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COST ANALYSIS OF LASERS FOR A LASER ISOTOPE SEPARATION SYSTEM

FINAL REPORT
Purchase Order 2411303

by

R.A. Mail
F.J. Markovich
R.H. Carr

January 1977

GENERAL
RESEARCH **CORPORATION**

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CR-2-718

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January 1977

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PREFACE

This is the final report of a cost study performed by General Research Corporation (GRC) under contract to the University of California, Lawrence Livermore Laboratories (LLL). The subject of the study was the estimation of costs for certain candidate lasers being considered for a full-scale production plant for laser isotope separation (LIS). Approximately six labor-months of effort were expended during the five-month course of the study, beginning in April 1976. The study was exploratory, with emphasis on the development of cost estimating methods and the collection of data. The cost estimating relationships which have resulted from the study can be used to compare system concepts and to aid in decisions on technology development. However, the lack of system definitions, the rapidly advancing technology of lasers, and the paucity of available cost data hindered our efforts to make definitive estimates of absolute costs. The study should thus be viewed as an initial effort to quantify LIS laser costs upon which more extensive studies can be founded.

The report begins with a summary that includes examples of the methods used to develop cost estimating relationships (CERs). This is followed by a section for each of the six candidate types of lasers and one for the other optical components of the system. Within each section are the CERs for capital and replacement costs, their explanation and limits of application, the rationale employed in their development, and their supporting data.

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1. INTRODUCTION AND SUMMARY

Separation of uranium isotopes by the use of lasers has become a very promising prospect. Sub-scale experiments at Lawrence Livermore Laboratory (LLL) have successfully separated U^{235} from U^{238} in small quantities. Current efforts to increase the scale of the process are pointing the way to a full-scale production plant. With the projected need for reactor fuel growing rapidly, the need for new isotope separation plants is great.

To be of practical significance, laser isotope separation (LIS) must exhibit attributes which make it preferable to expansion of the present facilities. Clearly the most attractive such attribute is the prospect of significant cost reductions, which preliminary studies at LLL suggest will amount to a factor of three and perhaps as much as ten.

From these preliminary studies, it appears that the lasers themselves account for a very substantial portion of the capital cost of a LIS system, and a significant portion of the equipment replacement costs. Since the laser costs are so pivotal to the system cost, and the system cost is so pivotal to the choice of separation techniques, it was clear that a more detailed investigation of laser costs was required.

This report presents the results of the study performed by General Research Corporation (GRC) to assess the cost of lasers in a production laser isotope separation (LIS) plant.

1.1 OBJECTIVES

The overall objective of this study is to improve the available means of estimating the cost of lasers used in the LIS process. To accomplish this general objective, four specific study objectives were established.

Objective 1. Review recent developments in laser technology, with emphasis on their economic consequences. This objective was set to enable the cost analysts to put into perspective the details of the candidate systems and to focus the estimation effort on the most significant aspects of the laser designs. The accomplishment of this objective opens lines of communication between the scientists and technologists, who are dealing with the design characteristics of the lasers, and the cost analysts, who are searching for the key elements of the lasers' costs.

Objective 2. Develop a data base of laser system costs. The collection of cost data for this study also has considerable value as a tool for continuing research. For this reason the data base must be organized for ease of future reference.

Objective 3. Identify significant cost determinants. This is the first result of the cost analysis performed on the collected data. Early in the study it points the direction for further analysis and further data collection; later, it forms the basis for the final choice of independent variables in the cost estimating relationships.

Objective 4. Formulate cost estimating relationships (CERs) for the capital and replacement costs of LIS lasers. This, of course, is the culmination of the cost analysis. Satisfying this objective provides the means to quantify the cost estimates and to examine the variation of cost with key parameters and design alternatives.

1.2 GROUND RULES

This was a parametric cost study in which the estimates are made from Cost Estimating Relationships (CERs) developed for the laser systems. A CER is an equation with cost as the dependent variable and selected design or performance characteristics as independent parameters. The parametric approach permits an examination of cost sensitivities as well as point estimates for a variety of particular systems. This

capability is particularly important for LIS, since designs are in a constant state of change as technology advances.

The LIS laser system for which CERs were developed is shown in Fig. 1.1. The system includes up to four visible-light laser beams with separately controlled wavelengths. Also shown is a carbon dioxide laser which in some systems provides the photoionization in a multistage separation process. This CO_2 laser is replaced in some designs by other energy sources which accomplish the same result. The elimination of the CO_2 laser tends to make the beam transport and control system easier to design and less expensive.

This study's scope included the lasers themselves; the optics (beam transport and control system); and power supplies for the lasers. Specifically excluded were elements of the separation chamber (except its

Figure 1.1. LIS Laser System

optical windows) and components associated with plant facilities (e.g., electrical power conditioning, transformers, vacuum pumps, and maintenance equipment).

The six types of lasers considered in this study were:

1. Copper vapor laser
2. Copper halide laser
3. Dye laser
4. Carbon dioxide laser
5. Rare gas halide laser
6. Frequency doubled neodymium:YAG laser

These lasers are listed in the order of their importance as it was seen at the beginning of the study (and in approximate order of the study emphasis placed on them). During the study, the Nd:YAG laser assumed greater importance and consequently received additional emphasis.

The generic system of Fig. 1.1 consists of pump lasers (in an oscillator/amplifier configuration) used to drive dye lasers (also in an oscillator/amplifier configuration). In specific system configurations, the pump lasers may be copper vapor, copper halide, Nd:YAG, or rare gas halide lasers. In one configuration, the rare gas halide laser is used directly without a dye laser. There are thus ten configurations to consider: four types of pump laser plus the direct rare gas halide configuration, and for each of these five cases the inclusion or exclusion of a CO_2 laser. The CERs developed for these components make it possible to estimate costs for any of these configurations.

1.3 STUDY ORGANIZATION AND APPROACH

The development of these CERs was a four-stage process:

1. Review background information
2. Formulate system description
3. Identify and collect data
4. Analyze data

The background information was obtained primarily from the staff at LLL. Other useful insights were obtained from the literature and from laser manufacturers. During this stage the study team became acquainted with the technical characteristics and tradeoffs for LIS systems.

In the second stage, the system elements were organized into a structure which was amenable to cost analysis and also descriptive of the system and its function. The primary consideration in this stage was to develop a structure which was detailed enough to examine system design parameters, yet not so detailed as to make the data collection task overwhelming. As a ground rule in this study, it was required that cost differences be distinguishable between laser types and over a range of key design parameters (power, electrical efficiency, pulse rate, etc.). Table 1.1 shows the organization of system elements as they were analyzed in the study. This organization represents all ten system configurations. It comprises four "levels of indenture." Where possible, primary CERs were developed at the lowest level (cavity, optics, structure, etc.) and then summed to obtain the costs at more aggregated levels (laser head, power supply, assembly and test, etc.).

The formulation of a system description and the collection of data must be carefully coordinated. The collection of data is typically the most time-consuming activity in a cost study, and therefore its efficiency is especially important. Too detailed a system description will require an unnecessarily large data collection effort. A properly formulated system description minimizes the required data collection and also helps to identify sources of data.

TABLE 1.1

WORK BREAKDOWN STRUCTURE

LASERS

Copper Vapor/Copper Halide Laser

Laser Head

Laser Cavity

Optics

Structure

Integration

Power Supply

High Voltage Source

Thyratron

Pulse Forming Network

Mechanical

Integration

Assembly and Test

Dye Laser

Laser Head

Carbon Dioxide Laser

Laser Head

Power Supply

Rare Gas Halide Laser

Laser Head

Power Supply

High Voltage Source

Thyratron

Pulse Forming Network

Mechanical

Integration

Assembly and Test

Neodymium:YAG Laser

Laser Head

Laser Cavity

Optical Pump

Heat Exchanger

Q-Switch

Doubling Crystal

Assembly and Test

OPTICAL AND MISCELLANEOUS COMPONENTS

Beam Combining and Turning

Mirrors

Coatings

Mounts

Expanders

Dichroic Element

Beam Alignment

Sensor

Global Mechanism

Electronics

Wavelength Control

Wavelength Acquisition

Control

Timing Control

Chamber Windows

Space Frame

The source data used in the study are of three types: analog data, estimated data, and actual data. Analog data are those for lasers, laser components, and other devices which are similar to LIS equipment in terms of their underlying technology or production methods. These data are usually in the form of price lists from suppliers. Estimated data are directly relevant to LIS equipment but contain the imprecision and potential bias of contractor estimates. Actual data on the cost of LIS experimental equipment are the most useful, since they represent a contractor's actual experience in cost. Additionally, the extrapolation of actual data from experimental to production versions is better understood.

The usefulness of the source data available to this study was, unfortunately, in an inverse ratio to its availability. The largest data source by far is price information for analogous equipment, but contractors are usually unwilling to divulge cost details, production quantities, influence of design variations, etc. Cost estimates are available for only a few of the LIS components of interest, and actual costs are available for even fewer. This situation results in significant uncertainty in the study results.

1.4 STUDY METHOD: EXAMPLE OF CER DEVELOPMENT

To illustrate the methods used to develop CERs, we will address the copper vapor laser. Recalling the general system configuration of Table 1.1, the laser consists of a laser head and a power supply. The laser head will be discussed first.

The cost of the laser head is made up of the costs for the cavity, the optics, the structure, and the integration of these devices. The consensus among persons knowledgeable about the fabrication of copper vapor lasers is that when they are produced in quantity, the laser cavity will be a sealed tube; that is, the problem of copper containment will be solved (and at comparatively low cost).

Another assessment by copper vapor laser suppliers is that the cost of the cavity is strongly correlated with its volume. This means that for a given volume efficiency (output power per unit volume), cost can be expressed as a function of power.

Analysis of cost and performance data from two General Electric copper vapor lasers, and estimates for a third laser, result in a cost of \$6,400 for a 5 watt laser cavity with a volume of 100 cc. This gives a volume efficiency of 0.05 W/cc.

The variation of cost with volume was derived from price data on three sizes of metal halide lamps. Such lamps are a fair analog to the copper vapor laser cavity as regards the process of manufacture, the materials, and quality control. The lamp data revealed a cost slope of 0.6 in a log-linear relationship. Expressed mathematically, the laser cavity cost is:

$$C_T = 0.404 V^{0.6}$$

where

C_T = first-unit cost of laser cavity, thousands of 1976 dollars

V = volume of laser cavity, cc

Expressing the volume (V) in terms of output power (P , watts) and volume efficiency (η) results in the following CER:

$$C_T = 0.404 (P/\eta_V)^{0.6}$$

The cost of the laser structure was assumed to scale directly with its length; that is, with the cube root of the volume. The GE laser data indicates that \$4,800 of the cost is associated with the structure and mechanical components. The resulting CER is:

$$C_S = 1.05 V^{0.33}$$

or

$$C_S = 1.05 (P/\eta_V)^{0.33}$$

where

C_S = first-unit cost of structure, \$K 1976

V = laser cavity volume, cc

P = output power, W

η_V = volume efficiency, W/cc

The cost of the optics for the laser is not expected to be a strong function of any of the laser's design characteristics. For this reason the cost is modeled as a constant. The estimate of first-unit optics cost is taken from the GE data as \$2,400.

The cost of integration for the components of the laser head is modeled as a multiplier of the cost of the components. A substantial body of data from manufacturers of lasers, electro-optical components, and electronics suggests that a 25% factor is appropriate for lasers.

Combining the elements of the laser-head cost discussed above results in:

$$C_H = [0.404 (P/\eta_V)^{0.5} + 1.05 (P/\eta_V)^{0.33} + 2.4] \times 1.25$$

where

C_H = first-unit cost of laser head, \$K 1976

P = laser power, W

η_V = volume efficiency, W/cc = 0.05

This CER results in the following costs versus laser output power.

<u>Power, W</u>	<u>Volume Efficiency, W/cc</u>	<u>Cost, \$K 1976</u>
2	0.05	12.01
5	0.05	16.95
10	0.05	21.07

The development of this CER is typical of the methods used where data are very limited. The validity of the CER depends largely on the accuracy of a few estimates and whether the analog assumptions are correct.

In developing a CER for the power supply for this laser a different situation arises. A critical component in the power supply is the thyatron. It is expected that a LIS system will use thyratrons of the same general type as those presently available, probably with somewhat different characteristics. Price data for off-the-shelf thyratrons are adequate to develop CERs. In Sec. 2 we shall present such data plotted against the most relevant design parameters: anode heating factor, peak voltage, and whether the thyatron is liquid-cooled. A multivariate regression analysis of the data for thyratrons resulted in the following CER:

$$C = 0.016 F_A^{0.25} V^{0.97} 1.84^{\delta_C}$$

where

C = first-unit cost of thyatron, \$K 1976

F = anode heating factor, 10^9 V·A/s

V = peak voltage, kV

δ_C = cooling index, 1 for liquid-cooled, 0 otherwise

Typical costs for liquid-cooled thyratrons as estimated from this CER are:

<u>Anode heating factor, 10^9 V·A/s</u>	<u>Peak Voltage, kV</u>	<u>Cost, \$K 1976</u>
1,000	15	2.29
1,000	30	4.48
500	15	1.92
500	30	3.77

The foregoing examples of CER development show the means by which first-unit costs are estimated. To complete the CERs, cost-quantity effects must be taken into account. These effects are frequently referred

to as "learning" effects, although they often reflect many factors besides learning. Some of the other reasons why articles produced in quantity cost less per unit are: amortization of fixed costs such as tooling and development; discounted volume purchases; and changes in production techniques. Without detailed information from the manufacturers, the influence of these factors cannot be separated. The result of the analysis is typically an approximate average of all of them.

1.5 ADVANCES IN TECHNOLOGY

This concludes the summary example given to illustrate the overall analytic approach. One additional consideration warrants comment. When possible, we have tried to isolate the year-to-year reduction in unit price due to improvements in production technology and other factors. In many cases the production of large numbers of articles of a given kind engenders efforts to improve the performance of the articles at the same or lower cost. This effect usually arises from competition between producers of similar items. Since any resulting cost reduction enhances a manufacturer's competitive position, they are understandably reluctant to discuss the details of the cost-quantity effects. Therefore a great deal of inference must be employed to try to distinguish the effects of technology advance from other cost-quantity factors.

During this study we were able to identify two areas where technology advances influence cost--neodymium:YAG lasers and sealed-tube gas lasers. Results for flowing gas lasers (rare gas halide and CO₂ lasers) were inconclusive. For dye lasers and system components, there are perceptible year-to-year changes in the cost per unit performance.

Using price data for sealed-tube argon lasers (non-UV) as representative of the class of sealed-tube lasers, it appears that prices were reduced by 26% from 1973 to 1976, for lasers with the same performance. (This reduction is adjusted to account for inflation.) Assuming a constant fractional reduction per year, the following expression can be derived:

$$C_Y = C_{76} (\Delta Y)^{-0.27}$$

where

C_Y = cost in future year Y

C_{76} = cost in 1976

ΔY = Y - 1976

For Nd:YAG lasers, year-to-year changes seem to be more significant. Price reductions of 52% were observed over the same three-year period. This result led to the following formulation, where the terms are as defined above:

$$C_Y = C_{76} (\Delta Y)^{-0.67}$$

While these effects have been observed over the past three years, it is somewhat speculative to suggest that they will continue at the same rate. The data from which these relationships were derived are influenced by improvements in technology, together with quantity effects, market effects, competitive factors, and, no doubt, a host of intangibles. Therefore, these results should be considered as bounding values, representing possible--but not certain--reductions from costs expressed by the derived CERS.

1.6 PRESENTATION OF RESULTS

Sections 2-8 contain the substantive results of this study. One section is devoted to each of the six types of laser and one to the other optical components of the system.

Each section begins with a work breakdown structure (WBS) showing the five-letter mnemonic name given to each cost element. These names, chosen to facilitate computer programming of the CERs, are constructed as follows. The last letter is C for Capital or R for Replacement. The preceding two letters indicate the type of laser or subsystem:

CV	Copper vapor laser
CH	Copper halide laser
DL	Dye laser
CD	Carbon dioxide laser
RG	Rare gas halide laser
NY	NeoJymium:YAG laser
OC	Optical components

The first two letters are chosen to suggest the particular cost element. For example, STCVC should be read as "Structure, copper vapor laser, capital cost."

Immediately after the definition of the work breakdown structure and mnemonics, the CERs are given. The mnemonics for the independent variables in the CERs are listed in the Glossary. They fall into three groups: technical and performance parameters; component lifetimes (beginning with L); and quantities procured (beginning with Q).

After the presentation of the CERs in each section, the data and reasoning on which the CERs are based is presented.

Costs are presented uniformly in thousands of 1976 dollars.

2 COPPER VAPOR LASERS

When copper vapor lasers are included in any of the system configurations, they are used to pump the dye lasers. They may be employed either as oscillators or as amplifiers. The WBS for a copper vapor oscillator is shown below. An amplifier is costed by the same CERs but with optics deleted. In an oscillator/amplifier configuration or in a multistage amplifier design, each stage's cost is estimated separately as a complete laser.

Copper Vapor Laser WBS

<u>Equation Number</u>	<u>Component or Function</u>	<u>Capital Costs</u>	<u>Replacement Costs</u>
1.	Laser Head	LHCVC	LHCVR
2.	Laser Cavity	LCCVC	LCCVR
3.	Optics	OPCVC	OPCVR
4.	Structure	STCVC	STCVR
5.	Integration	IHCVC	IHCVR
6.	Power Supply	PSCVC	PSCVR
7.	High Voltage Source	HVCVC	HVCVR
8.	Thyratron	THCVC	THCVR
9.	Pulse Forming Network	PFCVC	PFCVR
10.	Mechanical	MECVC	MECVR
11.	Integration	IPCVC	IPCVR
12.	Assembly and Test	ATCVC	ATCVR

2.1 CERs

2.1.1 Capital Costs

(1) Laser Head

$$LHCVC = LCCVC + OPCVC + STCVC + IHCVC$$

(2) Laser Cavity

$$\text{LCCVC} = .404 (P/V_{\text{EFF}})^{0.6} \text{QCVC}^{0.848}$$

(3) Optics

$$\begin{aligned} \text{OPCVC} &= 2.4 \text{QCVC}^{0.926} \text{ if oscillator} \\ &= 0 \text{ if amplifier} \end{aligned}$$

(4) Structure

$$\text{STCVC} = 1.04 (P/V_{\text{EFF}})^{0.33} \text{QCVC}^{0.766}$$

(5) Integration

$$\text{IHCVC} = 0.25 (\text{LCCVC} + \text{OPCVC} + \text{STCVC})$$

(6) Power Supply

$$\text{PSCVC} = \text{HVCVC} + \text{THCVC} + \text{PFCVC} + \text{MECVC} + \text{IPCVC}$$

(7) High Voltage Source

$$\text{HVCVC} = 0.08 \text{PE}^{0.29} \text{V}^{0.38} \text{QCVC}^{0.941}$$

(8) Thyatron

$$\text{THCVC} = 0.016 \text{FA}^{0.25} \text{PV}^{0.97} 1.84^{\text{DVTH}} (\text{NTH} \cdot \text{QCVC})^{0.895}$$

(9) Pulse Forming Network

$$\text{PFCVC} = (\text{EC} + 0.104 \text{SE}^{0.44} \text{NC}) \text{QCVC}^{0.848}$$

(10) Mechanical

$$MEVCV = ME \cdot QCVC^{0.678}$$

(11) Integration

$$IPCVC = (HVCVC + THCVC + PFCVC + MECVC) 0.10$$

(12) Assembly and Test

$$ATCVC = 0.15 (LHCVC + PSCVC)$$

2.1.2 Replacement Costs

(1) Laser Head

$$LHCVR = LCCVR + OPCVR + STCVR + IHCVR$$

(2) Laser Cavity

$$LCCVR = 0.404 (P/VEFF)^{0.6} (QCVC + QLCVR)^{0.848} - LCCVC$$

(3) Optics

$$OPCVR = 0.75 [2.4(QCVC + QOCVR)^{0.926} - OPCVC] \text{ if oscillator} \\ = 0 \text{ if amplifier}$$

(4) Structure

$$STCVR = 0 \text{ (No replacement of structure is expected over the} \\ \text{lifetime of the system.)}$$

(5) Integration (not applicable)

(6) Power Supply

$$PSCVR = HVCVR + THCVR + PFCVR + MECVR + IPCVF$$

(7) High Voltage Source

$$HVCVR = 0.08 PE^{0.29} V^{0.38} (QCVC + QHCVR)^{0.941} - HVCVC$$

(8) Thyratrons

$$THCVR = 0.016 FA^{0.25} PV^{0.97} 1.84^{DVTH} (NTH \cdot QCVC + QTCVR)^{0.895} - THCVC$$

(9) Pulse Forming Networks

$$PFCVR = EC [(QCVC + QECVR)^{0.848} - QCVC^{0.848}] + \\ 0.104 SE^{0.44} NC [(QCVC + QCCVR)^{0.848} - QCVC^{0.848}]$$

(10) Mechanical

$$MECVR = ME (QCVC + QMCVR)^{0.678} - MECVC$$

(11) Integration (not applicable)

(12) Assembly and Test (not applicable)

2.2 RATIONALE AND DATA

2.2.1 Laser Head

The CER for the copper vapor laser was developed primarily from information received from the General Electric Company. Their work on copper vapor lasers provides the perspective required to draw useful analogies between these lasers and other components for which a larger cost data base exists. The GE information is of two kinds. First, cost data and estimates were made available for (1) a laser system delivered to the US Army, (2) the lasers for LLL's SPP II experiment, and (3) a conceptual design of a LIS production laser. The second kind of information was a definition of the relationship between copper vapor lasers and their analogs.

The approach we took in the study was to employ the GE suggestions for design scaling, then relate the scaling models to cost data and thus formulate the CER. The first step was the disaggregation of the laser into the cost elements shown in the WBS. Estimating the cost of the laser tube began with the thesis put forward by GE staff that any production version of the copper vapor laser would use a sealed-tube cavity design. The implication of this assertion is that a production laser would not have the vacuum fittings, elaborate plumbing, sealing fixtures, and adjustments that the current laboratory designs have. The production version would consist of an integral tube incorporating the ceramic cavity, electrodes, radiation shield, cooling jackets, vacuum envelope, and window assemblies. This design concept suggests the use of high-temperature metal halide lamps as a cost analog to the laser tube. Further, it was suggested by GE staff (and borne out in analysis of the lamp data) that the cost of the tube was primarily driven by its volume. The basic form of the CER was thus postulated as:

$$\text{Cost} = (\text{constant})(\text{volume})^{(\text{exponent})}$$

The volume of the laser cavity is not a quantity of immediate interest in most systems studies. Therefore a first-order relationship

suggested by the physics of the laser cavity was employed. The power output of this type of laser is approximately in linear proportion to the volume of the cavity:

$$\text{Power} = (\text{volume}) \cdot (\text{volume efficiency})$$

The CER can therefore be written in the form

$$\text{Cost} = \text{constant} \left(\frac{\text{power}}{\text{volume efficiency}} \right)^{\text{exponent}}$$

This form of the CER has the desired dependence on power--a performance measure--and also a dependence on volume efficiency--a measure of technology advance for copper vapor lasers.

To find values for the constant and exponent, we used the available cost data. The exponent was derived from three data points for high-intensity metal halide lamps. We consider these lamps to be the best available analog to the copper vapor laser, since their manufacturing processes and operating temperatures are similar. The data, obtained from Westinghouse, * are:

High-Intensity Lamp Cost Data

<u>Ordering Code</u>	<u>Volume, cc</u>	<u>Cost, \$</u>
MH400BD/4	11.262	34.50
MH1000BD/4	37.089	76.50
MH1500BD/C	51.350	83.50

Fitting a least-squares line to the logarithms of these data results in the following expression:

* Letter from J. W. McNall, Westinghouse Lamp Research Manager, to Frank Markovich, 14 May 1976.

$$\text{Cost} = \text{constant (volume)}^{0.6}$$

This is the value of the exponent used in the laser CER.

To find the constant, we relied on a GE cost estimate and two costs of actual GE lasers. For one of the actual lasers, only the cost of parts was given; for the other, the cost of the manufactured article was given. Part of the estimation process was to derive the ratio between parts cost and finished product cost.

The two items of finished product cost data are 1) a copper vapor laser built for the US Army Missile Command, and 2) an estimate of the cost (first unit) of a production laser tube. Both lasers produce 5 watts of optical power from a 100 cc cavity.

The data for laser parts were derived from the purchase order to GE for the SPP II lasers. Two items are shown separately, the cost of the tube parts and the cost of the parts for the entire laser (including power supply). These data are shown below:

General Electric Copper Vapor Laser Cost Data

Finished Product Costs

1.	US Army Laser	***
	Laser Head	***
	Power Supply	
	Vacuum Pump	***
	Trailer & Misc.	
2.	Complete Laser Tube (estimate)	***

Parts Costs

1. Laser	
Laser Head	} ***
Power Supply	
2. Laser Tube	***

The factor applied to the parts cost to estimate finished product cost was derived by simply dividing the laser system cost *** by the laser system parts cost *** to obtain a factor of 4.32. A somewhat higher factor of *** was obtained for the laser tube. The lower value was used in the study as more representative of system manufacturing experience.

These data provide a basis for deriving the constant in the laser tube CER. The finished-product laser tube was estimated at ***. Assuming that 25% of this could be ascribed to integrating the laser tube into the laser system, we arrive at a first-unit cost of *** for the tube prior to integration. Solving for the constant we derive the laser tube CER (for first-unit cost):

$$C = 0.404 (\text{power/volume efficiency})^{0.6}$$

The estimate of first-unit cost for the optics was based on the SPP II purchase order to GE, cost data on other lasers, and reference to various optical component suppliers. Typical estimates for the optics, including resonator mirrors, coupling mirrors, and mounts, were \$3,000 as a finished product. Note that the cavity windows are not included in the optics, but are rather part of the laser tube. It was estimated by staff members at LLL, GE, and Westinghouse that the cost of the optics was relatively independent of the power of the laser. Therefore, the CER is simply a constant \$2400 (again ascribing 25% of the cost to integration). The optics CER (first unit) is:

$$C = 2.4$$

The cost of structure (mechanical and miscellaneous components) is estimated to be proportional to the length of the laser cavity. This relationship is derived from typical design requirements for the optical "bench" of the laser and the need to provide structural rigidity over the length of the cavity. At an even more fundamental level, this relation reflects a constant cost per unit weight of laser supporting structure (typical of structural and mechanical elements) and a constant support structure weight per unit length of laser.

The scaling of laser length to cavity volume is simply a cube root relationship, since the cavity diameter-to-length ratio is approximately fixed. The resulting form of the CER is therefore:

$$\text{Cost} = \text{constant} (\text{volume})^{0.33}$$

or

$$\text{Cost} = \text{constant} \left(\frac{\text{power}}{\text{volume efficiency}} \right)^{0.33}$$

The value of the constant is derived from GE data which suggests that first-unit structural and mechanical component costs will be \$6,000. Accounting for integration at 25% gives \$4,800 for a 100 cc cavity laser. Solving for the constant in the equation gives (first-unit cost):

$$C = 1.05 (\text{power/volume efficiency})^{0.33}$$

All the first-unit costs are adjusted for "learning" (see Appendix A). The learning rate for laser tubes is estimated to be 90% on the basis of their resemblance to other relatively complex electro-optical components which exhibit this rate. The optics typically learn at a lower rate than the electro-optical components; 95% learning was used. The fastest learning rate (80%) is applied to the structural components, since there are usually many more opportunities for cost reductions in producing such articles.

The CERs thus far discussed can be used to estimate the costs of the copper vapor laser head components as functions of power, volume efficiency, and quantity. The cost of integrating these components into a laser head is estimated at 25% of the cost of the components themselves. The total cost of the head is found by adding the cost of the components to the cost of integration.

2.2.2 Power Supply

High-Voltage Source. The high-voltage DC power source used in the copper vapor laser is expected to be of the same type as those currently available. No new technology is required; therefore cost (or more correctly, price) data for off-the-shelf high-voltage sources are quite relevant.

A review of price data and discussions with vendors revealed that the cost of high-voltage sources is primarily a function of power output, voltage, and fine regulation. There was considerable variation from one data set to another in line regulation, the largest percentage regulation being the least expensive. Since the regulation and control requirements for the copper vapor laser are less stringent than any of the sources in the data set, the data were used primarily to establish slopes.

The data used in deriving the CER is shown in Fig. 2.1. Performing a multi-variable regression on the data produced the following relationship (first-unit cost):

$$C = 0.175 P^{0.29} V^{0.38}$$

where

P = power output, watts

V = voltage, kilovolts

Figure 2.1. High Voltage Source Cost Data

This relationship was derived from data on sources which had better line regulation and more output control than would be necessary here. An additional piece of information was used to make the required adjustment. Universal Voltronics estimated that the kind of high-voltage source that would be required would cost *** for a *** source. The above equation was modified to coincide with this estimate, to:

$$C = 0.08 P^{0.29} V^{0.38}$$

The learning rate was also derived from Universal Voltronics data:

High-Voltage Source*

Cost (\$)

PROPRIETARY DATA DELETED

Quantity

At quantity 1,000 the cost has dropped to 67% of first-unit cost. This reduction corresponds to a 96% learning rate, which was used in the final CER.

Thyratrons. These are also in the class of power supply components for which the requirements of the LIS application are nearly met by currently available products. The principal improvement required of present design is the ability to withstand the combination of high pulse repetition rates (10-30 kHz) and high peak power (up to 10 MW). These combined requirements impose the need for thyratrons with a very high anode heating factor.** Commercially available thyratrons have anode heating factors as high as 5×10^{11} V·A/s; the LIS designs may require 10^{12} or somewhat higher. The cost of such thyratrons can be readily extrapolated from the cost of currently available designs.

The thyratron data used in the study is shown in Table 2.1. The three manufacturers are the principal producers of thyratrons and therefore represent good sources of cost data. These data are the prices of available thyratron tubes. No information was available on the number of tubes of any given model that have been produced. Qualitative statements by sales persons indicate, however, that tubes with large anode heating factors have been produced in very small quantities. Therefore the cost estimates derived from these data are taken as first-unit costs.

* This information is proprietary.

** The anode heating factor is defined as the product of peak forward voltage, peak anode current, and pulse repetition rate.

TABLE 2.1
THYRATRON COST DATA

<u>Manufacturer</u>	<u>Model</u>	<u>Voltage, kV</u>	<u>Anode Heating Factor, 10^3 V.A/a</u>	<u>Cooling A = air L = liquid</u>	<u>Cost, \$1976</u>
EG&G	7621	8	2.7	A	3260
	HY-60/6	16	5	A	260
	HY-61	16	5	A	330
	HY-1A/10/11	20	10	A	350
	7322, HY-31	25	25	A	687
	1802	25	50	A	600
	HY-32	35	50	A	695
	HY-5	40	160	A	1750
ITT	8613	16	10	A	350
	7665	20	7	A	200
	7620	20	10	A	350
	7322	25	20	A	640
	8354	25	25	A	640
	7390	33	30	A	900
	7390A	33	30	A	950
	7667	33	40	A	925
	7890	40	55	A	1200
	F117	33	30	A	900
	7866	50	55	A	1400
	F-104	50	55	A	1700
	8326	33	60	A	1800
	8479	50	400	A	4150
	F-146	33	400	A	3300
	F-103	16	10	A	400
	F-131	20	7	A	500
English Electric Valve	CX-1177	12	4	A	760
	CX-1157	20	7	A	680
	CX-1530	25	12	A	1025
	CX-1530D	35	12	A	1165
	CX-1180	25	12.5	A	1080
	CX-1154	40	30	A	1690
	CX-1168	80	70	A	3940
	CX-1171	120	70	A	6300
	CX-1199	160	70	A	7820
	CX-1174	40	60	A	2800
	CX-1175	80	140	A	6040
	CX-1192	120	140	A	7200
	CX-1193	160	140	A	9150
	CX-1527	40	200	L	7000
	CX-1528	70	70	L	2700
	CX-1529	40	200	L	7000
	CX-1525	25	500	L	1990
	CX-1536	70	300	L	9800
	CX-1164	12	7	A	680

Multiple regression analysis on these data produced the following first-unit CER:

$$C = 0.016 FA^{0.25} V^{0.97} 1.84^{DVTH}$$

where

FA = Anode heating factor, 10^9 V·A/s

V = Peak voltage, kV

DVTH = 1 if liquid-cooled

0 if air-cooled

The learning rate for thyratrons was estimated by analogy to other similar components. Electrical components in mass production have learning rates around 95%. Subassemblies of electrical components typically have learning rates of 90%. It was inferred that state-of-the-art thyratrons are somewhere between the two. Therefore, a 93% learning rate was applied to thyratrons in the LIS application.

Pulse Forming Network. The pulse forming network (PFN) is considered in two parts: the capacitors and everything else. "Everything else" consists of a charging inductor and miscellaneous components such as sockets, cable, and fittings; their total cost was estimated at \$450, based on catalog prices for various components. This assembly of components is expected to exhibit a learning rate of 90%, which is typical of such electrical equipment. Based on a reliability study performed by Martin Co., these components can expect to have a lifetime of about 65,000 hours. This value was used to compute the quantity of electrical assemblies required over the operational life of the LIS plant.

* Laser Reliability Prediction, Martin Marietta Aerospace, RADC-TR-75-210, August 1975.

The cost of capacitors was estimated from the price data for commercially available capacitors given in Table 2.2, which gives prices based on purchases of 50 units. The same information is shown graphically in Fig. 2.2. Note that there are two distinct sets of data, one for 10^6 -shot (nominal) capacitors, and one for 10^8 -shot (long life) capacitors. Regression analysis was performed on both data sets to derive the CERs. The CER for the "nominal" capacitors was preferred, because it appears that the longer life of the expensive capacitor can be achieved by using two of the less expensive ones. By using two capacitors in series (an approach suggested by a LLL design engineer), the charge voltage on each is one-half. Data sheets from Maxwell Labs indicate that by using capacitors at half their rated voltage, a factor of 100 increase in expected number of shots is obtained. Therefore, it seems economical to use two nominal (10^6 -shot) capacitors whenever they are less than half as expensive as 10^8 -shot capacitors, as they are for all energies greater than 0.1 joule.*

The CER for the nominal capacitors at quantity 50 is:

$$C = 0.018 SE^{0.44}$$

where

SE = stored energy, joules

To estimate the learning rate for the capacitors themselves, we relied on data obtained from QC Electronics:

<u>Identifier</u>	<u>Price @ Quantity 9</u>	<u>Price @ Quantity 200</u>	<u>Slope</u>
2510CM86	81.37	66.50	95.6%
2800CM91	136.96	109.57	95.1%
2866CM91	151.15	120.94	95.1%
2890CM91	162.72	130.24	95.4%

The clear trend of 95% learning was used to modify the CER above to give costs at quantity one rather than quantity 50. This gives the cost as:

* We have not examined the alternative of using a single capacitor of double the rated voltage.

TABLE 2.2
CAPACITOR COST DATA
At quantity of 50

<u>Supplier</u>	<u>Identifier</u>	<u>Capacitance, μF</u>	<u>Voltage, kV</u>	<u>Stored Energy, J</u>	<u>Lifetime, shots</u>	<u>Cost, \$</u>
Capacitor Specialists	100W258	0.075	100	360	10 ⁶	269.90
	100W329	0.035	100	180	10 ⁶	202.95
	100W330	0.015	100	90	10 ⁶	171.00
	70W331	0.200	70	500	10 ⁶	260.60
	70W274	0.100	70	250	10 ⁶	191.60
	70W332	0.040	70	100	10 ⁶	158.65
	60W257	0.200	60	360	10 ⁶	242.05
	60W333	0.100	60	180	10 ⁶	178.20
	60W294	0.050	60	90	10 ⁶	146.30
	50W334	0.300	50	375	10 ⁶	229.70
	50W335	0.150	50	190	10 ⁶	168.95
	50W336	0.075	50	90	10 ⁶	141.15
	35W337	0.600	35	360	10 ⁶	218.40
	35W338	0.300	35	180	10 ⁶	158.65
	35W339	0.150	35	90	10 ⁶	100.36
	35W081	0.050	35	30	10 ⁷	141.15
	35W328	0.025	35	15	10 ⁸	134.95
Condenser Products	(estimate)	0.220	15	25	10 ⁶	70.00
General Electric	SPP11	0.003	15	0.34	10 ⁸	35.51
	SPP11	0.001	15	0.11	10 ⁸	27.83
QC Electronics	-	0.100	2	0.2	10 ⁶	10.40
	-	0.250	2	0.5	10 ⁶	12.00
	-	0.500	2	1.0	10 ⁶	15.30
	-	0.050	3	0.23	10 ⁶	9.00
	-	0.100	3	0.45	10 ⁶	12.50
	-	0.010	5	0.13	10 ⁶	11.50
	-	0.050	5	0.63	10 ⁶	14.60
	-	0.010	10	0.50	10 ⁶	13.50
	-	0.020	10	1.00	10 ⁶	14.30
	2510CM86	0.001	20	0.20	10 ⁸	71.50
	2900CM91	0.001	30	0.45	10 ⁸	120.52
	2866CM91	0.005	15	0.56	10 ⁸	133.02
	2890CM91	0.010	10	0.50	10 ⁸	143.24

Figure 2.2. Capacitor Costs Vs. Stored Energy

$$C = 0.024 SE^{0.44}$$

In order to estimate the cost of the capacitors as an integral part of the PFN, the parts-to-finished-product ratio of 4.32 is applied.* This gives the final form of the capacitor part of the PFN as

$$C = 0.104 SE^{0.44} NC$$

where:

NC = number of capacitors per PFN

The number of capacitors should be chosen to correspond to the desired capacitor lifetime. Recall from the discussion above that the nominal life of a capacitor operating at rated voltage is 10^6 shots. At a pulse repetition rate of 20 kHz this is only 0.0139 hours (50 seconds). But by doubling the number of capacitors (NC) each capacitor lasts for 10^8 shots (5,000 seconds). Assuming that each doubling of NC results in 100 times more shots, the life of the PFN capacitors can be specified independently and NC can be computed as:

$$NC = 2^{1/2 \log_{10} (L \cdot PRF / 278)}$$

where

NC = Number of capacitors per PFN

L = Desired life of capacitors, hours

PRF = Pulse repetition frequency, hertz

For example, to obtain 8,760 hours (one calendar year) from the capacitors at 20 kHz, one obtains:

*The 4.32 factor is assumed to be applicable to capacitors in this case. This assumption is arbitrary and the result of a deficiency in data with regard to the PFN. The factor should be the subject of further analysis.

$$\begin{aligned}
 NC &= 2^{1/2 \log_{10}(8760 \times 2 \times 10^4 / 278)} \\
 &= 2^{1/2 \log(630216)} \\
 &= 2^{2.90} = 7.48 \text{ or } 8 \text{ capacitors}
 \end{aligned}$$

These equations are based on commercially available capacitors in large quantities.

The overall learning rate for the PFN is estimated at 90%, even though the learning for the capacitors themselves is much slower. This difference is attributed to the cost of assembly and inspection of the PFN of which the capacitors are a part. The finished product "learns" much faster than the cost of its components.

Mechanical. The cost estimate for the mechanical components of the power supply was derived from experience gained at GRC in specifying similarly complex electronic systems. In developing the command and control equipment for a large urban fire department, an estimate of \$1,400 was made for hardware items for a subsystem like the LIS power supply. This cost estimate accounts for the racks, brackets, hardware, switches, meters, interconnects, and other miscellaneous small mechanical items. Without a detailed specification of the LIS system layout, it is difficult to make a precise estimate of such equipment. A fixed cost of \$1,400 is of the right order, and the cost is small enough in any case to have little effect on the system total. Moreover, the relatively fast learning (80%) of these components lessens even further their effect on total cost.

Integration. The cost of integrating the components of the power supply is included in this category. Since the power supply is a relatively straightforward subsystem, an integration cost of 10% was estimated.

2.2.3 Assembly and Test

The cost to assemble the laser system and test it as an operational element was estimated by using analogs. Assembly and test include such functions as verifying that all components are within specifications, making fine adjustments, assuring that the unit operates as required, performing quality control tests, and correcting deficiencies. Examples of articles with similar assembly and test requirements are:

	<u>Article Supplier</u>	<u>Cost (percentage of part costs)</u>
Beam Alignment Subsystem	Perkin-Elmer	13%
Airborne Pointer Tracker	Hughes	10%
Radiometer Gimbal	LTV	23%

On the basis of these data and other cost experience, a 15% factor was estimated for LIS laser assembly and test.

It was further estimated that the relative cost of assembly and test would diminish as more systems were produced. A learning slope of 85% is applied to this function.

3 COPPER HALIDE LASERS

Like the copper vapor laser, the copper halide laser is used to pump the dye laser. It also may be used in either an oscillator or amplifier configuration. The WBS has exactly the same form as for the copper vapor laser, as shown below. In fact, most of the CERs are the same as well, and the only ones which differ are those for the laser cavity itself. To avoid redundancy, only the laser cavity CERs are discussed in this section. All other CERs for the elements of the WBS are the same as the corresponding ones in Sec. 2.

COPPER HALIDE LASER WBS

<u>Equation Number</u>	<u>Component or Function</u>	<u>Capital Cost</u>	<u>Replacement Cost</u>
1	Laser Head	LHCHC	LHCHR
2	Laser Cavity	LCCHC	LCCHR
3	Optics	OPCHC	OPCHR
4	Structure	STCHC	STCHR
5	Integration	INCHC	INCHR
6	Power Supply	PSCHC	PSCHR
7	High Voltage Source	HVCHC	HVCHR
8	Thyratron	THCHC	THCHR
9	Pulse Forming Network	PFCHC	PFCHR
10	Mechanical	MECHC	MECHR
11	Integration	IPCHC	IPCHR
12	Assembly and Test	ATCHC	ATCHR

3.1 CERS

3.1.1 Capital Costs

(2) Laser Cavity

$$LCCHC = 0.464 (P/VEFF)^{0.33} QCHC^{0.848}$$

3.1.2 Replacement Costs

(2) Laser Cavity

$$LCCHR = 0.464 (P/VEFF)^{0.33} (QCHC + QLCHR)^{0.848} - LCCHC$$

3.2 RATIONALE AND DATA

The copper halide CER was developed along the same lines as that for the copper vapor laser, starting with information obtained from Westinghouse Research Labs, which has done more production-oriented development of copper halide lasers than any other organization. Even Westinghouse, however, had very little data. Most of their assistance was in the form of design descriptions and suggestions for analogs. As with the copper vapor laser, the best analog to the cavity was expected to be high-intensity lamps.

In developing the copper halide CER, an important distinction should be noted. Whereas the copper vapor laser has a relatively complicated sealed tube design (consisting of a ceramic tube, inset electrodes, radiation shield, cooling jackets, and vacuum envelope), the copper halide cavity can consist primarily of a quartz tube because of the lower operating temperature of the copper halide (450°-625°, versus 1600° for copper vapor).

The scaling relationship for copper halide laser cavities was therefore derived from price data on flash lamps, rather than high-

intensity metal-halide lamps. It is our judgment that the design of the flash lamps is more analogous to the copper halide cavity.

The flash lamp data used to develop the CER is shown in Table 3.1. The information was obtained from ILC Technology, but is representative of a number of lamp suppliers. The intent in using these data is to capture cost variations representative of tubes with extensive production histories, since it is expected that in the quantities required for an LIS plant that form of tube production will apply.

The data in Table 3.1 confirm the validity of cost variation with volume for tubes of this type. The CER derived from regression analysis of these data is:

TABLE 3.1
FLASH LAMP PRICE DATA
(Source: ILC Technology)

<u>Model Identifier</u>	<u>Volume (cc)</u>	<u>Price (\$)</u>
10L12	23.9	\$ 91
10L18	35.9	105
10L24	47.9	121
13L4	13.5	108
13L6	20.2	112
13L18	60.7	149
13L24	80.9	160
19L8	57.6	155
19L12	86.4	164
19L18	129.6	177
19L24	172.8	190
19L48	345.7	303

$$C = 0.0376 V^{0.33}$$

where

V = tube volume, cc

It was indicated that these data were appropriate for tubes produced in quantities of 1,000. Assuming a 90% learning rate for the tubes, the CER for first-unit cost (\$K 1976) becomes

$$C = 0.107 V^{0.33}$$

In the final CER, V is (as before) replaced by (power)/(volume efficiency).

(Proprietary Information) A volume efficiency of *** suggested by Westinghouse for copper halide lasers. This value may be increased as more becomes understood of the cavity's physics. Westinghouse also indicated that the cavity could be scaled up to a maximum size of about *** , which at the stated efficiency means a maximum output of about *** . To achieve greater output power levels, multiple stages must be used.

Current lifetimes for the laboratory laser cavities are very short (tens of hours); however, Westinghouse staff members were confident that the application of lamp manufacturing techniques and quality control would result in lifetimes on the order of 10,000 hours. They indicated that this is consistent with lamp lifetimes and failure mechanisms. Lamps are commonly replaced at about 8,000 hours (40% output reduction) but this is due to darkening of the envelope, which is not a problem for lasers. Lamp electrode failures (the expected laser failure mechanism) do not usually occur before 10-15 thousand hours.

As for copper vapor lasers, the copper halide designs are expected to have a 90% learning rate.

4 DYE LASERS

The dye laser may be pumped by a copper vapor, copper halide, rare gas halide, or Nd:YAG laser. The cost difference between a dye laser employed as an oscillator and one employed as an amplifier is judged to be less than the uncertainty associated with the CER; hence, the same CER is applicable to both modes of operation. The WBS for the oscillator/amplifier dye laser is a single item:*

DYE LASER WBS

<u>Equation Number</u>	<u>Component or Function</u>	<u>Capital Costs</u>	<u>Replacement Costs</u>
1	Laser Head	LHDL	LHDLR

4.1 CERs

4.1.1 Capital Costs

$$(1) \text{ LHDL} = 3.0 \text{ QDL}^{.843}$$

4.1.2 Replacement Costs

$$\text{LHDLR} = 3.0 (\text{QDL} + \text{QLDLR})^{.848} - \text{LHDL}$$

4.2 RATIONALE AND DATA

Dye laser prices were obtained from the Molelectron Corporation, Spectra-Physics, Inc., and Systems, Science, and Software (S-Cubed) (Table 4.1). Because of its rugged uncomplicated design, reliability, and ease of operation, the S-Cubed dye laser was judged to be the most appropriate for the isotope separation process. The Molelectron and Spectra-Physics dye lasers incorporate features (e.g., adjustments and readouts)

*The dye laser does not require a separate power supply.

TABLE 4.1
REPRESENTATIVE DYE LASER COSTS

<u>Manufacturer</u>	<u>Model</u>	<u>Description</u>	<u>Price</u>
Molelectron	DL 100	Invar-stabilized cavity, grating, front mirror, curvette dye cell, focusing lens, grating sine drive, wavelength readout	\$7,985
	DL 062	Flowing dye cell with power supply, mounting hardware	<u>\$1,385</u>
TOTAL			\$9,370
Spectra-Physics	375	Circulator assembly, fine tuning assembly, tunable filter, adjustable pump focus reflector, high quality nozzle, snap-in cavity mirrors, quartz rod cavity	\$4,150
S-Cubed	DL 600	Quartz optics, quartz dye cell, grating coarse and fine adjustment of wavelength micrometer screw	\$2,700
	Dye Pump		195
	Dye Tank		<u>45</u>
TOTAL			\$2,940

which are required in the laboratory but not for an industrial process laser. It was assumed that future prices could be reasonably estimated by applying a 90% learning curve* to the current price. The resulting CER is as follows for the dye laser powers of interest (around 50 watts):**

$$(1) \quad \text{LHDLC} = 3.0 \text{ QDLC}^{.848}$$

where

LHDLC = Capital cost of dye lasers, \$K 1976

QDLC = Number of dye lasers in LIS

Data on replacement of dye lasers was not obtainable. A spokesman for S-Cubed did indicate, however, that the component most likely to fail would be the optics. S-Cubed also indicated that their dye lasers have been in use for up to three years without failure under varying duty cycles. A reasonable expectation for the heavy-duty DL 600 is a life-time of at least 5 years or 15,000 hours.

* Based upon an internal Molelectron study conducted in 1975 for dye and pulsed N₂ lasers.

** Available data did not support a correlation between price and power.

5 CARBON DIOXIDE LASERS

The WBS for the CO₂ laser used for photoionization in a multi-stage process is shown below.

CO₂ Laser WBS

<u>Equation Number</u>	<u>Component or Function</u>	<u>Capital Costs</u>	<u>Replacement Costs</u>
1	Laser Head	LHCDC	LHCDR
2	Power Supply*	PSCDC	PSCDR

5.1 CERS

5.1.1 Capital Costs

$$(1) \text{ LHCDC} = 2.216P^{.512} (1 + 1.426 \text{ DVCD}) (\text{QCDC})^{.848}$$

$$(2) \text{ PSCDC} = 1.478P^{.512} (1 + 1.426 (\text{DVCD})) (\text{QCDC})^{.848}$$

5.1.2 Replacement Costs

$$(1) \text{ LHCDR} = 2.216P^{.512} (1 + 1.426 \text{ DVCD}) (\text{QCDC} + \text{QLCDR})^{.848} - \text{LHCDC}$$

$$(2) \text{ PSCDR} = 1.478P^{.512} (1 + 1.426 (\text{DVCD})) (\text{QCDC} + \text{QPCDR})^{.848} - \text{PSCDC}$$

5.2 RATIONALE AND DATA

5.2.1 Capital Costs

A statistical analysis of CO₂ laser prices as a function of optical power output was conducted. The analysis was based upon data published

*Includes integration costs.

in Laser Focus.^{*} Although the LIS process utilizes a pulsed CO₂ laser, continuous-wave (CW) lasers have been included in the statistical analysis for several reasons. CW lasers have been fabricated which have been rated as "heavy duty" or "industrial" by their manufacturers, with average powers up to 10 kW. In contrast, pulsed CO₂ lasers are, for the most part, fabricated for laboratory uses and rated at lower average powers (up to 300 W). Hence, the CW laser data is included to bolster the data sample in the high power range and thereby assist in establishing a trend line for the related pulsed CO₂ laser. The cost of a new pulsed laser will differ from the cost of the present CW laser by the need for additional equipment to provide for pulsed rather than CW operation.

At the same time, the distinction between the CW and pulsed lasers has been retained by incorporating a dummy variable.

Regression analysis was applied to the data shown in Tables 5.1 and 5.2 for pulsed and CW lasers respectively. The analysis resulted in the following price algorithm for CO₂ lasers:^{**}

$$P_{CO_2} = 2.216P^{0.512} (1 + 1.426DVCD)$$

where

P_{CO_2} = Price per CO₂ laser, \$K 1976

P = Average optical power, watts

DVCD = Dummy variable: 1 for pulsed laser and 0 for CW laser

^{*} Laser Focus, Buyers' Guide, February 1976. Price data has not been normalized for quantity, because such data is not currently obtainable. The impact of this data gap is judged to be of secondary importance because of the damping effect on price differences between manufacturers by the competitive marketplace mechanism.

^{**} The multiple correlation coefficient is .86 with an F ratio of 287 (significant at the <.5% level).

TABLE 5.1
PULSED CO₂ LASER PRICE DATA

<u>Manufacturer</u>	<u>Model No.</u>	<u>Average Power, W</u>	<u>Price, \$</u>	<u>Plot ID</u>
Lumonics	TEA 103-1	30.0	\$14,000	P-1
Tac Histo	215A	4.0	7,975	P-2
Apollo Lasers	XFC	1.4	5,000	P-3
Advanced Kinetics	MIRL	16.9	11,500	P-4
Gen-Tec	DDL-2sh	1.0	6,500	P-5
Gen-Tec	R-200	100.0	17,150	P-6
Jodon Engineering	DD-250	300.0	24,650	P-7
Lumonics	TEA 601a	7.5	27,950	P-8
Lumonics	TEA 604	30.0	111,800	P-9
Lumonics	TEA 620	10.0	52,500	P-10
Lumonics	TEA 622	20.0	105,000	P-11

TABLE 5.2
CW CO₂ LASER PRICE DATA

<u>Manufacturer</u>	<u>Model No.</u>	<u>Average Power, W</u>	<u>Price, \$</u>	<u>Plot ID</u>
Apollo Lasers	X Series	3	4,000	C-1
Apollo Lasers	XF Series	9	7,500	C-2
Advanced Kinetics	MIRL	50	11,500	C-3
Korad	KG 35	50	11,500	C-4
Korad	KG 40	150	18,500	C-5
CILAS	260-7	250	36,250	C-6
Korad	K 645	300	23,000	C-7
CILAS	263	1,000	112,500	C-8
GTE Sylvania	971	1,250	70,000	C-9
United Technologies	-	2,000	120,000	C-10
United Technologies	-	4,000	250,000	C-11
United Technologies	-	8,000	375,000	C-12
Avco	HPL-10	10,000	500,000	C-13

That is, CO₂ laser prices scale with approximately the square root of the average power, and pulsed CO₂ lasers are approximately 2 1/2 times as expensive as CW lasers of the same average power. Assuming that this factor is due entirely to the pulsed laser's far more complicated power supply, it follows that for a new pulsed laser the head will account for 1/3 of the cost and the power supply for 2/3 of the cost.

As in any statistical analysis, there are anomalies. For example, in Fig. 5.1, which is a scatter diagram of CO₂ prices against average power, two pulsed lasers (P-6 and P-7) fall below the CW laser line. This kind of observation does not invalidate the price estimating relationship, but highlights the fact that the available sample is weighted at the higher powers by the heavy-duty CW lasers. It is important to remember that the CO₂ algorithm establishes a price trend for both CW and pulsed lasers at the expense of not accounting for point-by-point differences. This approach is valid until such time as a pulsed CO₂ laser point design can be costed by the traditional industrial engineering approach.

The CO₂ price algorithm may be adjusted for quantity purchases by incorporation of a 90% learning curve* (see discussion of dye laser learning curve factor). The resultant expression is:

$$TP_{CO_2} = 2.216P^{0.512} (1 + 1.426 DVCD)(QCDC)^{.848}$$

where

TP_{CO2} = Total price for QCDC CO₂ lasers

QCDC = Number of CO₂ lasers in LIS system

* The implicit assumption is that regardless of where the manufacturers are on their individual learning curves, they will subsequently sell based upon a 90% learning curve.

Figure 5.1. CO₂ Laser Price Vs. Power

The final expression for TP_{CO_2} is disaggregated to reflect the costs of the laser head and power supply separately in accordance with the relationship mentioned earlier:

$$\frac{\text{Laser Head Price}}{\text{Power Supply Price}} = \frac{1}{2}$$

5.2.2 Replacement Costs

According to a Martin Marietta report,^{*} the flowing CO_2 laser is much less susceptible to leaks and long-term decomposition than a sealed system. The flowing gas also acts as a purge to remove contamination and preclude its entrapment. As a result, except for tube breakage (a rare occurrence, according to the Martin report), the failure mechanism is primarily deterioration of the optics. Based on this reference, we take the mean time between failures (MTBF) of a CO_2 laser to be $3.33 \times 10^6/P$ hours.^{**} The predicted MTBF for the power supply according to the same source is approximately 6,690 hours (based upon MIL-HDBK-217B). "Failure" is broadly defined throughout the study, but seems to correspond to a 10% to 40% degradation in performance. We assume that a "failure" corresponds to a 10% replacement factor--i.e., that 10% of the cost of a laser must be expended every $3.33 \times 10^6/P$ hours, and 10% of the cost of a power supply every 6,690 hours, for replacement costs.

^{*} Laser Reliability Prediction, Martin Marietta Corp., RADC-TR-75-210, August 1975 (UNCLASSIFIED).

^{**} As before, P is power output in watts.

6 RARE GAS HALIDE LASERS

The details of the rare gas halide (RGH) laser design were unavailable at the time the following CERs were developed. A "best estimate" approach was therefore taken to construct the system's WBS, shown below. Reflected in this form of the WBS is the assumption that the RGH laser head resembles that of a flowing gas CO₂ laser and that the power supply is like that employed on the copper vapor lasers.

RARE GAS HALIDE LASER WBS

<u>Equation Number</u>	<u>Component or Function</u>	<u>Capital Costs</u>	<u>Replacement Costs</u>
1.	Laser Head	LHRGC	LHRGR
2.	Power Supply	PSRGC	PSRGR
3.	High Voltage Source	HVRGC	HVRGR
4.	Thyratron	THRGC	THRGR
5.	Pulse Forming Network	PFRGC	PFRGR
6.	Mechanical	MERGC	MERGR
7.	Integration	IPRGC	IPRGR
8.	Assembly and Test	ATRGC	ATRGR

6.1 CERs

6.1.1 Capital Costs

(1) Laser Head

$$LHRGC = 4.83P^{0.512} QRCC^{0.848}$$

(2) - (8) Same as (6) - (12) for copper vapor lasers, Sec. 2

6.1.2 Replacement Costs

(1) Laser Head

$$\text{LHRGR} = 0.75 [4.83P^{0.512} (\text{QRGC} + \text{QLRGR})^{0.848} - \text{LHRCC}]$$

(2) - (8) Same as (6) - (12) for copper vapor lasers, Sec. 2.

6.2 RATIONALE AND DATA

As stated above, the information available to the study concerning rare gas halide lasers was sketchy. The results therefore are somewhat speculative. They are based in large part on what amount to guesses on the part of research staff currently engaged in RGH development. The reader is cautioned to treat these CERS as preliminary.

The general type of RGH laser considered is a flowing gas system. Most of the knowledgeable people consulted agreed that the flowing CO_2 lasers were a fair design analog to the RGH lasers. However, there were also some who strenuously disputed the validity of this analog, primarily on the basis of the different material requirements imposed by the corrosive RGH reactants. The study team was unable to resolve these opposed viewpoints, and selected the CO_2 analog substantially as a majority opinion.

A further assumption about the RGH lasers is that the power supply will be of the same type as that for the copper vapor lasers. For this reason all the power supply CERS are the same as those discussed in Sec. 2.

The CER for the laser head was derived from the CO_2 laser CER discussed in Sec. 5. Since we are dealing only with the RGH laser head, only the CW CO_2 laser components are of interest. To review, the CER for the CW CO_2 laser is:

$$C_{CO_2} = 2.216P^{0.512}$$

where

C_{CO_2} = first-unit cost of CO_2 laser, \$K 1976

P = optical power output, watts

Staff members of Systems Research Laboratories* estimated that RGH lasers would cost two or three times as much as conventional CO_2 lasers. This added cost was meant to account for corrosion resistant material, acoustic dampers, fluorine filtration components, and a make-up gas supply system. We chose a factor of two, since the resulting cost estimates were more in line with previous estimates made by LLL staff and others. This choice was largely arbitrary and could easily result in estimates one-third lower than actuals.

A further modification to the CER was made to account for the different efficiencies of the CO_2 and RGH lasers. Current CO_2 efficiencies are about 6% (output optical power to input electrical power) according to sources at GTE Sylvania. These sources also say that RGH efficiencies may be realized as high as 5% (though 1% was said to be typical of present lasers). The power parameter in the CER was multiplied by the ratio of these efficiencies to reflect the larger device required by RGH to obtain the same output power. The modified CER is thus written:

$$\begin{aligned} C &= (2.216 \times 2) [P(0.06/0.05)]^{0.512} \\ &= 4.43 (0.06/0.05)^{0.512} P^{0.512} \\ &= 4.87 P^{0.512} \end{aligned}$$

* SRL is developing a long-run-time, closed-cycle, high PRF, rare gas electric discharge laser for the Air Force Aero Propulsion Laboratory.

There were insufficient design details available for this laser to estimate what limits might be placed on the range of P. Caution is therefore urged in selecting a value for P.

The learning rate for RGH is expected to be the same 90% as the other types, since there seem to be no peculiar production requirements in its manufacture.

A previously noted Martin Company study indicated that lifetimes of 10,000 hours might be expected for CO₂ lasers. Because of the added corrosiveness of RGH gases, we estimate that the RGH laser lifetime would be one-half of the CO₂ devices. This is a crude estimate which should be studied further.

7 NEODYMIUM:YAG LASERS

At the beginning of the study there was relatively little interest in Nd:YAG lasers as a means to pump the dye lasers. Though theoretical results held promise, it appeared doubtful that such lasers (in the frequency-doubled configuration) could be made powerful enough for the application. Therefore, little effort was made to gather detailed cost data; it was deemed sufficient to use aggregated data to develop an aggregated CER.

Subsequently, however, the interest in frequency-doubled Nd:YAG lasers increased, and greater study resources were directed to this class of lasers. This belated effort produced the partly disaggregated WBS shown below. The individual CERs, however, are largely derived as factors developed from a small data base.

FREQUENCY DOUBLED Nd:YAG LASER WBS

<u>Equation Number</u>	<u>Component or Function</u>	<u>Capital Cost</u>	<u>Replacement Cost</u>
1.	Laser Head	LHNYC	LHNYR
2.	Laser Cavity	LCNYC	LCNYR
3.	Optical Pump and Power Supply	OPNYC	OPNYR
4.	Heat Exchanger	HENYC	HENYR
5.	Q-Switch	QSNYC	QSNYR
6.	Doubling Crystal	DCNYC	DCNYR
7.	Assembly and Test	ATNYC	ATNYR

7.1 CERs

7.1.1 Capital Costs

(1) Laser Head

$$LHNYC = LCNYC + OPNYC + HENYC$$

(2) Laser Cavity

$$LCNYC = 0.86 (P/DEFF)^{0.49} QNYC^{0.848}$$

(3) Optical Pump and Power Supply

$$OPNYC = 0.50 (P/DEFF)^{0.49} QNYC^{0.848}$$

(4) Heat Exchanger

$$HENYC = 0.65 (P/DEFF)^{0.49} QNYC^{0.848}$$

(5) Q-Switch

$$QSNYC = 5.5 (NQS \cdot QNYC)^{0.848}$$

(6) Doubling Crystal

$$DCNYC = 5.0 QNYC^{0.848}$$

(7) Assembly and Test

$$ATNYC = 0.15 (LHNYC + QSMYC + DCNYC) QNYC^{0.765}$$

7.1.2 Replacement Costs

(1) Laser Head

$$LHNYR = LCNYR + OPNYR + HENYR$$

(2) Laser Cavity

$$LCNYR = [0.86 (P/DEFF)^{0.49} (QNYC + QLNYR)^{0.848}] - LCNYC$$

(3) Optical Pump

$$OPNYR = 0.8[0.5(P/DEFF)^{0.49} (QNYC + QONYR)^{0.848} - OPNYC]$$

(4) Heat Exchanger

$$HENYR = 0 \quad (\text{No expected heat exchanger failures})$$

(5) Q-Switch

$$QSNYR = 5.5 [NQS \cdot QNYC + QQNYR]^{0.848} - QSNYC$$

(6) Doubling Crystal

$$DCNYR = 5.0 (QNYC + QDNYR)^{0.848} - DCNYC$$

(7) Assembly and Test

(not applicable)

7.2 RATIONALE AND DATA

The development of a Nd:YAG laser CER was based on the assumption that LIS lasers can be scaled from commercially available models. The development was conducted in three steps. First an aggregated CER was derived from supplier price data. The resulting CER gives the cost as a function of power output at 1.06 μm (undoubled) for CW lasers which are not Q-switched. Next, a first-level disaggregation was performed, based on limited data, and the resulting factors applied to the CER. In the last step, the cost of the Q-switch and the cost of the frequency doubler were estimated independently and added to that of the laser head. This development is reflected in the WBS.

The laser head C&R was the result of regression analysis on the data tabulated in Table 7.1 and plotted in Fig. 7.1. These data were obtained from the Laser Focus 1976 buyer's guide. Only non-Q-switched, CW lasers are included. Other lasers have components which either are not relevant to the LIS requirements or are accounted for in the other elements of the WBS. The regression line for these data has the following equation:

$$C = 2.33 P^{0.49}$$

where

C = cost of Nd:YAG laser, \$K 1976

P = output power (at $\lambda = 1.06 \mu\text{m}$), watts

This CER aggregates the cost of the laser cavity, the optical pump, and the heat exchanger, as noted in the WBS formulation. Numerous attempts were made to obtain cost data from laser manufacturers which would permit an apportionment of laser head costs over these components, all unsuccessfully. Finally, the factors used to disaggregate the costs were developed from ERDA data and an industrial user of lasers. These data, somewhat reorganized, are shown in Table 7.2. The user source asked not to be identified in order to protect his proprietary interests.

Notice that the cost reported by LASL for the ILS laser is much higher in aggregate than the previous CER would estimate. This is because the ILS laser is a specially designed, low-repetition-rate laser with high energy per pulse. The LASL data were used to develop the relative factors for the laser cavity and optical pump, since these two components were combined in the other data. Notice also that the heat exchanger cost is much lower for the ILS laser because of its low average power. For the higher-powered devices, the heat exchanger costs scale reasonably well by the same power of P as the aggregate CER. This scaling is given by the expression:

TABLE 7.1

CW Nd:YAG LASER PRICE DATA

<u>Supplier</u>	<u>Identifier</u>	<u>Power, W</u>	<u>Price, \$K 1976</u>
Holobeam	255	25	10
	256	50	13
	2550-1R	125	15 (est.)
	2550-2R	250	26 (est.)
	2550-3R	375	40 (est.)
	2550-4R	500	51 (est.)
	2550-5R	625	64 (est.)
	2550-6R	750	76 (est.)
	2550-7R	875	88 (est.)
	2550-8R	1,000	100 (est.)
Quantronix	260T	200 (est.)	20
	114-21	100	16
	115-1	8	8
	114-1	40	12
	114-2	50	15
GTE Sylvania	612	200	20
	606	5	4.3
	607	8	5.5
Korad	KY3	20	12.75
	KY5	40	21.945
Garching Instrumente	YAL-216	10	12 (DM 30K)
	YAL-22	50	17.6 (DM 44K)
	RL-22a	0	20 (DM 50K)
Laser Technique	255	25	7.26 (Fr 33K)
	256	50	9.68 (Fr 44K)
Control Laser	510	30	9.25
	512	50	11.7

Figure 7.1. CW Nd:YAG Laser Price Data

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TABLE 7.2
DISAGGREGATION OF Nd:YAG LASER COSTS

Data Source	LASL	LLL	User
Laser Manufacturer	International Laser Systems	GTE Sylvania model 612	Hughes
Power output, W			
Costs			
Laser Head			
Laser Cavity	*** PROPRIETARY DATA DELETED ***		
Optical Pump			
Heat Exchanger			
Q-Switch			

$$C_{HE} = 0.75 P^{0.49}$$

The laser cavity and optical pump make up the remaining costs. We find their combined CER as follows:

$$C = C_{LC} + C_{OP} + C_{HE}$$

$$2.33P^{0.49} = (C_{LC} + C_{OP}) + 0.75 P^{0.49}$$

therefore

$$C_{LC} + C_{OP} = (2.33 - 0.75) P^{0.49} = 1.58 P^{0.49}$$

From the LASL data we deduce that the laser cavity costs 1.67 times as much as the optical pump. Solving for the individual terms, we obtain

$$C_{LC} = 0.99 P^{0.49}$$

and

$$C_{OP} = 0.59 P^{0.49}$$

In the development of these CERs we have assumed that the laser cavity and the optical pump both scale with the 0.49 power of P. Although it seems quite reasonable that they would, available data does not specifically support the assumption.

The CER for replacement cost of the laser head was derived from results in the referenced study of laser reliability, which concluded that the laser cavity and heat exchanger had indefinite lifetimes. The replacement costs for these components are thus estimated to be zero. The lamps in the optical pump are quite another matter.

The usual operating mode for high-repetition-rate Q-switched lasers is to run the lamps continuously. In this mode, the lamp lifetime is estimated at 500 hours. Hughes staff members estimate that advanced designs may achieve 1,000 hours. The higher estimate was used.

The cost of the Q-switch was estimated from the data in Table 7.2 and from price information in the 1976 Laser Focus buyer's guide. In the buyer's guide, a wide variety of acoustic-optical Q-switches are listed, at prices from \$1,000 to over \$6,000. It was determined that the LIS requirements for pulse control, rise time, and pulse width would necessitate the higher-priced switches. This is substantiated by the data in Table 7.2; for the two lasers in that table that used Q-switches, the costs varied from \$5 to 7K.* The choice was made to use a \$6,000 estimate for the LIS application. This was then reduced by 10% to account for integration and rounded to \$5,500, the number used in the final CER. Provision is also made in the CER for incorporating more than one Q-switch in the system.

*The GTE Sylvania laser system employed two Q-switches at \$7,000 each.

The lifetime of the Q-switch is estimated at 8,000 hours (approximately 1 year), based on information from suppliers, a Hughes estimate, and the referenced Martin report.

The frequency doubler is a component whose costs can only be surmised. At present, only the Hughes design is sufficiently developed to be a candidate for a LIS production plant. The Hughes staff were unwilling to estimate its cost, for proprietary reasons. They did, however, provide an aggregated estimate for a laser system that included their frequency doubler. This system was estimated to cost ***

*** PROPRIETARY DATA DELETED***

One staff member at Hughes also volunteered that, once perfected, their doubler would not be appreciably more costly than somewhat similar commercially available designs. For example, Quantum Technology Ltd. sells a frequency doubler for \$3,000. Since the Hughes device is an acousto-optical component, it seems reasonable that the Q-switches discussed above might also be a fair analog for cost estimating. In that case, the cost could be \$5 to 7K. A compromise estimate of \$5,000 was used as the final CER.

The replacement cost of the doubling crystal is based on an estimated 3,000 hour life, derived from discussions at Hughes and an assessment that the more critical geometry of the doubling crystal would shorten its life compared to an equivalent Q-switch. This is a very rough estimate.

The capital cost CERs discussed above were derived from data on components which were fully assembled and tested. Since assembly and test costs were estimated separately at 15%, each CER was adjusted downward by the 15% factor. For example, the final CER for the heat exchanger is:

$$C_{HE} = 0.65 P^{0.49}$$

rather than

$$C_{HE} = 0.75 P^{0.49}$$

which includes assembly and test costs.

A final adjustment to the CERs enables the user to relate cost to the power output at 0.53 μm wavelength rather than 1.06 μm . This is accomplished by simply dividing the output power at 0.53 μm by the efficiency of the doubling crystal, DEFF. The heat exchanger CER, for example, thus becomes

$$C_{HE} = 0.65 (P/DEFF)^{0.49}$$

8 OPTICAL AND MISCELLANEOUS COMPONENTS

This category includes the optical components which condition the laser beams and transport them from place to place within the system. The conditioning function has three constituents: control of the laser beam angle, wavelength, and pulse train timing. Each of these functions is highly specialized to the LIS application and much research is still necessary to determine the extent to which each will be required in a production LIS plant. In the absence of the final specification, the following WBS and CERs are based on characteristics of the SPP II experimental configuration.

OPTICAL AND MISCELLANEOUS COMPONENT WBS

<u>Equation Number</u>	<u>Component or Function</u>	<u>Capital Cost</u>	<u>Replacement Cost</u>
1.	Beam Combining and Turning	BCOCC	BCOCR
2.	Mirrors	MIOCC	MIOCR
3.	Coatings	COOCC	COOCR
4.	Mounts	MOOCC	MOOCR
5.	Expanders	EXOCC	EXOCR
6.	Dichroic element	DIOCC	DIOCR
7.	Beam Alignment	BAOCC	BAOCR
8.	Sensor	SEOCC	SEOCR
9.	Gimbal Mechanism	GMOCC	GMOCR
10.	Electronics	ELOCC	ELOCR
11.	Wavelength Control	WCOCC	WCOCR
12.	Acquisition	ACOCC	ACOCR
13.	Control	CNOCC	CNOCR
14.	Timing Control	TCOCC	TCOCR
15.	Chamber Windows	CWOCC	CWOCR
16.	Space Frame	SFOCC	SFOCR

8.1 CERS

8.1.1 Capital Cost

(1) Beam Combining and Turning

$$BCOCC = MIOCC + COOCC + MOOCC + EXOCC + DIOCC$$

(2) Mirrors

$$MIOCC = 6.22 \times 10^{-3} DM^{1.615} (NMW \cdot QLT)^{0.926}$$

(3) Coatings

$$COOCC = 0.286 \times 10^{-3} DM^{1.89} (NMW \cdot QLT)^{0.485}$$

(4) Mounts

$$MOOCC = 0.015 DM^{0.9} (NMW \cdot QLT)^{0.765}$$

(5) Expanders

$$EXOCC = 0.17 DEA^{1.37} (2 \cdot QSC)^{0.926} (DCDL)$$

(6) Dichroic Element

$$DIOCC = 0.1 DD^2 QSC^{0.926} (DCDL)$$

(7) Beam Alignment

$$BAOCC = SEOCC + GMOCC + ELOCC$$

(8) Sensor

$$SEOCC = 3.7 (QLT)^{0.848}$$

(9) Gimbal Mechanism

$$GMOCC = 1.8 QLT^{0.848}$$

(10) Electronics

$$ELOCC = 0.6 QLT^{0.848}$$

(11) Wavelength Control

$$WCOCC = ACOCC + CNOCC$$

(12) Wavelength Acquisition

$$ACOCC = 117 (QLT/NAS)^{0.848}$$

(13) Control

$$CNOCC = 21 QLT^{0.848}$$

(14) Timing Control

$$TCOCC = 10.6 QDLC^{0.848}$$

(15) Chamber Windows

$$CWOCC = 7.1 (NCW \cdot QSC)^{0.926} (0.07 + .93 DCCL)$$

(16) Space Frame

$$\text{SFOCC} = 29.6 \text{ QSC}^{0.687}$$

8.1.2 Replacement Costs

(1) Beam Combining and Turning

$$\text{BCOCR} = \text{MIOCR} + \text{COOCR} + \text{MOOCR} + \text{EXOCR} + \text{DIOCR}$$

(2) Mirrors

$$\text{MIOCR} = 0.5 [6.22 \times 10^{-3} \text{ DM}^{1.615} (\text{NMW} \cdot \text{QLT} + \text{QMIRR})^{0.926} - \text{MIOCC}]$$

(3) Coatings

$$\text{COOCR} = 0.28 \times 10^{-3} \text{ DM}^{1.89} (\text{NMW} \cdot \text{QLT} + \text{QCOTR})^{0.485} - \text{COOCC}$$

(4) Mounts

$$\text{MOOCR} = 0 \text{ (No replacement of mounts is required during system lifetime)}$$

(5) Expanders

$$\text{EXOCR} = 0.5 \{0.17 \text{ DEA}^{1.37} (2 \cdot \text{QSC} + \text{QEXPR})^{0.926} (\text{DCDL})\} - \text{EXOCC}$$

(6) Dichroic Elements

$$\text{DIOCR} = 0.1 \text{ DD}^2 (\text{QSC} + \text{QDICR})^{0.926} \text{DCDL} - \text{DIOCC}$$

(7) Beam alignment

$$BAOCR = SEOCR + GMOCR + ELOCR$$

(8) Sensor

$$SEOCR = 3.7 (QLT + QSENR)^{0.848} - SEOCC$$

(9) Gimbal Mechanism

$$GMOCR = 1.8 (QLT + QGIMR)^{0.848} - GMOCC$$

(10) Electronics

$$ELOCR = 0.6 (QLT + QELER)^{0.848} - ELOCC$$

(11) Wavelength Control

$$WCOCR = ACOCR + CNOCR$$

(12) Wavelength Acquisition

$$ACOCR = 0.5 [117 (QLT/NAS + QACQR)^{0.848} - ACQCC]$$

(13) Control

$$CNOCR = 0.5 [21 (QLT + QCTLR)^{0.848} - CNOCC]$$

(14) Timing Control

$$TCOCR = 0.5 [10.6 (QDLC + QTIMR)^{0.848} - TCQCC]$$

(15) Chamber Windows

$$\text{CWOCR} = 0.5 \{7.1(\text{NCW} \cdot \text{QSC} + \text{QWINR})^{0.926} (0.07 + 0.93 \text{DCDL}) - \text{CWOCCL}\}$$

(16) Space Frame

SFOCR = 0 (No replacement of space frame is required during system lifetime)

8.2 RATIONALE AND DATA

The CERs for most of the optical and miscellaneous components are of a very preliminary nature. This is due primarily to the fact that there is no detailed definition of these components and their functions. Until more research is conducted on the LIS process, it will not be known whether current requirements for these components can be relaxed or must be more stringent; or indeed whether certain components will be required at all. Our approach therefore was to use the configuration and cost estimates for the SPP II system, taking into account wherever possible the differences between SPP II and a production LIS plant.

The cost of mirrors was estimated from the catalog data shown in Fig. 8.1, which are appropriate for the kind of mirrors expected to be required in the LIS system. A straightforward regression of these data led to the CER:

$$C = 6.22 \times 10^{-3} \text{DM}^{1.615}$$

where

DM = mirror diameter, cm

Figure 8.1. Flat Mirror Price Vs. Mirror Diameter

Mirror lifetimes have been variously estimated from 5,000 hours to "indefinite." Based on conversations with staff at Aerojet and information in the referenced Martin reliability study, a value of 15,000 hours was chosen. At such intervals, it was determined that the mirrors would be refurbished at a cost equal to half of their original cost.

The cost of mirror coatings is based on data from Optical Coating Laboratory, Inc., and Perkin-Elmer. The coating cost is small, as is apparent from the CER and furthermore, the learning rate is very high (69%). The cost impact on the system is almost negligible. The lifetime of the coating is estimated to be equal to that of the mirror, i.e., 15,000 hours.

Mount costs are based on price data from numerous suppliers. The type of mount under consideration is a precision laboratory-style mount with minimal provision for adjustment.

Beam expanders are included in the CO_2 laser system in order to reduce the incident flux on the dichroic element that this system includes. In systems without CO_2 lasers, the flux levels are low enough that the beam combination can be accomplished without expansion, thus saving the associated cost. Note that two expanders are required, one to expand the beam before it strikes the dichroic element, and another to reduce it afterward. The CER for expanders is based on the data shown in Fig. 8.2.

The dichroic element is another component required only if a CO_2 laser is used. The CER is based on a single point estimate of a zinc selenide high-energy laser window costing about \$560K. This window had a diameter of 75 cm. The scaling was assumed to go as the area of the element (or the square of the diameter), thus giving the CER:

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Figure 8.2. Price of Beam Expanders (Laser Collimators and Various Lenses)

$$C = 0.1 \text{ DD}^2$$

The beam alignment, the wavelength control, and the timing control components were all estimated at constant values. These values were taken directly from SPP II working notes obtained from LLL staff. As the system becomes better defined, more complete parametric relationships can be derived.

APPENDIX A

COST/QUANTITY VARIATIONS

The CERs discussed in this report estimate the cost of the "first unit" of a production run. In producing almost any article, the cost per article drops as more are produced. There are many reasons. Some have to do with the cost of raw material; when buying in larger quantity, the manufacturer can obtain discounts. Others have to do with the manufacturing process; as more articles are produced, the workers become more experienced and efficient. Shortcuts are discovered, innovations are applied, scrap factors are reduced, the number of rejects declines, specialized tools are used, and a host of other effects make their impact.

Still others have to do with the market, the competition, and the accounting methods of the producer. If, for example, a company cannot be assured of a substantial order for a newly developed product, it will try to recoup the development costs by raising the price of the first production articles. If the market and competition are such that nearly any price can be charged, then the entire development may be written off against the first few articles. Then, if orders continue to come in, that much extra profit can be realized--or, as is more usual, the price can be reduced to forestall inroads by the competition.

As might be expected, these effects are highly interactive. In most system-level studies (including this one) these effects are treated in aggregate. The average cost per unit is treated as a decreasing function of quantity in the form

$$C_Q = C_1 Q^b$$

where

C_Q = Cumulative average cost of articles produced in quantity Q

C_1 = Cost of the first article

Q = Quantity

b = Derived constant (negative valued)

This expression produces what is commonly referred to as a "learning curve," although--as discussed above--the effect which is modeled encompasses much more than just learning.* The formulation of learning effects in this form is empirical. The exponent is usually derived by fitting historical cost/quantity data.

It is important to note that technology effects are not taken into account in the derivation of learning curves. Every effort is made to separate those effects which result in lower costs for items of the same type from those effects which result in a reduced cost per unit performance as a result of technology advance. This separation is sometimes difficult, since technology advance and continued production are occurring simultaneously. Since these are distinctly different effects, it is incumbent upon the analyst to estimate their cost consequences independently.

The slope of the learning curve is given by convention in terms of a "learning rate," defined as the amount by which the cost is reduced when the quantity produced doubles. For example, if the first unit costs \$100 and the average cost of the first two units is \$90, then this product has a 0.90 learning rate. The learning rate is related to the exponent in the cost/quantity equation by

*The original development of learning curves addressed only the man-hours of labor expended on the direct production articles. The concept of learning curves has since been more broadly applied to the total recurring cost of production.

$$b = \log (\text{learning rate}) / \log 2$$

The cost/quantity equation was given above in "cumulative average" form. The total cost of Q items is given by the same equation multiplied by Q; that is, with the exponent b increased by 1:

$$C_T = (C_1 Q^b) Q = C_1 Q^{1+b}$$

which has the same form as the cumulative average equation.

The table below gives some examples of common learning rates and the corresponding exponents for cumulative average and total costs.

<u>Learning Rate</u>	<u>Cumulative Average Exponent (b)</u>	<u>Total Cost Exponent (1+b)</u>
0.98	-0.029	0.971
0.95	-0.074	0.926
0.93	-0.105	0.895
0.90	-0.152	0.848
0.87	-0.201	0.799
0.85	-0.234	0.766
0.80	-0.322	0.678
0.75	-0.415	0.585

On a strictly qualitative basis, the relative incidence of learning rates for equipment such as that used in MIS systems is as follows:

<u>Learning Rate</u>	<u>"Degree" of Learning</u>	<u>Relative Incidence</u>
0.98	Very slow learning	Very few instances
0.95	Slow learning	Few instances
0.90	Nominal learning	Most instances
0.85	Nominally fast learning	Many instances
0.80	Fast learning	Few instances
0.75	Very fast learning	Very few instances

GLOSSARY

Symbols for the dependent variables (costs) in the CERs are defined in Sec. 1.6 and are not included here.

The symbols for the independent variables in the CERs fall into three groups: technical and performance parameters, quantities procured, and component lifetime parameters. All are defined in this Glossary; nominal values are given in [square brackets] where applicable. Definitions are in the order of appearance in the text. Note that the component lifetime parameters do not appear directly in the CERs given in the text, but only in the defining equations given here for replacement quantities.

TECHNICAL AND PERFORMANCE PARAMETERS

P	laser output power, W
VEFF	laser volume efficiency, W/cm^3 {0.05(CV), 0.10(CH)}
PE	Power supply output power, W
V	power supply output voltage, V
FA	thyatron anode heating factor, $10^9 \text{ V}\cdot\text{A/s}$
FV	thyatron peak voltage, kV
DVTH	thyatron liquid cooling, 1 = yes, 0 = no
NTH	number of thyatrons per laser power supply [usually 1]
EC	cost for electronic components of PFN, \$K [0.45]
SE	stored energy per capacitor in PFN, J
NC	number of capacitors in PFN = $2^{\log_{10} \text{LCA/LNOM}}$
ME	cost for mechanical components of power supply, \$K [1.4]
DVCD	CO_2 laser pulsing, 1 = yes, 0 = no
DEFF	efficiency of frequency-doubling crystals for Nd:YAG laser [0.4]
NQS	number of Q-switches per Nd:YAG laser [1 or 2]
DM	mirror diameter, cm
NMW	number of mirrors per laser train
NW	number of wavelengths used
NSTG	number of stages per LIS module [3 typical]

QUANTITIES PROCURED

QCVC	copper vapor lasers
QCHC	copper halide lasers
QDLC	dye lasers
QCDC	carbon dioxide lasers
QRGC	rare gas halide lasers
QNYC	neodymium:TAG lasers
QLT	laser trains (= QSC $\times$ NW)
QSC	separation chambers (= NSTG $\times$ NMOD)

QLCVR laser cavities, CV	= (LLIS·FOP/LLH)QVCV
QQCVR optics, CV [*]	= (LLIS·FOP/LC ²)QVCV
QHCVR high-voltage sources, CV ^{**}	= (LLIS·FOP/LHV)QVCV
QTCVR thyratrons, CV ^{**}	= (LLIS·FOP/LTH)QVCV·NTH
QECVR electronic components of PFN, CV ^{**}	= (LLIS·FOP/LEC)QVCV
QCCVR capacitors in PFN, CV ^{**}	= (LLIS·FOP/LCA)QVCV·NC
QMCVR mechanical components of power supply, CV ^{**}	= 0.05 QVCV
QLCHR laser cavities, CH	= (LLIS·FOP/LLH)QCHC
QLDLR laser heads, DL	= (LLIS·FOP/LLH)QDLC
QLCDR laser heads, CD	= (LLIS·FOP/MTBFH)QCDC·RFCDH

** And CH and RG, with QCHC or QRGC substituted

QPCDR power supplies, CD	= (LLIS·FOP/MTBFP)QCDC·RFCDP
QLRGR laser heads, RG	= (LLIS·FOP/LLH)QRGC
QLNYR laser cavities, NY	= (LLIS·FOP/LLH)QNYC
QONYR optical pumps, NY	= (LLIS·FOP/LL)QNYC
QQNYR Q-switches, NY	= (LLIS·FOP/LQS)QNYC·NQS
QDNYR doubling crystals, NY	= (LLIS·FOP/LDC)QNYC
QMIRR mirrors	= (LLIS·FOP/LMIR)QLT·NMW
QCOTR coatings	= (LLIS·FOP/LCT)QLT·NMW
QEXPR beam expanders (CD only)	= (LLIS·FOP/LEX)QSC·2
QDICR dichroic elements (CD only)	= (LLIS·FOP/LDI)QSC
QSENR alignment sensors	= (LLIS·FOP/LSN)QLT
QGIMR alignment gimbal sets	= (LLIS·FOP/LGM)QLT
QELER alignment electronics	= (LLIS·FOP/LEL)QLT
QACQR wavelength acquisition	= (LLIS·FOP/LAC)QLT·NAS
QCTLR wavelength control	= (LLIS·FOP/LCN)QLT
QTIMR timing control	= (LLIS·FOP/LTC)QDLC
QWINR chamber windows	= (LLIS·FOP/LCW)QSC·NCW

COMPONENT LIFETIME PARAMETERS [hours]

LLIS	system [130,000 (15 yr)]
FOP	fraction of time system is operating [0.9--fraction, not hours]
LLH	laser head [5,000(CV), 10,000(CH), 15,000(DL), 10,000(RG), 13,000(NY)]
LQP	optics [18,000]
LHV	high-voltage source [75,000]
LTH	thyatron [1,000 × NTH]
LEC	electronic components of PFN [65,000]
LCA	desired capacitor lifetime in PFN
LNOM	nominal capacitor lifetime [278/PRF (10 ⁶ shots)]
MTBFH	laser head (between failures), CO ₂ laser [3.33 × 10 ⁶ /P]
MTBFP	power supply (between failures), CO ₂ laser [6,692]
RFCDH	laser head (replacement factor), CO ₂ laser [0.1--fraction, not hours]
RFCDP	power supply (replacement factor), CO ₂ laser [0.1--fraction, not hours]

LL	optical pump (lamp) for Nd:YAG laser [1,000]
LQS	Q-switch for Nd:YAG laser [8,000]
LDC	doubling crystal for Nd:YAG laser [3,000]
LMIR	mirror [15,000]
LCT	mirror coating [15,000]
LEX	beam expander for CO ₂ laser [15,000]
LDI	dichroic element for CO ₂ laser [15,000]
LSN	alignment sensor [8,000]
LGM	alignment gimbal set [15,000]
LEL	alignment electronics [15,000]
LAC	wavelength acquisition system [4,000]
LCN	wavelength control system [4,000]
LTC	timing control system [8,000]
LCW	chamber window [15,000]

NOTICE

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