TOTAL ENGR HRS	TOTAL MM	TOTAL ($K)	w/ OTS, travel and computers
Spill Management	*993*	362	302	289	316	144	83	148	282	2,919	18	179	239
Nitrogen System	*2,783*	1,015	847	811	887	404	232	414	792	8,186	50	502	669
Low head tankage	*589*	215	179	172	188	86	49	88	168	1,734	11	106	142
High Head tankage	*589*	215	179	172	188	86	49	88	168	1,734	11	106	142
Fill and Transfer System	*591*	215	180	172	188	86	49	88	168	1,738	11	107	142
Spill Management	*1,014*	370	309	295	323	147	84	151	288	2,981	18	183	244
Exhaust Fans	*870*	317	265	254	277	126	72	129	248	2,560	16	157	209
Control System	*2,279*	831	694	664	727	331	190	339	649	6,704	41	411	548
Control Room	*520*	190	158	152	166	76	43	77	148	1,530	9	94	125
Above Ground Cryogenics Specs.	*3,703*	1,350	1,128	1,079	1,180	538	308	551	1,054	10,892	67	668	891
Instrumentation	*1,600*	583	487	466	510	232	133	238	455	4,707	29	289	385
Facilities T&H	*2,639*	962	803	769	841	383	220	393	751	7,760	48	476	635
Calorimeter Installation	*913*	333	278	266	291	133	76	136	260	2,685	16	165	220

Other Technical Services (OTS) Hours	$3,769	
Travel Dollars ($K)	$534	
ODC Dollars ($K)	$44	
Computer Dollars ($K)	$2,680	
Computer Labor Dollars ($K)	$161	
	$7,188	added to labor

Table A-8. SPACAL EDI Cost Estimate

Engineering Bottoms-Up	ENGINEERING Design Engr	Design Analysis	Engr Support	Test Engr	Systems Engr	Logistics Engr	Engr Admin	Engr Labs	Safety	TOTAL ENGR HRS	TOTAL MM	TOTAL ($K)	TOTAL ($K) w/OTS, travel and computers
Spaghetti Calorimeter EDI	*116,764*	41,972	35,663	33,963	36,839	16,860	9,710	17,422	33,303	342,495	2,101	21,012	$30,320
Test Article	*9,928*	3,569	3,032	2,888	3,132	1,434	826	1,481	2,832	29,121	179	1,787	$2,578
Central Calorimeter Installation	*44,447*	15,977	13,575	12,928	14,023	6,418	3,696	6,632	12,677	130,373	800	7,998	$11,541
Super Ring Installation	*1,403*	504	429	408	443	203	117	209	400	4,116	25	253	$364
Super Ring Assembly	*8,791*	3,160	2,685	2,557	2,773	1,269	731	1,312	2,507	25,785	158	1,582	$2,283
Tower Assembly	*25,292*	9,092	7,725	7,357	7,980	3,652	2,103	3,774	7,214	74,188	455	4,551	$6,568
Central Tower Assembly	*8,791*	3,160	2,685	2,557	2,773	1,269	731	1,312	2,507	25,785	158	1,582	$2,283
Lead Details	*5,078*	1,825	1,551	1,477	1,602	733	422	758	1,448	14,895	91	914	$1,319
Fiber Details	*5,078*	1,825	1,551	1,477	1,602	733	422	758	1,448	14,895	91	914	$1,319
End Fittings	*5,078*	1,825	1,551	1,477	1,602	733	422	758	1,448	14,895	91	914	$1,319
Light Detector	*1,021*	367	312	297	322	147	85	152	291	2,994	18	184	$265
Optical Fiber	*247*	89	75	72	78	36	21	37	70	723	4	44	$64
Photomultiplier Installation	*865*	311	264	252	273	125	72	129	247	2,538	16	156	$225
Cable Installation	*1,748*	628	534	508	551	252	145	261	498	5,126	31	314	$454
Support Structure	*1,382*	497	422	402	436	200	115	206	394	4,053	25	249	$359
Inner Tension Liner	*494*	178	151	144	156	71	41	74	141	1,449	9	89	$128
End Cap Calorimeter Installation	*48,131*	17,301	14,701	14,000	15,185	6,950	4,002	7,181	13,728	141,179	866	8,661	$12,498
End Cap Installation	*998*	359	305	290	315	144	83	149	285	2,928	18	180	$259
End Cap assembly	*887*	319	271	258	280	128	74	132	253	2,601	16	160	$230
Super Ring	*41,413*	14,886	12,649	12,046	13,066	5,980	3,444	6,179	11,812	121,474	745	7,452	$10,754
Super Ring Assembly	*10,097*	3,630	3,084	2,937	3,186	1,458	840	1,507	2,880	29,618	182	1,817	$2,622
Tower Assembly	*28,601*	10,281	8,736	8,319	9,024	4,130	2,378	4,267	8,158	83,894	515	5,147	$7,427
End Cap Tower Assembly	*10,097*	3,630	3,084	2,937	3,186	1,458	840	1,507	2,880	29,618	182	1,817	$2,622
Lead Details	*5,828*	2,095	1,780	1,695	1,839	841	485	870	1,662	17,094	105	1,049	$1,513
Fiber Details	*5,828*	2,095	1,780	1,695	1,839	841	485	870	1,662	17,094	105	1,049	$1,513
End Fittings	*5,828*	2,095	1,780	1,695	1,839	841	485	870	1,662	17,094	105	1,049	$1,513
Light Detector	*1,021*	367	312	297	322	147	85	152	291	2,994	18	184	$265
Photomultiplier Installation	*473*	170	144	137	149	68	39	71	135	1,387	9	85	$123
Cable Installation	*1,748*	628	534	508	551	252	145	261	498	5,126	31	314	$454
Sub Structure	*494*	178	151	144	156	71	41	74	141	1,449	9	89	$128
External Structure	*865*	311	264	252	273	125	72	129	247	2,538	16	156	$225
Calorimeter Installation	*701*	252	214	204	221	101	58	105	200	2,057	13	126	$182
Forward Calorimeter	*7,232*	2,600	2,209	2,103	2,282	1,044	601	1,079	2,063	21,212	130	1,301	$1,878
T & H Equipment	*7,910*	2,843	2,416	2,301	2,496	1,142	658	1,180	2,256	23,202	142	1,423	$2,054

Other Technical Services (OTS) Hours	$4,424		
Travel Dollars ($K)	$676		
ODC Dollars ($K)	$48		
Computer Dollars ($K)	$3,668		
Computer Labor Dollars ($K)	$491		
	$9,308	added to labor	
Test Article Material/Fab	$3,727	added to labor	TOTAL EDI = $34,047 K

Table A-9. LAC Manufacturing and Services Cost Estimate

WBS Number	WBS Level	Program Element	Manufacturing Estimate: Unit Measure	# Units	Qty	Material Type	$/unit	Total Cost	Methodology
5.2.1.2	4	Liquid Argon Calorimeter						98,495	sum of lower levels
5.2.1.2.1	5	Central Calorimeter						55,503	sum of lower levels
5.2.1.2.1.1	6	Central Vacuum Vessel	lbs	30,209	2	Al	7.76	469	vendor estimate
5.2.1.2.1.2	6	Central Argon Vessel						1,442	sum of lower levels
5.2.1.2.1.2.1	7	Vessel	lbs	39,499	2	Al	7.76	613	vendor estimate
5.2.1.2.1.2.2	7	Stay Inner	lbs	24,497	2	Al	7.76	380	vendor estimate
5.2.1.2.1.2.3	7	Stay Outer	lbs	18,510	2	Al	7.76	287	vendor estimate
5.2.1.2.1.2.4	7	Washer	lbs	10,384	2	Al	7.76	161	vendor estimate
5.2.1.2.1.3	6	Feed-thrus	LF	9.85	32	Al	4180	1,317	feed lines parametric
5.2.1.2.1.4	6	Support Tube	lbs	220,500	1	Al	7.76	1,711	vendor estimate
5.2.1.2.1.5	6	Cooling Coils	lbs	1,340	1		79	106	bottoms-up cryogenic est.
5.2.1.2.1.6	6	Cooling Piping	LF					126	bottoms-up cryogenic est.
5.2.1.2.1.7	6	Insulation	SF	1,200	1	Super	0.93	1	vendor estimate
5.2.1.2.1.8	6	Support Tube Support	lbs	16,841	1	SS	11.44	193	structure parametric
5.2.1.2.1.9	6	Modules						44,450	sum of lower levels
5.2.1.2.1.10.1	7	1 - End Outer						8,452	modules (Tables 5,6,7,A-11)
5.2.1.2.1.10.2	7	2 - End Inner						11,007	modules (Tables 5,6,7,A-11)
5.2.1.2.1.10.3	7	3 - Central Outer						13,181	modules (Tables 5,6,7,A-11)
5.2.1.2.1.10.4	7	4 - Central Inner						8,646	modules (Tables 5,6,7,A-11)
5.2.1.2.1.10.5	7	5 - EM End						1,761	modules (Tables 5,6,7,A-11)
5.2.1.2.1.10.6	7	6 - EM Central						1,401	modules (Tables 5,6,7,A-11)
5.2.1.2.1.11	6	Assembly & Test	hours	37,164			$45	1,672	mfg estimate (Table 8)
5.2.1.2.1.12	6	Tooling	%	5.95%				3,063	historical detector factor
5.2.1.2.1.13	6	Test Equipment	%	1.85%				953	historical detector factor
5.2.1.2.2	5	Endcap Calorimeter						42,992	sum of lower levels
5.2.1.2.2.1	6	Endcap Vacuum Vessel	lbs	30,354	1	Al	6.89	209	vendor estimate
5.2.1.2.2.2	6	Feed-thrus	LF	9.85	32	Al	4914	1,549	feed lines parametric
5.2.1.2.2.3	6	Endcap Argon Vessel						661	sum of lower levels
5.2.1.2.2.3.1	7	Vessel	lbs	36,949	2	Al	7.76	573	vendor estimate
5.2.1.2.2.3.2	7	Stay Inner	lbs	1,157	2	Al	7.76	18	vendor estimate
5.2.1.2.2.3.3	7	Stay Outer	lbs	1,035	2	Al	7.76	16	vendor estimate
5.2.1.2.2.3.4	7	Washer	lbs	3,467	2	Al	7.76	54	vendor estimate
5.2.1.2.2.4	6	Cooling Coils	lbs	1,340	2		79	212	bottoms-up cryogenic est.
5.2.1.2.2.5	6	Cooling Piping	LF		2			253	bottoms-up cryogenic est.
5.2.1.2.2.6	6	Insulation	SF	1,200	1	Super	0.93	1	vendor estimate
5.2.1.2.2.7	6	Modules						34,349	sum of lower levels
5.2.1.2.2.8.1	7	1 - End Outer						7,965	modules (Tables 5,6,7,A-11)
5.2.1.2.2.8.2	7	2 - End Inner						7,092	modules (Tables 5,6,7,A-11)
5.2.1.2.2.8.3	7	3 - Forward Outer						13,158	modules (Tables 5,6,7,A-11)
5.2.1.2.2.8.4	7	4 - Forward Inner						5,022	modules (Tables 5,6,7,A-11)
5.2.1.2.2.8.5	7	5 - EM Outer						770	modules (Tables 5,6,7,A-11)
5.2.1.2.2.8.6	7	6 - EM Inner						342	modules (Tables 5,6,7,A-11)
5.2.1.2.2.9	6	Assembly & Test	hours	29,422	2		$45	2,648	mfg estimate (Table 8)
5.2.1.2.2.10	6	Tooling	%	5.95%				2,373	historical detector factor
5.2.1.2.2.11	6	Test Equipment	%	1.85%				738	historical detector factor

Table A-9. LAC Manufacturing and Services Cost Estimate

WBS Number	WBS Level	Program Element	Manufacturing Estimate					Total Cost	Methodology
			Unit Measure	# Units	Qty	Material Type	$/unit		
	4	Services						3,728	sum of lower levels
	5	Local Argon Storage LN Systems						1,470	cryo est (Table A-12)
	5	LN Source System at Surface						266	cryo est (Table A-12)
	5	LN Conditioning Systems						98	cryo est (Table A-12)
	5	Argon Dewar Fill and Distr Sys						114	cryo est (Table A-12)
	5	Argon Dewar to Argon Cond Sys						104	cryo est (Table A-12)
	5	Argon Conditioner System						116	cryo est (Table A-12)
	5	Module Cooling System						163	cryo est (Table A-12)
	5	Argon Boiler						125	cryo est (Table A-12)
	5	LN Cooling System Boiler						124	cryo est (Table A-12)
	5	Argon Supply Storage Dewars						750	cryo est (Table A-12)
	5	Installation						399	cryo est (Table A-12)

Table A-10. SPACAL Manufacturing Cost Estimate

WBS Number	WBS Level	Program Element	Manufacturing Estimate						Methodology
			Unit Measure	# Units	Qty	Material Type	$/unit	Total Mfg Cost ($K)	
5.2.1.2	4	Spaghetti Calorimeter						153,678	sum of lower levels
5.2.1.2.1	5	Super Ring Construction						118,267	sum of lower levels
5.2.1.2.1.1	6	Central Barrel	MT	582	2			59,579	sum of lower levels
5.2.1.2.1.1.1	7	Ring 1	MT	99	2			7,680	sum of lower levels
5.2.1.2.1.1.1.1	8	Assemble Towers	hrs/tower	29	3514		45	4,586	mfg, IE estimate (Table 10)
5.2.1.2.1.1.1.2	8	Tower Assemblies						3,094	sum of lower levels
5.2.1.2.1.1.1.2.1	9	Lead (rolled & grooved)	MT	124	2		3308	818	vendor quote
5.2.1.2.1.1.1.2.2	9	Fiber (2mm)	km	2057	2		300	1,234	vendor quote
5.2.1.2.1.1.1.2.3	9	Glue (lead powder)	gallons	639	2		213	272	vendor quote
5.2.1.2.1.1.1.2.4	9	Photomultipliers (1.5",6 stage,30,000 gain)	towers	1757	2		200	703	vendor quote
5.2.1.2.1.1.1.2.5	9	Tower End Fittings	lbs	0.96	3514	Al	20	67	mfg estimate
5.2.1.2.1.1.2	7	Ring 2	MT	101	2			7,730	sum of lower levels
5.2.1.2.1.1.2.1	8	Assemble Towers	hrs/tower	29	3514		45	4,586	mfg, IE estimate (Table 10)
5.2.1.2.1.1.2.2	8	Tower Assemblies						3,144	sum of lower levels
5.2.1.2.1.1.2.2.1	9	Lead (rolled & grooved)	MT	126	2		3308	835	vendor quote
5.2.1.2.1.1.2.2.2	9	Fiber (2mm)	km	2101	2		300	1,261	vendor quote
5.2.1.2.1.1.2.2.3	9	Glue (lead powder)	gallons	652	2		213	278	vendor quote
5.2.1.2.1.1.2.2.4	9	Photomultipliers (1.5",6 stage,30,000 gain)	towers	1757	2		200	703	vendor quote
5.2.1.2.1.1.2.2.5	9	Tower End Fittings	lbs	0.96	3514	Al	20	67	mfg estimate
5.2.1.2.1.1.3	7	Ring 3	MT	106	2			7,852	sum of lower levels
5.2.1.2.1.1.3.1	8	Assemble Towers	hrs/tower	29	3514		45	4,586	mfg, IE estimate (Table 10)
5.2.1.2.1.1.3.2	8	Tower Assemblies						3,266	sum of lower levels
5.2.1.2.1.1.3.2.1	9	Lead (rolled & grooved)	MT	133	2		3308	878	vendor quote
5.2.1.2.1.1.3.2.2	9	Fiber (2mm)	km	2209	2		300	1,325	vendor quote
5.2.1.2.1.1.3.2.3	9	Glue (lead powder)	gallons	686	2		213	292	vendor quote
5.2.1.2.1.1.3.2.4	9	Photomultipliers (1.5",6 stage,30,000 gain)	towers	1757	2		200	703	vendor quote
5.2.1.2.1.1.3.2.5	9	Tower End Fittings	lbs	0.96	3514	Al	20	67	mfg estimate
5.2.1.2.1.1.4	7	Ring 4	MT	98	2			6,892	sum of lower levels
5.2.1.2.1.1.4.1	8	Assemble Towers	hrs/tower	29	3012		45	3,931	mfg, IE estimate (Table 10)
5.2.1.2.1.1.4.2	8	Tower Assemblies						2,961	sum of lower levels
5.2.1.2.1.1.4.2.1	9	Lead (rolled & grooved)	MT	122	2		3308	810	vendor quote
5.2.1.2.1.1.4.2.2	9	Fiber (2mm)	km	2036	2		300	1,222	vendor quote
5.2.1.2.1.1.4.2.3	9	Glue (lead powder)	gallons	632	2		213	269	vendor quote
5.2.1.2.1.1.4.2.4	9	Photomultipliers (1.5",6 stage,30,000 gain)	towers	1506	2		200	602	vendor quote
5.2.1.2.1.1.4.2.5	9	Tower End Fittings	lbs	0.96	3012	Al	20	58	mfg estimate
5.2.1.2.1.1.5	7	End Ring	MT	178	2			29,426	sum of lower levels
5.2.1.2.1.1.5.1	8	Assemble Towers	hrs/tower	29	16566		45	21,619	mfg, IE estimate (Table 10)
5.2.1.2.1.1.5.2	8	Tower Assemblies						7,807	sum of lower levels
5.2.1.2.1.1.5.2.1	9	Lead (rolled & grooved)	MT	222	2		3308	1,469	vendor quote
5.2.1.2.1.1.5.2.2	9	Fiber (2mm)	km	3696	2		300	2,218	vendor quote
5.2.1.2.1.1.5.2.3	9	Glue (lead powder)	gallons	1147	2		213	489	vendor quote
5.2.1.2.1.1.5.2.4	9	Photomultipliers (1.5",6 stage,30,000 gain)	towers	8283	2		200	3,313	vendor quote
5.2.1.2.1.1.5.2.5	9	Tower End Fittings	lbs	0.96	16566	Al	20	318	mfg estimate
5.2.1.2.1.2	6	End Caps	MT	593	2			58,689	sum of lower levels
5.2.1.2.1.2.1	7	Ring 1	MT	114	2			11,567	sum of lower levels
5.2.1.2.1.2.1.1	8	Assemble Towers	hrs/tower	29	6024		45	7,861	mfg, IE estimate (Table 10)

Table A-10. SPACAL Manufacturing Cost Estimate

WBS Number	WBS Level	Program Element	Manufacturing Estimate						Methodology
			Unit Measure	# Units	Qty	Material Type	$/unit	Total Mfg Cost ($K)	
5.2.1.2.1.2.1.2	8	Tower Assemblies						3,706	sum of lower levels
5.2.1.2.1.2.1.2.1	9	Lead (rolled & grooved)	MT	143	2		3308	945	vendor quote
5.2.1.2.1.2.1.2.2	9	Fiber (2mm)	km	1877	2		300	1,126	vendor quote
5.2.1.2.1.2.1.2.3	9	Glue (lead powder)	gallons	738	2		213	314	vendor quote
5.2.1.2.1.2.1.2.4	9	Photomultipliers (1.5",6 stage,30,000 gain)	towers	3012	2		200	1,205	vendor quote
5.2.1.2.1.2.1.2.5	9	Tower End Fittings	lbs	0.96	6024	Al	20	116	mfg estimate
5.2.1.2.1.2.2	7	Ring 2	MT	196	2			14,811	sum of lower levels
5.2.1.2.1.2.2.1	8	Assemble Towers	hrs/tower	29	7028		45	9,172	mfg, IE estimate (Table 10)
5.2.1.2.1.2.2.2	8	Tower Assemblies						5,640	sum of lower levels
5.2.1.2.1.2.2.2.1	9	Lead (rolled & grooved)	MT	246	2		3308	1,624	vendor quote
5.2.1.2.1.2.2.2.2	9	Fiber (2mm)	km	3225	2		300	1,935	vendor quote
5.2.1.2.1.2.2.2.3	9	Glue (lead powder)	gallons	1268	2		213	540	vendor quote
5.2.1.2.1.2.2.2.4	9	Photomultipliers (1.5",6 stage,30,000 gain)	towers	3514	2		200	1,406	vendor quote
5.2.1.2.1.2.2.2.5	9	Tower End Fittings	lbs	0.96	7028	Al	20	135	mfg estimate
5.2.1.2.1.2.3	7	Ring 3	MT	144	2			17,067	sum of lower levels
5.2.1.2.1.2.3.1	8	Assemble Towers	hrs/tower	29	9220		45	12,032	mfg, IE estimate
5.2.1.2.1.2.3.2	8	Tower Assemblies						5,035	sum of lower levels
5.2.1.2.1.2.3.2.1	9	Lead (rolled & grooved)	MT	181	2		3308	1,194	vendor quote
5.2.1.2.1.2.3.2.2	9	Fiber (2mm)	km	2371	2		300	1,423	vendor quote
5.2.1.2.1.2.3.2.3	9	Glue (lead powder)	gallons	932	2		213	397	vendor quote
5.2.1.2.1.2.3.2.4	9	Photomultipliers (1.5",6 stage,30,000 gain)	towers	4610	2		200	1,844	vendor quote
5.2.1.2.1.2.3.2.5	9	Tower End Fittings	lbs	0.96	9220	Al	20	177	mfg estimate
5.2.1.2.1.2.4	7	Ring 4	MT	138	2			15,243	sum of lower levels
5.2.1.2.1.2.4.1	8	Assemble Towers	hrs/tower	29	8118		45	10,594	mfg, IE estimate (Table 10)
5.2.1.2.1.2.4.2	8	Tower Assemblies						4,649	sum of lower levels
5.2.1.2.1.2.4.2.1	9	Lead (rolled & grooved)	MT	172	2		3308	1,137	vendor quote
5.2.1.2.1.2.4.2.2	9	Fiber (2mm)	km	2258	2		300	1,355	vendor quote
5.2.1.2.1.2.4.2.3	9	Glue (lead powder)	gallons	888	2		213	378	vendor quote
5.2.1.2.1.2.4.2.4	9	Photomultipliers (1.5",6 stage,30,000 gain)	towers	4059	2		200	1,624	vendor quote
5.2.1.2.1.2.4.2.5	9	Tower End Fittings	lbs	0.96	8118	Al	20	156	mfg estimate
5.2.1.2.2	5	Silicon Detector						3,865	sum of lower levels
5.2.1.2.2.1	6	Silicon Diodes	cm2	416000	1		2	832	silicon EM estimate (Table 13)
5.2.1.2.2.2	6	Preamps	each	416000	1		2.5	1040	silicon EM estimate (Table 13)
5.2.1.2.2.3	6	Electronics	channels	15000	1		10	150	silicon EM estimate (Table 13)
5.2.1.2.2.4	6	Lead	lbs	8000	1		1.50	12	silicon EM estimate (Table 13)
5.2.1.2.2.5	6	Assembly	%	90%				1831	ratio from LAC modules assembly
5.2.1.2.3	5	Super Ring Support Structure						461	sum of lower levels
5.2.1.2.3.1	6	Central Barrel	lbs	18000	1		8.53	154	vendor quote
5.2.1.2.3.2	6	End Cap	lbs	18000	2		8.53	307	vendor quote
5.2.1.2.3	5	Preshower Detector Inner Tube	lbs	8000	1	Steel	4.00	32	vendor quote
5.2.1.2.4	5	Support Tube	lbs	220,500	1	Al	7.76	1,711	vendor quote
5.2.1.2.5	5	"Support Tube" Support	lbs	16,841	1	SS	11.44	193	vendor quote
5.2.1.2.6	5	Tooling	%	14.88%				19,338	ratio from LAC tooling
5.2.1.2.7	5	Central Barrel Assembly & Test	hrs	96,153	1		45	4,327	mfg estimate (Table 12)
5.2.1.2.8	5	End Cap Assembly & Test	hrs	34,227	2		45	3,080	mfg estimate (Table 12)
5.2.1.2.9	5	Test Equipment	%	1.85%				2,405	ratio from LAC test equipment

Table A-11. LAC Module Assembly Hours

CENTRAL CALORIMETER	*1 - End Outer*			
Part Name	Set-Up	Run	Qty	Total Time (Hours)
Channel	1.57	3.00	1	4.57
Plate	0.67	1.74	1	2.41
Strongback	0.52	5.18	1	5.70
End Cap	1.48	2.79	2	7.06
Uranium Sheets	2.16	2.55	*102*	262.57
Bridge	0.98	0.63	20	13.58
Bond G10/U	0.65	2.20	51	112.98
Strap	0.57	0.22	20	4.97
Spacer	0.33	0.01	4,085	41.18
Segment Assy	0.82	8.50	1	9.32
TOTAL LABOR/MODULE				464.34

END CAP CALORIMETER	*1 - End Outer*			
Part Name	Set-Up	Run	Qty	Total Time (Hours)
Channel	1.57	3.00	1	4.57
Plate	0.67	1.74	1	2.41
Strongback	0.52	5.18	1	5.70
End Cap	1.48	2.79	2	7.06
Uranium Sheets	2.16	2.55	*88*	225.43
Bridge	0.98	0.63	20	13.58
Bond G10/U	0.65	2.20	44	96.96
Strap	0.57	0.22	20	4.97
Spacer	0.33	0.01	3,502	35.35
Segment Assy	0.82	8.50	1	9.32
TOTAL LABOR/MODULE				405.36

CENTRAL CALORIMETER	*2 - End Inner*			
Part Name	Set-Up	Run	Qty	Total Time (Hours)
Channel	1.57	3.00	1	4.57
Plate	0.67	1.74	1	2.41
Strongback	0.52	5.18	1	5.70
End Cap	1.48	2.79	2	7.06
Uranium Sheets	2.16	2.55	*133*	341.31
Bridge	0.98	0.63	20	13.58
Bond G10/U	0.65	2.20	67	146.95
Strap	0.57	0.22	20	4.97
Spacer	0.33	0.01	5,320	53.53
Segment Assy	0.82	8.50	1	9.32
TOTAL LABOR/MODULE				589.40

END CAP CALORIMETER	*2 - End Inner*			
Part Name	Set-Up	Run	Qty	Total Time (Hours)
Channel	1.57	3.00	1	4.57
Plate	0.67	1.74	1	2.41
Strongback	0.52	5.18	1	5.70
End Cap	1.48	2.79	2	7.06
Uranium Sheets	2.16	2.55	*78*	200.98
Bridge	0.98	0.63	20	13.58
Bond G10/U	0.65	2.20	39	86.42
Strap	0.57	0.22	20	4.97
Spacer	0.33	0.01	3,119	31.52
Segment Assy	0.82	8.50	1	9.32
TOTAL LABOR/MODULE				366.52

CENTRAL CALORIMETER	*3 - Central Outer*			
Part Name	Set-Up	Run	Qty	Total Time (Hours)
Channel	1.57	3.00	1	4.57
Plate	0.67	1.74	1	2.41
Strongback	0.52	5.18	1	5.70
End Cap	1.48	2.79	2	7.06
Uranium Sheets	2.16	2.55	*159*	408.29
Bridge	0.98	0.63	20	13.58
Bond G10/U	0.65	2.20	80	175.84
Strap	0.57	0.22	20	4.97
Spacer	0.33	0.01	6,371	64.04
Segment Assy	0.82	8.50	1	9.32
TOTAL LABOR/MODULE				695.78

END CAP CALORIMETER	*3 - Forward Outer*			
Part Name	Set-Up	Run	Qty	Total Time (Hours)
Channel	1.57	3.00	1	4.57
Plate	0.67	1.74	1	2.41
Strongback	0.52	5.18	1	5.70
End Cap	1.48	2.79	2	7.06
Uranium Sheets	2.16	2.55	*145*	371.01
Bridge	0.98	0.63	20	13.58
Bond G10/U	0.65	2.20	72	159.76
Strap	0.57	0.22	20	4.97
Spacer	0.33	0.01	5,786	58.19
Segment Assy	0.82	8.50	1	9.32
TOTAL LABOR/MODULE				636.57

CENTRAL CALORIMETER	*4 - Central Inner*			
Part Name	Set-Up	Run	Qty	Total Time (Hours)
Channel	1.57	3.00	1	4.57
Plate	0.67	1.74	1	2.41
Strongback	0.52	5.18	1	5.70
End Cap	1.48	2.79	2	7.06
Uranium Sheets	2.16	2.55	*104*	268.56
Bridge	0.98	0.63	20	13.58
Bond G10/U	0.65	2.20	52	115.57
Strap	0.57	0.22	20	4.97
Spacer	0.33	0.01	4,179	42.12
Segment Assy	0.82	8.50	1	9.32
TOTAL LABOR/MODULE				473.86

END CAP CALORIMETER	*4 - Forward Inner*			
Part Name	Set-Up	Run	Qty	Total Time (Hours)
Channel	1.57	3.00	1	4.57
Plate	0.67	1.74	1	2.41
Strongback	0.52	5.18	1	5.70
End Cap	1.48	2.79	2	7.06
Uranium Sheets	2.16	2.55	*55*	142.94
Bridge	0.98	0.63	20	13.58
Bond G10/U	0.65	2.20	28	61.38
Strap	0.57	0.22	20	4.97
Spacer	0.33	0.01	2,208	22.41
Segment Assy	0.82	8.50	1	9.32
TOTAL LABOR/MODULE				274.35

Table A-11. LAC Module Assembly Hours

CENTRAL CALORIMETER	*5 - EM End*				END CAP CALORIMETER	*5 - EM Outer*			
Part Name	Set-Up	Run	Qty	Total Time (Hours)	Part Name	Set-Up	Run	Qty	Total Time (Hours)
Channel	1.57	3.00	1	4.57	Channel	1.57	3.00	1	4.57
Plate	0.67	1.74	1	2.41	Plate	0.67	1.74	1	2.41
Strongback	0.52	5.18	1	5.70	Strongback	0.52	5.18	1	5.70
End Cap	1.48	2.79	2	7.06	End Cap	1.48	2.79	2	7.06
Uranium Sheets	2.16	2.55	*24*	63.36	Uranium Sheets	2.16	2.55	*10*	26.50
Bridge	0.98	0.63	20	13.58	Bridge	0.98	0.63	20	13.58
Bond G10/U	0.65	2.20	12	27.05	Bond G10/U	0.65	2.20	5	11.15
Strap	0.57	0.22	20	4.97	Strap	0.57	0.22	20	4.97
Spacer	0.33	0.01	960	9.93	Spacer	0.33	0.01	382	4.15
Segment Assy	0.82	8.50	1	9.32	Segment Assy	0.82	8.50	1	9.32
TOTAL LABOR/MODULE				147.95	TOTAL LABOR/MODULE				89.41

CENTRAL CALORIMETER	*6 - EM Central*				END CAP CALORIMETER	*6 - EM Inner*			
Part Name	Set-Up	Run	Qty	Total Time (Hours)	Part Name	Set-Up	Run	Qty	Total Time (Hours)
Channel	1.57	3.00	1	4.57	Channel	1.57	3.00	1	4.57
Plate	0.67	1.74	1	2.41	Plate	0.67	1.74	1	2.41
Strongback	0.52	5.18	1	5.70	Strongback	0.52	5.18	1	5.70
End Cap	1.48	2.79	2	7.06	End Cap	1.48	2.79	2	7.06
Uranium Sheets	2.16	2.55	*19*	50.87	Uranium Sheets	2.16	2.55	*4*	12.96
Bridge	0.98	0.63	20	13.58	Bridge	0.98	0.63	20	13.58
Bond G10/U	0.65	2.20	10	21.66	Bond G10/U	0.65	2.20	2	5.31
Strap	0.57	0.22	20	4.97	Strap	0.57	0.22	20	4.97
Spacer	0.33	0.01	764	7.97	Spacer	0.33	0.01	169	2.02
Segment Assy	0.82	8.50	1	9.32	Segment Assy	0.82	8.50	1	9.32
TOTAL LABOR/MODULE				128.11	TOTAL LABOR/MODULE				67.91

Table A-11. LAC Module Assembly Hours

COMPONENT	Specs	Qty	Cost
Cryogenic Services			$3,728,032
Local Argon Storage LN Systems			$1,470,000
Dewars	15x32 ft	3	$1,360,000
LN Control Valves			$25,500
1" supply	1"	3	$7,500
1-1/2" exhaust	1-1/2"	3	$9,000
controllers		6	$9,000
LN Transfer Lines (surface to below)	2"	250'	$27,500
LN Transfer Lines (conditioner to dewars)	1"	100'	$21,000
1-1/2" ID Vacuum Insulated Exhaust Lines	1-1/2"		$27,000
Controllers		6	$9,000
LN Source System at Surface			$265,500
Dewars	60,000 liters		$200,000
Filling Station			$30,000
Valves	2"	4	$14,000
Transfer Lines	2"	100'	$11,000
ID Redundant Valves	2"	3	$10,500
LN Conditioning Systems			$97,500
Dewar	1000 liter		$50,000
Valve	2"		$3,500
Controllers			$1,500
LN Depth Gage			$5,000
Control Pressure Valve	1"		$2,500
Controller			$1,500
Dewar Outlet Valve	1000L-2"		$3,500
Vent System	3"	200'	$30,000
Argon Dewar Fill and Distribution System			$114,000
Surface Filling Station			$30,000
Depth Gage			$10,000
Valves (fill line to below)	2"		$3,000
Transfer Line (station to distribution manifold)	2"	250'	$27,500
Valves (dewar fill line)	2"	3	$10,500
Transfer Lines (fill line to dewar)	2"	100'	$33,000
Argon Dewar to Argon Conditioner System			$103,500
Valves (Dewar liquid outlet)	2"	3	$10,500
Transfer Lines (valves to Argon conditioner)	2"	50'	$16,500
Liquid Line	2"		$16,500
Valves (return gaseous Argon)	3"	3	$15,000
Transfer Line (return gaseous Argon)	3"	50'	$22,500
Transfer Line (gas phase of conditioner)	3"	150'	$22,500
Argon Conditioner System			$116,300
Dewar	1000 liter		$50,000
Liquid Nitrogen Cooling System for Ar Conditioner			$11,500
Cryo valve proportional control for liquid IN	1"		$3,500
Cryo valve proportional controller for gas OUT	1-1/2"		$3,000
Controllers		2	$3,000
Heater control	10kw		$2,000
Argon Transfer Lines			$7,800
Liquid Supply Line	2"	30'	$3,300
Gas Return Line	3"	30'	$4,500
Argon Control Valve Rack			$47,000
Liquid Ar Control Cryo Valves	2"		$10,500
Gaseous Argon Control Cryo Valves	3"		$15,000
Cryo Valves to Vent Ar to Boiler	3"		$15,000
Controllers			$4,500
Switch Control System for Vent Valves			$2,000
Module Cooling System			$162,800
Central Barrel			$94,800
LN Supply Valves	1-1/2"	6	$18,000
LN Exhaust Valves	2"	6	$21,000
Controllers		12	$18,000
Transfer Lines			$37,800
Transfer	30', 1-1/2"	6	$18,000
Exhaust	30', 2"	6	$19,800

Table A-12. Cryogenic Services Cost Analysis

End Caps			$68,000
Inlet Valves		8	$20,000
Exhaust Valves		8	$24,000
Controllers		16	$24,000
Argon Boiler			$125,000
Collector Transfer Line			$20,000
Vacuum Insulated Line		100'	$15,000
Boiler and Heaters			$50,000
Vent Line	6"	200'	$40,000
LN Boiler			$124,000
Collector Transfer Line	4"	100'	$20,000
Boiler with Heater and Controllers			$50,000
Partially Insulated Line to Surface	6"	180'	$54,000
Argon Supply Storage Dewars	200,000 l		$750,000
Installation			$399,432

Table A-12. Cryogenic Services Cost Analysis

WBS Number	WBS Level	Program Element	Total Cost	Methodology	Nominal Estimate	Lower Limit	Upper Limit	Risk Range % LOW	% HIGH
5.2.1.2	4	Liquid Argon Calorimeter	98,495	sum of lower levels					
5.2.1.2.1	5	Central Calorimeter	55,503	sum of lower levels					
5.2.1.2.1.1	6	Central Vacuum Vessel	469	vendor estimate	469	422	516	10%	10%
5.2.1.2.1.2	6	Central Argon Vessel	1,442	sum of lower levels		0	0		
5.2.1.2.1.2.1	7	Vessel	613	vendor estimate	613	552	674	10%	10%
5.2.1.2.1.2.2	7	Stay Inner	380	vendor estimate	380	304	456	20%	20%
5.2.1.2.1.2.3	7	Stay Outer	287	vendor estimate	287	230	345	20%	20%
5.2.1.2.1.2.4	7	Washer	161	vendor estimate	161	129	193	20%	20%
5.2.1.2.1.3	6	Feed-thrus	1,317	feed lines parametric	1317	988	1383	25%	5%
5.2.1.2.1.4	6	Support Tube	1,711	vendor estimate	1711	1369	2053	20%	20%
5.2.1.2.1.5	6	Cooling Coils	106	bottoms-up cryogenic est.	106	85	127	20%	20%
5.2.1.2.1.6	6	Cooling Piping	126	bottoms-up cryogenic est.	126	101	152	20%	20%
5.2.1.2.1.7	6	Insulation	1	vendor estimate	1	1	1	20%	20%
5.2.1.2.1.8	6	Support Tube Support	193	structure parametric	193	144	241	25%	25%
5.2.1.2.1.9	6	Modules	44,450	sum of lower levels		0	0		
5.2.1.2.1.10.1	7	1 - End Outer	8,452	modules (Tables 5, 6, 7,A-11)	8452	7184	10565	15%	25%
5.2.1.2.1.10.2	7	2 - End Inner	11,007	modules (Tables 5, 6, 7,A-11)	11007	9356	13759	15%	25%
5.2.1.2.1.10.3	7	3 - Central Outer	13,181	modules (Tables 5, 6, 7,A-11)	13181	11204	16477	15%	25%
5.2.1.2.1.10.4	7	4 - Central Inner	8,646	modules (Tables 5, 6, 7,A-11)	8646	7349	10808	15%	25%
5.2.1.2.1.10.5	7	5 - EM End	1,761	modules (Tables 5, 6, 7,A-11)	1761	1497	2201	15%	25%
5.2.1.2.1.10.6	7	6 - EM Central	1,401	modules (Tables 5, 6, 7,A-11)	1401	1191	1752	15%	25%
5.2.1.2.1.11	6	Assembly & Test	1,672	mfg estimate (Table 8)	1672	1505	2090	10%	25%
5.2.1.2.1.12	6	Tooling	3,063	historical detector factor	3063	2298	4595	25%	50%
5.2.1.2.1.13	6	Test Equipment	953	historical detector factor	953	714	1429	25%	50%
5.2.1.2.2	5	Endcap Calorimeter	42,992	sum of lower levels		0	0		
5.2.1.2.2.1	6	Endcap Vacuum Vessel	209	vendor estimate	209	188	230	10%	10%
5.2.1.2.2.2	6	Feed-thrus	1,549	feed lines parametric	1549	1162	1626	25%	5%
5.2.1.2.2.3	6	Endcap Argon Vessel	661	sum of lower levels		0	0		
5.2.1.2.2.3.1	7	Vessel	573	vendor estimate	573	516	631	10%	10%
5.2.1.2.2.3.2	7	Stay Inner	18	vendor estimate	18	14	22	20%	20%
5.2.1.2.2.3.3	7	Stay Outer	16	vendor estimate	16	13	19	20%	20%
5.2.1.2.2.3.4	7	Washer	54	vendor estimate	54	43	65	20%	20%
5.2.1.2.2.4	6	Cooling Coils	212	bottoms-up cryogenic est.	212	169	254	20%	20%
5.2.1.2.2.5	6	Cooling Piping	253	bottoms-up cryogenic est.	253	202	303	20%	20%
5.2.1.2.2.6	6	Insulation	1	vendor estimate	1	1	1	10%	10%
5.2.1.2.2.7	6	Modules	34,349	sum of lower levels		0	0		
5.2.1.2.2.8.1	7	1 - End Outer	7,965	modules (Tables 5, 6, 7,A-11)	7965	6770	9956	15%	25%
5.2.1.2.2.8.2	7	2 - End Inner	7,092	modules (Tables 5, 6, 7,A-11)	7092	6029	8866	15%	25%
5.2.1.2.2.8.3	7	3 - Forward Outer	13,158	modules (Tables 5, 6, 7,A-11)	13158	11184	16447	15%	25%
5.2.1.2.2.8.4	7	4 - Forward Inner	5,022	modules (Tables 5, 6, 7,A-11)	5022	4269	6278	15%	25%
5.2.1.2.2.8.5	7	5 - EM Outer	770	modules (Tables 5, 6, 7,A-11)	770	654	962	15%	25%
5.2.1.2.2.8.6	7	6 - EM Inner	342	modules (Tables 5, 6, 7,A-11)	342	290	427	15%	25%
5.2.1.2.2.9	6	Assembly & Test	2,648	mfg estimate (Table 8)	2648	2383	3310	10%	25%
5.2.1.2.2.10	6	Tooling	2,373	historical detector factor	2373	1780	3559	25%	50%
5.2.1.2.2.11	6	Test Equipment	738	historical detector factor	738	553	1107	25%	50%

Table A-13. LAC Cost Risk Analysis Ranges

WBS Number	WBS Level	Program Element	Total Cost	Methodology	Nominal Estimate	Lower Limit	Upper Limit	Risk Range % LOW	Risk Range % HIGH
						0	0		
5.2.1.2.7	5	Services	3,728	sum of lower levels		0	0		
5.2.1.2.7.1	6	Local Argon Storage LN Systems	1,470	cryo est (Table A-12)	1470	1176	1764	20%	20%
5.2.1.2.7.2	6	LN Source System at Surface	266	cryo est (Table A-12)	266	212	319	20%	20%
5.2.1.2.7.3	6	LN Conditioning Systems	98	cryo est (Table A-12)	98	78	117	20%	20%
5.2.1.2.7.4	6	Argon Dewar Fill and Distr Sys	114	cryo est (Table A-12)	114	91	137	20%	20%
5.2.1.2.7.5	6	Argon Dewar to Argon Cond Sys	104	cryo est (Table A-12)	104	83	124	20%	20%
5.2.1.2.7.6	6	Argon Conditioner System	116	cryo est (Table A-12)	116	93	140	20%	20%
5.2.1.2.7.7	6	Module Cooling System	163	cryo est (Table A-12)	163	130	195	20%	20%
5.2.1.2.7.8	6	Argon Boiler	125	cryo est (Table A-12)	125	100	150	20%	20%
5.2.1.2.7.9	6	LN Cooling System Boiler	124	cryo est (Table A-12)	124	99	149	20%	20%
5.2.1.2.7.10	6	Argon Supply Storage Dewars	750	cryo est (Table A-12)	750	600	900	20%	20%
5.2.1.2.7.11	6	Installation	399	cryo est (Table A-12)	399	320	479	20%	20%
				R&D	7023	5970	8779	15%	25%
				EDI	28784	24466	35980	15%	25%
				ELECTRONICS	78844	70960	86728	10%	10%
				TOTAL	216,874	187,223	259,842		

Table A-14. SPACAL Cost Risk Analysis Ranges

WBS Number	WBS Level	Program Element	Total Mfg Cost ($K)	Methodology	Nominal Estimate	Lower Limit	Upper Limit	Risk Range % LOW	% HIGH
5.2.1.2	4	Spaghetti Calorimeter	153,678	sum of lower levels					
5.2.1.2.1	5	Super Ring Construction	118,267	sum of lower levels					
5.2.1.2.1.1	6	Central Barrel	59,579	sum of lower levels					
5.2.1.2.1.1.1	7	Ring 1	7,680	sum of lower levels					
5.2.1.2.1.1.1.1	8	Assemble Towers	4,586	mfg, IE estimate (Table 10)	4586	4356	5732	5%	25%
5.2.1.2.1.1.1.2	8	Tower Assemblies	3,094	sum of lower levels					
5.2.1.2.1.1.1.2.1	9	Lead (rolled & grooved)	818	vendor quote	818	695	900	15%	10%
5.2.1.2.1.1.1.2.2	9	Fiber (2mm)	1,234	vendor quote	1234	987	1358	20%	10%
5.2.1.2.1.1.1.2.3	9	Glue (lead powder)	272	vendor quote	272	245	299	10%	10%
5.2.1.2.1.1.1.2.4	9	Photomultipliers (1.5",6 stage,30,000 gain)	703	vendor quote	703	527	808	25%	15%
5.2.1.2.1.1.1.2.5	9	Tower End Fittings	67	mfg estimate	67	54	81	20%	20%
5.2.1.2.1.1.2	7	Ring 2	7,730	sum of lower levels					
5.2.1.2.1.1.2.1	8	Assemble Towers	4,586	mfg, IE estimate (Table 10)	4586	4356	5732	5%	25%
5.2.1.2.1.1.2.2	8	Tower Assemblies	3,144	sum of lower levels					
5.2.1.2.1.1.2.2.1	9	Lead (rolled & grooved)	835	vendor quote	835	710	919	15%	10%
5.2.1.2.1.1.2.2.2	9	Fiber (2mm)	1,261	vendor quote	1261	1008	1387	20%	10%
5.2.1.2.1.1.2.2.3	9	Glue (lead powder)	278	vendor quote	278	250	306	10%	10%
5.2.1.2.1.1.2.2.4	9	Photomultipliers (1.5",6 stage,30,000 gain)	703	vendor quote	703	527	808	25%	15%
5.2.1.2.1.1.2.2.5	9	Tower End Fittings	67	mfg estimate	67	54	81	20%	20%
5.2.1.2.1.1.3	7	Ring 3	7,852	sum of lower levels					
5.2.1.2.1.1.3.1	8	Assemble Towers	4,586	mfg, IE estimate (Table 10)	4586	4356	5732	5%	25%
5.2.1.2.1.1.3.2	8	Tower Assemblies	3,266	sum of lower levels					
5.2.1.2.1.1.3.2.1	9	Lead (rolled & grooved)	878	vendor quote	878	746	966	15%	10%
5.2.1.2.1.1.3.2.2	9	Fiber (2mm)	1,325	vendor quote	1325	1060	1458	20%	10%
5.2.1.2.1.1.3.2.3	9	Glue (lead powder)	292	vendor quote	292	263	321	10%	10%
5.2.1.2.1.1.3.2.4	9	Photomultipliers (1.5",6 stage,30,000 gain)	703	vendor quote	703	527	808	25%	15%
5.2.1.2.1.1.3.2.5	9	Tower End Fittings	67	mfg estimate	67	54	81	20%	20%
5.2.1.2.1.1.4	7	Ring 4	6,892	sum of lower levels					
5.2.1.2.1.1.4.1	8	Assemble Towers	3,931	mfg, IE estimate (Table 10)	3931	3734	4913	5%	25%
5.2.1.2.1.1.4.2	8	Tower Assemblies	2,961	sum of lower levels					
5.2.1.2.1.1.4.2.1	9	Lead (rolled & grooved)	810	vendor quote	810	688	890	15%	10%
5.2.1.2.1.1.4.2.2	9	Fiber (2mm)	1,222	vendor quote	1222	977	1344	20%	10%
5.2.1.2.1.1.4.2.3	9	Glue (lead powder)	269	vendor quote	269	242	296	10%	10%
5.2.1.2.1.1.4.2.4	9	Photomultipliers (1.5",6 stage,30,000 gain)	602	vendor quote	602	452	693	25%	15%
5.2.1.2.1.1.4.2.5	9	Tower End Fittings	58	mfg estimate	58	46	69	20%	20%
5.2.1.2.1.1.5	7	End Ring	29,426	sum of lower levels					
5.2.1.2.1.1.5.1	8	Assemble Towers	21,619	mfg, IE estimate (Table 10)	21619	20538	27023	5%	25%
5.2.1.2.1.1.5.2	8	Tower Assemblies	7,807	sum of lower levels					
5.2.1.2.1.1.5.2.1	9	Lead (rolled & grooved)	1,469	vendor quote	1469	1249	1616	15%	10%
5.2.1.2.1.1.5.2.2	9	Fiber (2mm)	2,218	vendor quote	2218	1774	2440	20%	10%
5.2.1.2.1.1.5.2.3	9	Glue (lead powder)	489	vendor quote	489	440	538	10%	10%
5.2.1.2.1.1.5.2.4	9	Photomultipliers (1.5",6 stage,30,000 gain)	3,313	vendor quote	3313	2485	3810	25%	15%
5.2.1.2.1.1.5.2.5	9	Tower End Fittings	318	mfg estimate	318	254	382	20%	20%
5.2.1.2.1.2	6	End Caps	58,689	sum of lower levels					
5.2.1.2.1.2.1	7	Ring 1	11,567	sum of lower levels					
5.2.1.2.1.2.1.1	8	Assemble Towers	7,861	mfg, IE estimate (Table 10)	7861	7468	9827	5%	25%

Table A-14. SPACAL Cost Risk Analysis Ranges

WBS Number	WBS Level	Program Element	Total Mfg Cost ($K)	Methodology	Nominal Estimate	Lower Limit	Upper Limit	Risk Range % LOW	% HIGH
5.2.1.2.1.2.1.2	8	Tower Assemblies	3,706	sum of lower levels					
5.2.1.2.1.2.1.2.1	9	Lead (rolled & grooved)	945	vendor quote	945	803	1040	15%	10%
5.2.1.2.1.2.1.2.2	9	Fiber (2mm)	1,126	vendor quote	1126	901	1239	20%	10%
5.2.1.2.1.2.1.2.3	9	Glue (lead powder)	314	vendor quote	314	283	346	10%	10%
5.2.1.2.1.2.1.2.4	9	Photomultipliers (1.5",6 stage,30,000 gain)	1,205	vendor quote	1205	904	1386	25%	15%
5.2.1.2.1.2.1.2.5	9	Tower End Fittings	116	mfg estimate	116	93	139	20%	20%
5.2.1.2.1.2.2	7	Ring 2	14,811	sum of lower levels					
5.2.1.2.1.2.2.1	8	Assemble Towers	9,172	mfg, IE estimate (Table 10)	9172	8713	11464	5%	25%
5.2.1.2.1.2.2.2	8	Tower Assemblies	5,640	sum of lower levels					
5.2.1.2.1.2.2.2.1	9	Lead (rolled & grooved)	1,624	vendor quote	1624	1380	1786	15%	10%
5.2.1.2.1.2.2.2.2	9	Fiber (2mm)	1,935	vendor quote	1935	1548	2128	20%	10%
5.2.1.2.1.2.2.2.3	9	Glue (lead powder)	540	vendor quote	540	486	594	10%	10%
5.2.1.2.1.2.2.2.4	9	Photomultipliers (1.5",6 stage,30,000 gain)	1,406	vendor quote	1406	1054	1616	25%	15%
5.2.1.2.1.2.2.2.5	9	Tower End Fittings	135	mfg estimate	135	108	162	20%	20%
5.2.1.2.1.2.3	7	Ring 3	17,067	sum of lower levels					
5.2.1.2.1.2.3.1	8	Assemble Towers	12,032	mfg, IE estimate	12032	11430	15040	5%	25%
5.2.1.2.1.2.3.2	8	Tower Assemblies	5,035	sum of lower levels					
5.2.1.2.1.2.3.2.1	9	Lead (rolled & grooved)	1,194	vendor quote	1194	1015	1313	15%	10%
5.2.1.2.1.2.3.2.2	9	Fiber (2mm)	1,423	vendor quote	1423	1138	1565	20%	10%
5.2.1.2.1.2.3.2.3	9	Glue (lead powder)	397	vendor quote	397	357	437	10%	10%
5.2.1.2.1.2.3.2.4	9	Photomultipliers (1.5",6 stage,30,000 gain)	1,844	vendor quote	1844	1383	2121	25%	15%
5.2.1.2.1.2.3.2.5	9	Tower End Fittings	177	mfg estimate	177	142	212	20%	20%
5.2.1.2.1.2.4	7	Ring 4	15,243	sum of lower levels					
5.2.1.2.1.2.4.1	8	Assemble Towers	10,594	mfg, IE estimate (Table 10)	10594	10064	13242	5%	25%
5.2.1.2.1.2.4.2	8	Tower Assemblies	4,649	sum of lower levels					
5.2.1.2.1.2.4.2.1	9	Lead (rolled & grooved)	1,137	vendor quote	1137	966	1251	15%	10%
5.2.1.2.1.2.4.2.2	9	Fiber (2mm)	1,355	vendor quote	1355	1084	1490	20%	10%
5.2.1.2.1.2.4.2.3	9	Glue (lead powder)	378	vendor quote	378	340	416	10%	10%
5.2.1.2.1.2.4.2.4	9	Photomultipliers (1.5",6 stage,30,000 gain)	1,624	vendor quote	1624	1218	1867	25%	15%
5.2.1.2.1.2.4.2.5	9	Tower End Fittings	156	mfg estimate	156	125	187	20%	20%
5.2.1.2.2	5	Silicon Detector	3,865	sum of lower levels					
5.2.1.2.2.1	6	Silicon Diodes	832	silicon EM estimate (Table 13)	832	624	1040	25%	25%
5.2.1.2.2.2	6	Preamps	1040	silicon EM estimate (Table 13)	1040	780	1300	25%	25%
5.2.1.2.2.3	6	Electronics	150	silicon EM estimate (Table 13)	150	113	188	25%	25%
5.2.1.2.2.4	6	Lead	12	silicon EM estimate (Table 13)	12	9	15	25%	25%
5.2.1.2.2.5	6	Assembly	1831	ratio from LAC modules assembly	1831	1373	2288	25%	25%
5.2.1.2.3	5	Super Ring Support Structure	461	sum of lower levels					
5.2.1.2.3.1	6	Central Barrel	154	vendor quote	154	115	192	25%	25%
5.2.1.2.3.2	6	End Cap	307	vendor quote	307	230	384	25%	25%
5.2.1.2.3	5	Preshower Detector Inner Tube	32	vendor quote	32	24	40	25%	25%
5.2.1.2.4	5	Support Tube	1,711	vendor quote	1711	1369	2053	20%	20%
5.2.1.2.5	5	"Support Tube" Support	193	vendor quote	193	144	241	25%	25%
5.2.1.2.6	5	Tooling	19,338	ratio from LAC tooling	19338	14503	22238	25%	15%
5.2.1.2.7	5	Central Barrel Assembly & Test	4,327	mfg estimate (Table 12)	4327	3894	5409	10%	25%
5.2.1.2.8	5	End Cap Assembly & Test	3,080	mfg estimate (Table 12)	3080	2772	3851	10%	25%
5.2.1.2.9	5	Test Equipment	2,405	ratio from LAC test equipment	2405	1804	2766	25%	15%

Table A-14. SPACAL Cost Risk Analysis Ranges

WBS Number	WBS Level	Program Element	Total Mfg Cost ($K)	Methodology	Nominal Estimate	Lower Limit	Upper Limit	Risk Range % LOW	% HIGH
				R&D	4678	3976	5848	15%	25%
				EDI	34047	28940	42559	15%	25%
				ELECTRONICS	59765	53789	65742	10%	10%
				TOTAL	252,168	221,122	298,812		