U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

AD-A016 437

LASER RELIABILITY PREDICTION

MARTIN MARIETTA AEROSPACE

PREPARED FOR
ROME AIR DEVELOPMENT CENTER

AUGUST 1975

This information product distributed by

NTIS U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161

RADC-TR-75-210
Final Technical Report
August 1975

LASER RELIABILITY PREDICTION

Martin Marietta Aerospace

Approved for public release;
distribution unlimited.

Rome Air Development Center
Air Force Systems Command
Griffiss Air Force Base, New York 13441

This report has been reviewed by the RADC Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

This technical report has been reviewed and approved for publication.

APPROVED:

PAUL H. WENDZIKOWSKI, Capt., USAF
Project Engineer

APPROVED:

RUDOLF C. PALTAUF, Lt Col., USAF
Chief, Surveillance Division

FOR THE COMMANDER:

JOHN P. HUSS
Acting Chief, Plans Office

Do not return this copy. Retain or destroy.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER RADC-TR-75-210	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) LASER RELIABILITY PREDICTION		5. TYPE OF REPORT & PERIOD COVERED Final Technical Report 27 Dec 73 - 28 Feb 75
		6. PERFORMING ORG. REPORT NUMBER OR 13,667
7. AUTHOR(s) T. R. Gagnier E. W. Kimball R. R. Selleck		8. CONTRACT OR GRANT NUMBER(s) F30602-74-C-0091
9. PERFORMING ORGANIZATION NAME AND ADDRESS Martin Marietta Aerospace P. O. Box 5837 Orlando FL 32805		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62702F 55190269
11. CONTROLLING OFFICE NAME AND ADDRESS Rome Air Development Center (OCTM) Griffiss AFB NY 13441		12. REPORT DATE August 1975
		13. NUMBER OF PAGES 116
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Same		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE N/A
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release. Distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) Same		
18. SUPPLEMENTARY NOTES RADC Project Engineer: Capt Paul H. Wendzikowski (OCTM)		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Laser Reliability; Laser Reliability Prediction Models; Laser Reliability Data; Life Characteristics; Failure Mechanisms; Design Criteria; Manufacturing Problems; Quantitative Math Models; Failure Rates		

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of a program to locate, collect, and analyze laser reliability data, to construct laser reliability models, and to prepare revision sheets suitable for inclusion as a revision of Section 2.4, Lasers, in Mil-HDBK-217B. The report describes the methodology, analyses, models, failure rates, factors, and ground rules involved in the effort. It summarizes 10 million item-hours and 4 billion item-pulses of operating data collected from a sample of 1321 lasers, 2206 laser diodes, and 1750 laser subassemblies.

cont'd

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Lasers discussed in detail include argon ion, flowing CO_2, sealed CO_2, dye, helium/cadmium, helium/neon, heterojunction, gallium arsenide injection, solid state, and transversely excited atmospheric pressure lasers. Major laser subassemblies, parts, and components are also included. In addition, the discussion covers failure modes and mechanisms; design criteria and notes; manufacturing criteria, problems, and burn-in; quantitative math models; failure rates; and life characteristics. A detailed bibliography and a list of data sources and contributors are included.

PREFACE

This final technical report was prepared by the Orlando Division of Martin Marietta Corporation, Orlando, Florida, under Contract No. F30602-74-C-0091 and Job Order No. 55191078. This report is submitted as the data item input for CDRL Sequence No. A003. It covers the period from January 1974 to April 1975.

This report was prepared under the direction of Mr. T. R. Gagnier. Major technical contributors were T. R. Gagnier, E. W. Kimball, and R. R. Selleck. Additional technical support and advice were received from D. F. Cottrell, N. Johnson, T. E. Kirejczyk, T. Romans, E. Sonnenshine, and E. L. Weaver. The RADC Project Engineer was Capt. Paul Wendzikowski.

CONTENTS

SYMBOLOGY

SYMBOL	MEANING
ADP	Ammonium dihydrogen phosphate
A/O	Acousto-optical
AR	Anti-reflective
BeO	Beryllium oxide
CdTe	Cadmium telluride
CDA	Cesium dihydrogen arsenate
CD*A	Deuterated cesium dihydrogen arsenate
CO	Carbon monoxide
CO_2	Carbon dioxide
CW	Continuous wave
DDC	Defense Documentation Center
DF	Deuterium fluoride
DoD	Department of Defense
DMSO	Dimethyl sulfoxide
E/O	Electro-optical
FTIR	Flustrated total internal reflection
GaAs	Gallium arsenide
GaAlAs	Gallium aluminum arsenide
He	Helium
HF	Hydrogen fluoride
HDBK	Handbook
Hr	Hour(s)
KCl	Potassium chloride
KDP	Potassium dihydrogen phosphate
KD*P	Deuterated potassium dihydrogen phosphate
KHz	Kilohertz
Kw	Kilowatts
LCL	Lower confidence limit
LED	Light emitting diode
$LiIO_3$	Lithium iodate
$LiNbO_3$	Lithium niobate
λ	Lambda or failure rate
mA	Milliamperes
MgF_2	Magnesium fluoride
MIL	Military
MTBF	Mean-time-between-failures
mW	Milliwatts
MW	Megawatts
NaCl	Sodium chloride
N.A.	Not applicable
NASA	National Aeronautics and Space Administration

Nd	Neodymium
Nd:Glass	Neodymium doped glass rod
Nd:YAG	Neodymium doped yttrium-aluminum-garnet rod
Ne	Neon
nm	Nanometer
ns	Nanosecond
N_2	Nitrogen
N_2O	Nitrous oxide
PFN	Pulse forming network
pps	Pulses per second
PR	Partially reflective
RADC	Rome Air Development Center
R6G	Rhodamine 6G dye
SHG	Second harmonic generators
TEA	Transversely excited atmospheric pressure
TR	Totally reflective
UCL	Upper confidence limit
μm	Micrometer or microns
W	Watts
YAG	Yttrium-aluminum-garnet
Yr	Year
ZnS	Zinc sulfide
ZnSe	Zinc selenide

FIGURES

TABLES

EVALUATION

Project No: 5519
Contract No: F30602-74-C-0091
Effort Title: Laser Reliability Prediction
Contractor: Martin Marietta Aerospace, Orlando, Florida

This contractual program was the first major effort within the DoD to address the area of laser reliability using the standard reliability engineering methods of collecting failure and lifetime data, analyzing the data, and formulating quantitative reliability prediction models based on the data. In this way, models have been constructed for the six laser types which comprise over 90 percent of the total number of lasers presently in use. This kind of quantitative answer to the question of laser reliability has a great and ever increasing significance to the DoD in view of the multiplying numbers of lasers and laser applications and the need to conserve resources through greater system reliability.

The impetus for this effort was the need to revise and expand sections of Mil-HDBK-217B, "Reliability Prediction of Electronic Equipment", a DoD Military Standardization Handbook prepared by RADC which will now include the laser reliability models developed here. This area of emphasis is covered in the RADC Technology Planning Objective Number 13, "Reliability".

Paul H. Wendzikowski

PAUL H. WENDZIKOWSKI
Capt USAF
Project Engineer

1.0 INTRODUCTION

Although the commercial, medical, military, and aerospace use of lasers has increased tremendously in the last decade, no standard reference for laser reliability prediction methods, models, and failure data has been assembled to date. Mindful of the importance of lasers to the DoD operational inventory and desiring to obtain comprehensive and current quantifications of laser reliability, Rome Air Development Center (RADC) awarded a contract to Martin Marietta in December 1973:

"LASER RELIABILITY PREDICTION"
Contract Number F30602-74-C-0091

The purpose of the contract was to formulate models for predicting the failure rates of coherent light emitting devices such as lasers and laser diodes. Such models have been constructed, exercised, and validated. They will facilitate reliability assessment based on device type, complexity, application, stresses, operational environment, or other significant influence factors. This report details the results of the contractual effort by providing a complete listing of the data collected by laser item type, discusses the methodology for data analysis and modeling, and gives the assumptions and procedures followed for constructing laser reliability prediction models and failure rate data suitable for future incorporation into Section 2.4 of MIL-HDBK-217B.

2.0 SUMMARY

This report comprises the results of a 15-month program conducted by Martin Marietta Corporation. The purpose of the program was to locate collect, and analyze laser reliability data, to construct laser reliability prediction models, and to prepare revision sheets suitable for inclusion as Section 2.4, Lasers, of MIL-HDBK-217B. The actual revision sheets to Section 2.4 have been provided as Section 6.0 of this report.

The information used to prepare the future revision for Section 2.4 was obtained as a result of an extensive data collection program. This program extended to laser manufacturers, aerospace contractors, government facilities, research organizations, and educational institutions throughout the United States and Canada. The collected laser data were grouped, analyzed, and statistically tested for homogeneity before being combined. In addition, two-sided limits of the 90 percent confidence interval were calculated for all laser component data under evaluation and for which greater than zero failures were observed. This report contains a complete component type listing of the data used to generate the operating failure rates for Section 2.4.

More than 10 million item-hours and 4 billion item-pulses of operating data have been collected from a sample of 1321 lasers, 2206 laser diodes, and 1750 laser subassemblies. The data cover over 50 major laser items, components, subassemblies, and assemblies. A new determination of laser life characteristics has been made with analysis concentrated on the yttrium-aluminum-garnet, argon ion, helium/neon, helium/cadmium, carbon dioxide, and ruby types which comprise greater than 90 percent of the total number of lasers presently in use.

3.0 DATA COLLECTION

3.1 Literature Review

Data have been collected by Martin Marietta from more than 200 contractors, institutions, and government agencies. A comprehensive literature review of approximately 300 documents was also made to obtain laser information and data pertinent to this study. The majority of these documents were obtained from Defense Documentation Center (DDC), RADC, NASA, and other government installations or agencies. Documents were also obtained from several private contractors, vendors, research institutions, educational institutions, and other nongovernment sources.

The primary source was DDC from which classified bibliographies, microfiche, microfilm, and technical reports were obtained. These materials were reviewed for data, and appropriate documents were requested for additional review. All pertinent documents obtained from DDC, as well as those obtained from other sources, are listed in the bibliography of this report.

3.2 Data Source Contacts

Approximately 400 potential data sources were initially contacted by letter questionnaires in which personnel were requested to describe any laser component life test or laser system field data that they may have accumulated in the past 5 years.

The responses were reviewed and a determination made of all those sources which appeared to have pertinent data. Each of these sources was then contacted by telephone. Useful data were subsequently obtained by a telephone request or by personal visits.

A summary of the 200 sources contributing to this study program is shown in Appendix A.

4.0 LASER FAILURE MODE MECHANISM DATA AND RELIABILITY DESIGN NOTES

Laser failure mode and mechanism data together with some design note information were obtained from telephone conversations and visits to major component and system manufacturers as well as from a broad cross-section of users. The objective of this comprehensive industry survey was to identify problem areas and, wherever possible, suggest methods to improve reliability of future laser systems. The collected failure mode and mechanism data for the various laser categories are presented in the following sections. Table 4.0-I presents a summary of the kind of information which was collected.

4.1 Argon Ion Lasers

Argon ion lasers have not been used extensively by the military services; they have, however, a number of commercial and research applications. Among the most important of these are detached retina photocoagulators, dye pumping, spectroscopy, holography, optical memories, and medical research. Typical power output for these lasers range from 200 mW to greater than 10 watts.

The major failure modes with argon ion and other gas lasers are envelope integrity problems, outgassing, and diffusion. A primary source of outgassing can be avoided by using inorganic materials and optically flat seals for Brewster windows instead of epoxy seals. Continuously active flash-type barium getters can be employed to eliminate unwanted gasses. It is often advisable to flash the getter after an extended period of storage. Brewster windows and outside mirrors prevent mirror coating damage from hard ultraviolet radiation, but solarization can also occur with quartz windows. Either beryllium oxide (BeO) or graphite have been used for the bore of the plasma tube. There were a number of failures attributed to the use of BeO in early lasers, but the reliability of this material is now believed to be equal to that of graphite.

Many argon ion lasers are water cooled. There has been experimentation using oil and fluorocarbon coolants when high resistivity or low-temperature operation is desired. There have been reports of tube failures attributed to the use of hard tap water in water-cooled machines. A pulsed, air-cooled model is also available.

Argon ion lasers sometimes use gas refill systems, but this may not be necessary providing the gas cleanup rate is very low. Gas cleanup is the term used to describe the sputter entrapment of helium or of argon ions on the tube wall. This changes the gas pressure and can cause malfunctions.

TABLE 4.0-I

SUMMARY OF TYPICAL LASER RELIABILITY CHARACTERISTICS

LASER TYPE	WAVE LENGTH (Microns μm)	POWER LEVELS	MANUFACTURING BURN-IN	WARRANTY	APPLICATION	FAILURE MODES
Argon ion	0.514	0.2 to 10W	100hr	1000 hr to 1 year	surgery, dye pumping, memories, research	bore erusion, gas clean up, solarization, envelope integrity, outgassing
CO_2 flowing	10.6	·1W to > 1KW	N.A.	1 year	hole drilling, heat treating, cutting, welding metal parts	dirty mirrors, windows
CO_2 sealed	10.6	1 to 20W	24 hr	1 year	hole drilling, heat treating, cutting, welding metal parts	tube leaks, electrode degradation, helium diffusion, dirt on mirrors
TEA	10.6	>1MW peak	N.A.	1000 hr to 1 year	research, communications, radar	thyratron wear out, optics damage, dirty spark gaps
Helium/Cadmium	0.442	5 to 40 mW	24 hr	1000 hr	facsimile machines, blood cell analyzers	He ion entrapment, cadmium depletion
Helium/Neon	0.633	1 to 10 mW	24 to 36 hr	1.5 years to 2 years	alignment, metrology, scanners, gyros	epoxy outgassing, He diffusion, seal leaks
Heterojunction GaAs	0.8 to 0.904	1 to > 300W peak	10^5 pulses	1 year	military operations, air pollution sensing	power output degradation, distorted beam patterns
Ruby	0.694	0.3 to > 1MW peak	N.A.	1 year	rangefinders, holography, manufacturing applications	lamps, dirty optics, coolant system malfunctions, misalignment
Nd:YAG	1.06	0.1 to > 1MW peak	N.A.	1 year	rangefinders, designators, illuminators scribing, welding, drilling	lamps, dirty optics, coolant system malfunctions, misalignment

Capillary tube bore erosion is a phenomenon causing discharge instability and results in an end-of-life which has been reported to occur from 1350 to 6000 hours (see Table 6.3-I). End-of-life is a function of output power. High discharge currents result in short lifetimes. Manufacturers have been found to provide warranties for argon ion lasers which range from 1000 hours to 1 year of unlimited use; normally, very few users operate these lasers more than 1500 hours per year.

Infant mortality failures associated with minute leakage have been reported. This phenomenon results in hard starts (2 or 3 minutes delay before lasing). To overcome this, some manufacturers have employed a 100 hour burn-in to screen out this type of defect. The power output of argon ion lasers tends to slowly degrade throughout its life. This problem has been attributed to solarization of the windows, contamination on the windows, or disassociated bore material in the capillary tube. Improving the purity of the window material may overcome the solarization failure mechanism. The use of a hermetic seal between the tube and the mirrors eliminates dust and moisture contamination which has been another major cause of unreliability.

4.2 FLOWING CO_2 LASERS

Flowing CO_2 lasers typically use a vacuum pump connected to one end of a glass tube. The tube is evacuated, and mixed gasses such as He, N_2, and CO_2 are introduced at a low bleed rate at the opposite end of the tube from the vacuum pump. CO is sometimes substituted for N_2, and Xenon has also been tried. Metal anodes and cathodes are normally made of nickel although zirconium, platinum, tungsten, and silver have also been used. A water jacket may be added for cooling with a totally reflective (TR) and partially reflective (PR) mirror attached to each end of the tube. Brewster windows may be included at the tube ends to isolate the mirrors from the discharge.

Many investigators believe that low power (<50W), flowing CO_2 lasers have an infinite life, providing that mirror cleanliness has been properly maintained whenever exposed to an environment containing contaminants or particulates. The principle reason for this infinite life appears to be that the flowing gas acts as a purging medium by removing the contamination introduced by electrode sputter.

Typical wattage of flowing CO_2 machines is from 1 watt up to several kilowatts. Window replacement is often required on the high power lasers. Their applications include hole drilling, heat treating, cutting, and welding of metal parts.

4.3 Sealed CO_2 Lasers

Sealed CO_2 lasers are similar in construction to the low power, flowing CO_2 lasers except that the tube has been sealed. It is normal for these lasers to be warrantied for 1 year of unlimited use, and power ratings are in the 1 to 20 watt range. Some of the lasers contain a high vacuum valve so the tube can be refilled.

CO_2 lasers are considered to have a marginal reliability for fire control applications because they lack stability at temperature extremes. Vibration may also be a problem. Hard starting has been reported at low temperature, and in one instance, a Tesla coil had to be utilized to ionize the gas. In the last 5 years, mirror coating vendors and window crystal suppliers have improved the quality of their product so much that failures of these components are now rarely observed. So many variables influence sealed CO_2 lasers' end-of-life (average ≈ 3000 hr), that it is very difficult to pinpoint the exact mechanism of failure. Tube leaks, CO_2 disassociation, electrode deterioration, and helium diffusion are most often advanced as the primary reasons. Some researchers recommend the use of a metallic alloy to seal Brewster windows to the tube as opposed to epoxy or optically flat glass seals. Manufacturing burn-in is necessary to screen out bad seals. In later life, the tubes tend to devitrify around and near the electrodes. Dirt or improper cleaning can result in surface damage to mirrors.

Applications for sealed CO_2 lasers include vocal cord surgery, hole drilling, ceramic scribing, spectroscopy, atmospheric measurements, communications experiments, and air pollution monitoring.

Figure 4.3-1 is a sketch of a typical sealed CO_2 gas laser. E_1 and E_2 are the two electrodes. The glass or quartz tube is terminated by exit windows, W_1 and W_2, which have been oriented at Brewster's angle to eliminate reflections and polarize the output beam. Lasing action is provided by two external mirrors carefully aligned with the axis of the tube. R_1 is a totally reflective (TR) mirror. R_2 is a partially reflective (PR) mirror and provides the exit port for the laser beam.

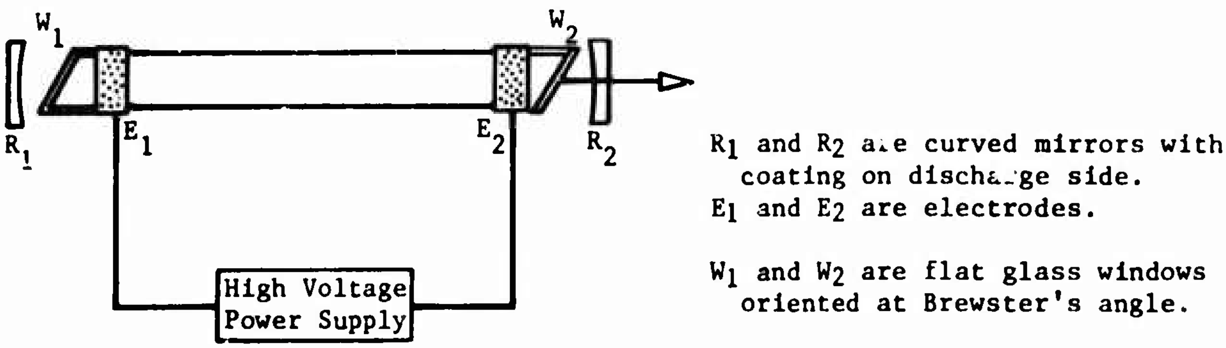


Figure 4.3-1. Typical Sealed CO_2 Laser Schematic

4.4 Dye Lasers

Dye lasers fall into two general categories. There are those that are flashlamp pumped and those that contain dye cells or jets pumped by an external laser (typically argon ion). There are a large number of dyes which have been found to lase, but the most efficient dye in common usage is rhodamine 6G (R6G). Other well known dyes are fluorescein, coumarin, cresyl violet, and nile blue.

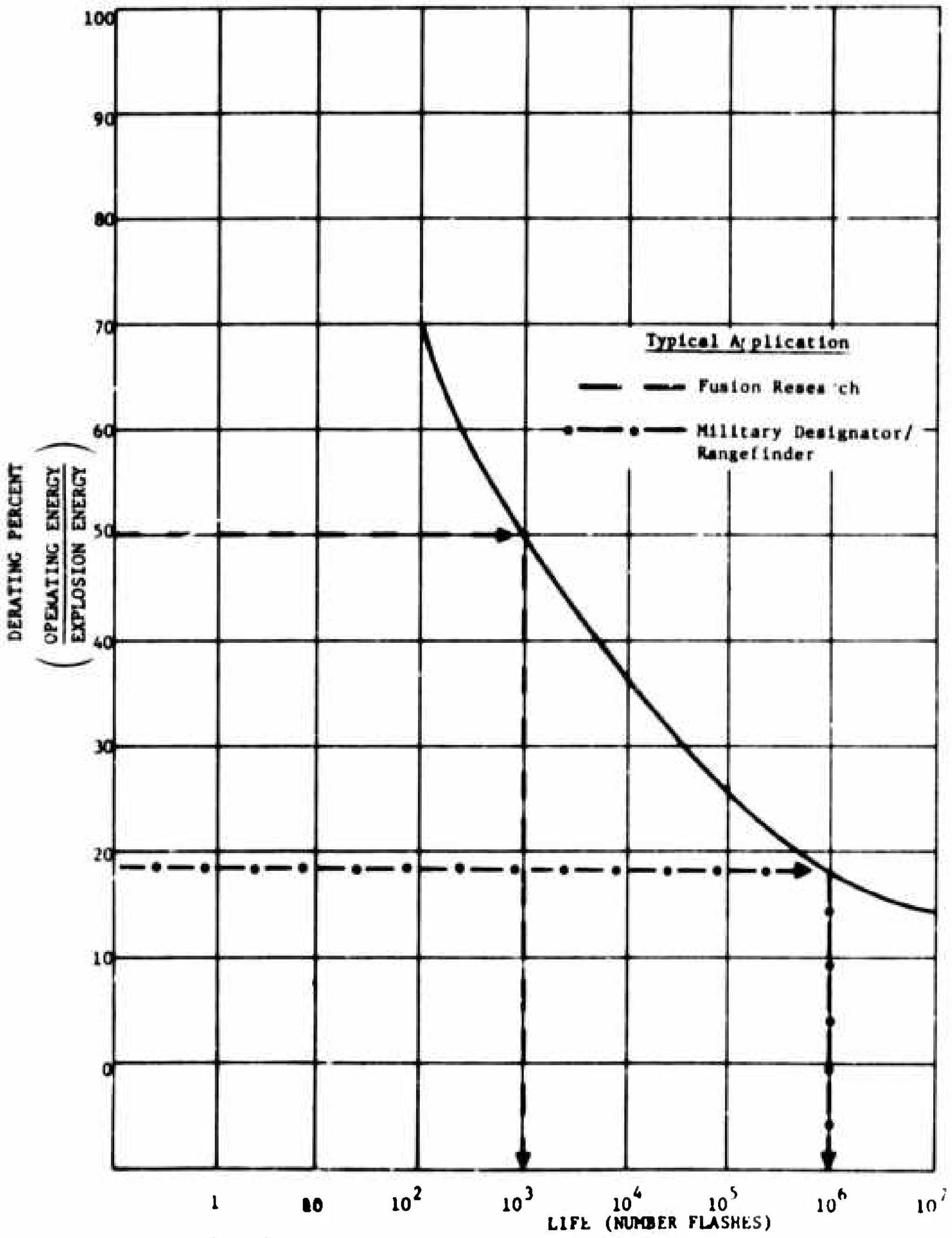
Typical solvents for the dye include ethyl alcohol, dimethyl sulfoxide (DMSO), ethylene glycol, or water. Loss of dye fluorescence yield, which has been termed as bleaching, occurs over extended usage. It is the only life limiting photochemical stability phenomenon which has been reported in the readily available literature. The output of one R6G dye laser was observed to have degraded about 20 percent after having been operated at a rate of 5 hours each week over a 6 month calendar period or an approximate lasing factor of 130 hours in 6 months.

Dye lasers have been employed primarily in research applications to date. Additional pertinent data on dye lasers can be found in References 1, 2, and 3.

4.5 Flashlamps

Solid-state lasers using yttrium-aluminum-garnet (YAG) or ruby rods are pumped with flashlamps. The two most common types are filled with xenon or krypton, and can be formed in either the linear or helical configuration. In addition to these variables, some lamps use a graded seal between the electrodes and the quartz tube. The graded seal contains three different "grades" of glass to minimize stress problems caused by coefficients of expansion. A second concept also in general usage is a metal end-cap type which uses a mechanical solder seal. A third design utilizing an inner seal inside the quartz tube rather than outside has recently been undergoing evaluation testing. At present, there appears to be little correlation between seal design and lamp life.

By far the most predominant failure mode of flashlamps is degradation sputter resulting from a deposition mechanism which is a function of derating as shown in Figure 4.5-1. Degradation can also be caused by light absorption in color centers formed by impurities (chiefly aluminum and lithium) in the quartz tube. Failure of pulsed flashlamps is defined by different users as anywhere from 20 to 50 percent degradation from the initial or original output. Many investigators believe that liquid cooling will improve lamp life by one order to magnitude as opposed to gaseous cooling. Design of the pulse forming network (PFN) can effect lamp life because if current overswings are not eliminated, electrode sputtering occurs. Prepulsing or simmering each lamp may lower peak power, but will increase lamp life. Oscillatory currents or current reversals cause the anode to sputter rapidly because it temporarily acts as a cathode and is not designed for that purpose.



NOTE: Life Defined as ~ 50% Degradation

Figure 4.5-1. Typical Effect of Derating on Xenon Linear Flashlamp Life

Most military lasers that have been designed in designators or rangefinders employ small linear xenon lamps derated to no more than 15 to 20 percent of the explosion energy (the energy required to cause the lamp to explode). Flashlamp life in this application can then typically be expected to be equal to or greater than one million (10^6) flashes or "shots." Fusion research applications require higher power and employ larger and longer lamps with approximately a 50 percent derating. For this application the linear helical lamp life will be in the 10^3 "shot" range. Again, the failure mechanism is noncatastrophic electrode sputtering and the mode is decreased output. Helical lamps are preferred for some high power lasers because of their longer arc length, but these entail special manufacturing considerations since it is difficult to wind a stress-free helix. In addition, high quality quartz must be utilized and is not readily available. Procurement presents a problem. Impure quartz entraps energy and results in a hotter tube. This causes the entrapped impurities to boil off and contaminate the xenon or krypton gas.

Manufacturing burn-in is both a desirable and useful tool to screen leaking or unreliable flashlamps. One supplier operates his lamps for 0.5 hour at a high energy level to remove defective products.

Krypton lamps, in general, will not last as long as xenon because their arc is hotter. Many commercial YAG lasers used in semiconductor scribing employ continuous wave (CW) linear krypton flashlamps which have a lifetime of about 200 hours when operating at full or nearly full power. Other similar lasers contain tungsten filament/halogen CW lamps which exhibit approximately the same life as the krypton lamp.

4.6 Helium/Cadmium Lasers

Helium/cadmium lasers are similar in construction to other gas lasers except that they contain a cadmium reservoir near the anode end. Over the lifetime of the laser which is typically 2000 hours, the cadmium vapor is gradually transported to the cathode end where it is deposited. When the cadmium has been depleted the machine will cease to lase. While it is theoretically possible to provide more cadmium to extend life, another failure mechanism begins to predominate. This mechanism is triggered by cadmium sputter trapping the helium ions near the cathode. The use of a helium ballast tends to counteract this problem by replacing the lost gas. Another important design consideration is the control of the location of cadmium deposition to avoid excess entrapment of helium ions. An alternate design concept known as "diffusion return" recirculates the cadmium vapor. Loss of power over the life span of this configuration has also been noted in the literature.

The main use of these lasers is for facsimile machines, blood cell analyzers, pollution monitoring equipment, and Raman spectroscopy. Its blue beam is absorbed efficiently by dry-processed film and is more easily detectable than the red output of helium/neon lasers due to the greater energy in the photons of helium/cadmium lasers.

Typical power range of helium/cadmium lasers is from 5 to 40 mW. Warranties of 1000 hours are available from manufacturers. Manufacturing burn-in for 24 hours is advisable, and this should be extended to 50 hours if there is any evidence of helium cleanup problems.

4.7 Helium/Neon Lasers

It has been estimated that more than 100,000 low power milliwatt-range helium/neon lasers have been manufactured, and this type is the most widely used of any laser. Low-cost types are available with mirrors epoxied to the gas tube, but other models may use Brewster windows to isolate the mirrors. Manufacturing burn-in ranges from 24 to 36 hours and is necessary to eliminate oxygen which outgasses or escapes from bubbles in the epoxy. The aluminum cathode itself acts as a getter in achieving gas cleanup. When epoxy bonding is not used, helium diffusion through the quartz tube may become the principal failure mechanism. The rate of diffusion through glass is much less than for quartz.

The usual manufacturers' warranties range from 18 months up to 2 years of unlimited use. Life test failures observed have been mostly seal problems or discharge contamination. Average life has been found to be about 12,000 hours. It is possible for humidity to penetrate epoxy seals, and this can result in storage related malfunctions. Hard, optically-flat, glass seals are more costly, but they have been shown to withstand a 1 year humidity test. In addition, glass to metal electrode seals appear more desirable than epoxy.

A barium getter can be used to eliminate unwanted gases in a tube, but once the getter has been exhausted, many tubes will have failed within 2 or 3 months. Intermittent or cyclic operation of low power helium/neon lasers has been found to result in problems. A greater reliability can be attained by continuous laser operation. Outgassing from epoxy may become serious after 3 months storage; to prevent problems, laser operation for 24 hours, once a month, has been recommended for gas cleanup. Other researchers believe that turning the laser on two or three times a year is sufficient, while a third scientist operates his machines 15 minutes, once a week, while on the shelf. Data collected by the Bureau of Radiological Health (Figure 4.7-1) indicates that the aging problem may not be too serious, but additional controlled experiments are required to provide a definitive answer.

A study has shown that introducing minute quantities of hydrogen or water vapor can extend helium/neon laser life. Optimization during design and close control of the ratio of helium to neon gas during production are also important.

The many uses of helium/neon lasers include alignment applications in the construction and mining industries, metrological purposes, zip code sorting in the Postal Service, light sources for automated supermarket checkout systems, scanners for transceiving news pictures, and gyros which employ three helium/neon ring lasers arranged in mutually perpendicular axes.

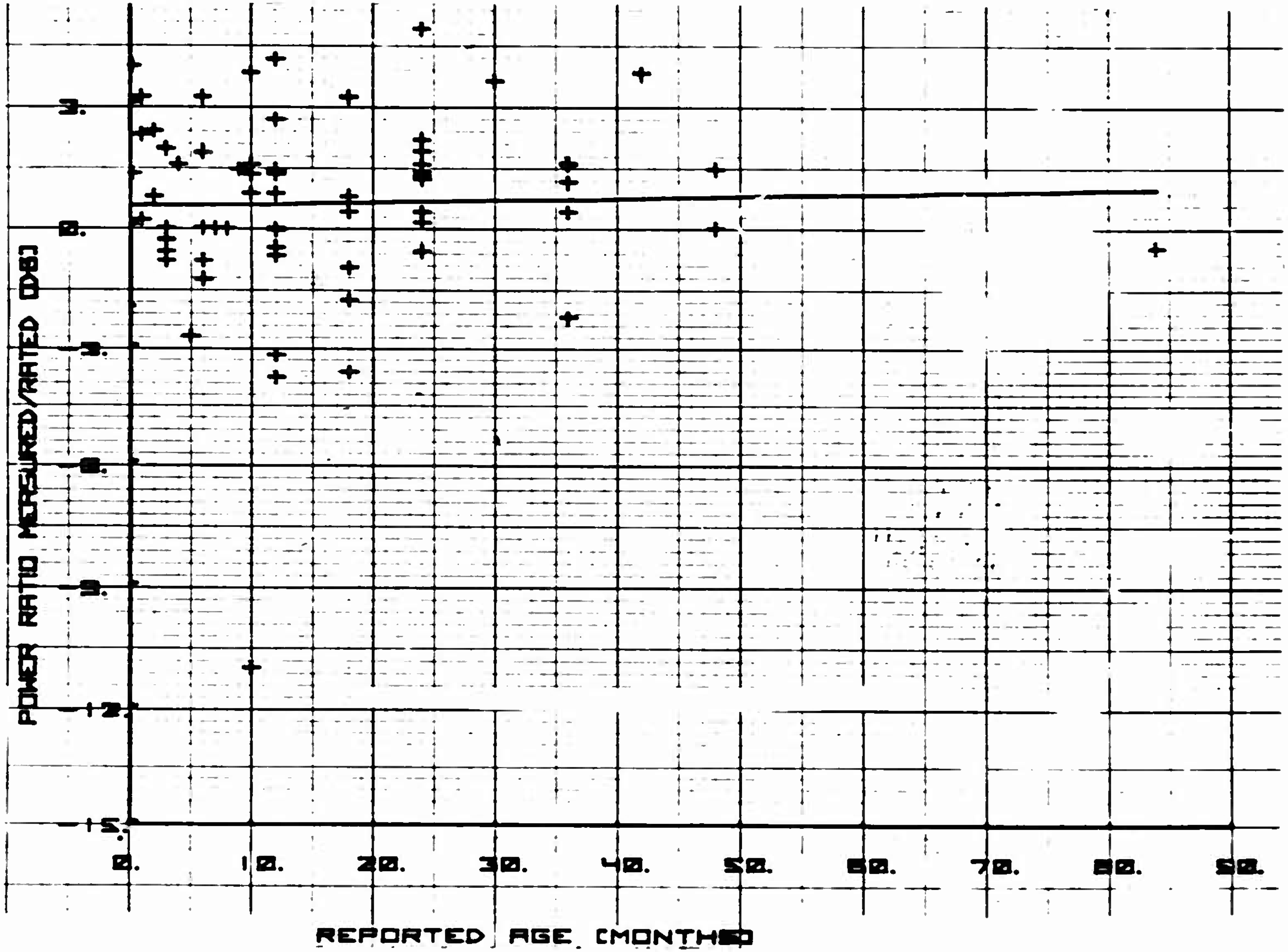


Figure 4.7-1. Helium/Neon Laser Power Ratio versus Age

4.8 Heterojunction Gallium Arsenide Injection Lasers

Injection lasers are small components similar in size to light emitting diodes (LED's). Gallium arsenide (GaAs) and gallium aluminum arsenide (GaAlAs) devices lase in wavelengths ranging between 800 and 904 nanometers. Single laser diodes are being produced with room temperature peak powers from 1 to 50 watts, and higher power stacks can produce greater than 300 watts. Typical pulse rate is in the neighborhood of 3 kHz. with a pulse width of 120 ns. These devices appear to have a nonlinear failure mechanism which is a function of pulse width. Thus, if pulse width is lengthened to 200 ns, more failures will be observed.

Design life for these devices is in excess of 5000 hours, but no verification data are available because tests-to-failure have been truncated prior to attainment of this duration. Substantial, statistically significant samples have been tested for 1000 hours and for 4000 hours with no catastrophic failures observed. Drift type failure has been defined in various literature sources as greater than 20 or 25 percent degradation. Typically 10 percent degradation in output power has been observed after 500 hours of operation, but 8,000 to 10,000 hours of operation may be required to reach 20 percent degradation. This observation has been extrapolated from the curve of the mean life value derived from the samples tested. It appears that a major factor in cathode degradation is the result of impurities released from the metallic anode which are then absorbed on the emitting GaAs surface. Additional data on this subject can be found in Reference 4. Occasional weak junctions and distorted beam patterns have been observed in the field. Very few crystal defects have been observed by users; however, a well-designed heat sink is advantageous for many applications.

Manufacturing screening tests have been run at high and low temperature with a fallout of about 2.5 percent. Ten to 20 percent overstress has also been used as a production burn-in with good success. While burn-in is desirable for high reliability systems, it may not be required with the mature commercial product. Warranties of up to 1 year of unlimited use are given from the manufacturer.

Uses for laser diodes include small lightweight ranging devices as well as designators employed in tactical war game maneuvers. Laser diode chips are also incorporated into hybrid flatpack transmitter assemblies for remote sensing of air pollutants.

4.9 Solid State Lasers

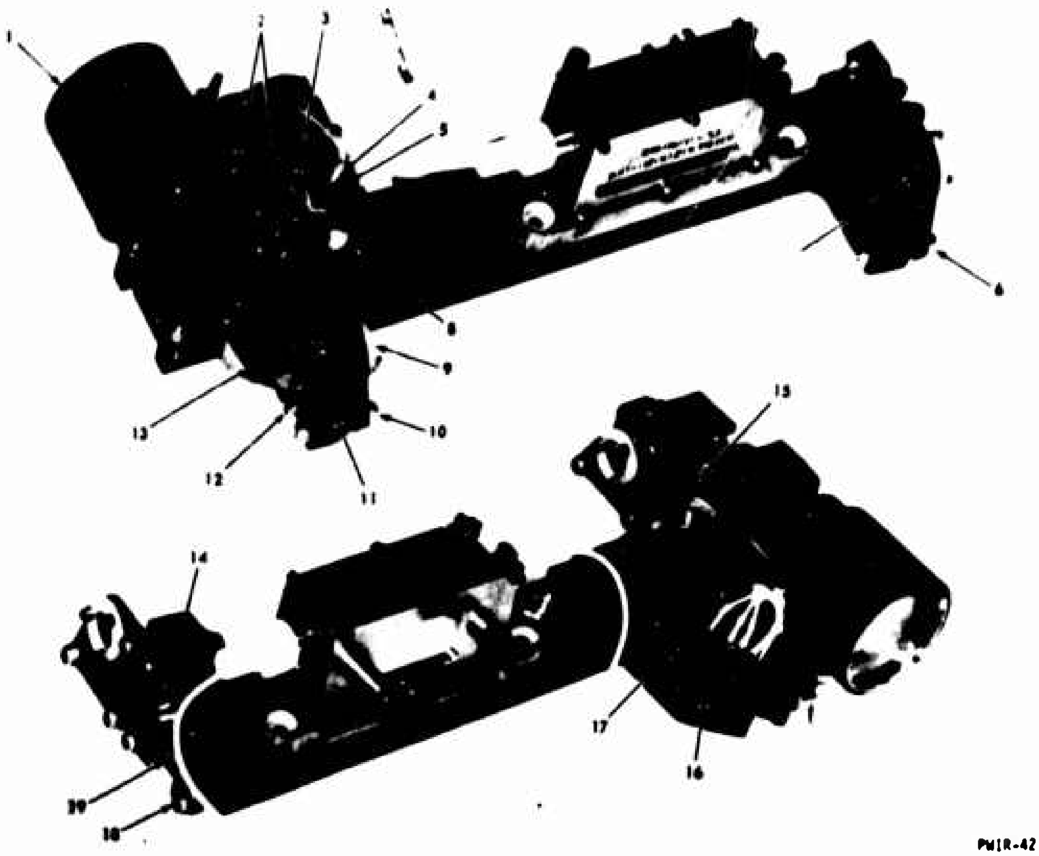
Flashlamp-pumped solid-state lasers, using a ruby rod, were first demonstrated in 1960. More recently, neodymium doped glass rods (Nd: Glass) have been used for high-power applications, but the large majority of solid-state lasers use neodymium doped yttrium-aluminum-garnet (Nd:YAG) rods.

The solid-state laser rod and flashlamp refer to Figure 4.9-1 and -2, are usually housed in an elliptical cavity, the inner surface of which is a highly reflective gold-plated mirror. De-ionized water or other suitable fluids flow through the cavity for cooling purposes. Military lasers ordinarily use liquid fluorocarbons or water-glycol mixtures for low temperature operation. As with gas lasers, a TR mirror is positioned at the far end of the cavity and a PR mirror is normally used at the output end. Other components may include a mode selector between the cavity and the TR mirror plus a telescope-type beam expander at the exit end. The optical train (see Figure 4.9-2) is completed by a "Q" switch located between the PR mirror and the cavity. "Q" switching is a technique for obtaining short duration laser pulses from a rod pumped by a CW lamp or for decreasing the time scale of the pulse when the rod is pumped by a flashlamp. As a result, peak power per pulse is increased by several orders of magnitude. "Q" switch technology has progressed from rotating prisms or mirrors to electro-optical (E/O) Pockels Cells. At the present time the most reliable method appears to be the acousto-optical (A/O) solid state switch. Solid-state laser components are discussed in more detail in Section 4.13.

There is considerable evidence available to prove that solid-state lasers do not wear out. The major life-limiting characteristic is a requirement for periodic replacement of flashlamps. Greater than 90 percent of the "random" type failure mechanisms are associated with dust on optical surfaces, misalignment, or the cooling system. The dust problem is being eliminated by protective bellows type shields to completely enclose the optical train. New designs are available which are aligned at the factory and do not require adjustment in the field. Cooling system malfunctions can be eliminated by proper selection of the tubing and heat exchanger materials as well as by placing a de-ionizer upstream of the cavity. With unsealed designs, it may be necessary to control coolant temperature to avoid humidity condensation on the rod ends.

Manufacturers' warranties on commercial solid-state lasers range from 6000 hours to 1 year of unlimited use with lamps excluded. Some evidence has been seen that leads to the conclusion that certain commercial YAG lasers have achieved better MTBF's than military YAG lasers for both laboratory and ground environments. The probable reason for this unusual occurrence is that intense competition has forced the incorporation of improved process control, simplification, rugged construction, or other beneficial design innovations.

Applications for solid state lasers up to the megawatt peak power range include welding, hole drilling, fusion experiments, resistor trimming, and scribing of chips in the semiconductor industry. The military uses these lasers in the lower power milliwatt range for target illumination, designation, or rangefinding. Rangefinders measure distance by timing the interval between a transmitted laser pulse and the reflected return from the target object. This time interval is then converted to a digital display of range. Ranging errors have been experienced at low temperature but this appears to be an electronics design problem. Designators are used by ground or aircraft observers to illuminate the target for tactical missiles equipped with photodiode type seekers.



1 - Collimating telescope
2 - Collimating telescope X-axis adjustment screw
3 - Magnetic pickup mount adjustment lockscrew (2)
4 - Magnetic pickup
5 - Magnetic pickup locknut
6 - Folding mirror adjustment nut (3)
7 - Folding mirror
8 - Q-switch head
9 - Exit mirror (sapphire etalon)
10 - Exit mirror adjustment nut (3)
11 - 45° prism adjustment screw
12 - 45° prism adjustment lockscrew (2)
13 - 45° prism
14 - Porro prism
15 - Collimating telescope X-axis adjustment lockscrew (4)
16 - Q-switch tilt adjustment screw
17 - Q-switch tilt adjustment lockscrew (4)
18 - Porro prism adjustment nut (3)
19 - Porro prism mounting screw (2)

Figure 4.9-1. Typical Solid State Laser

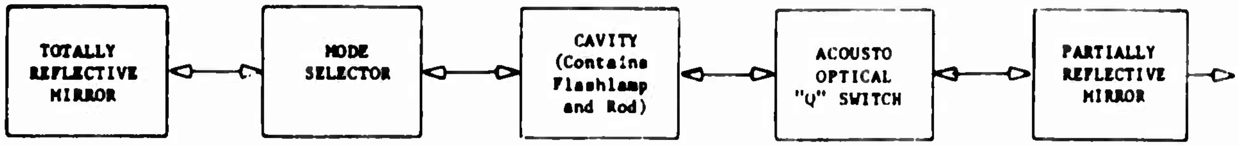


Figure 4.9-2. Typical Solid State Laser Optical Train

4.10 TEA Lasers

Transversely excited atmospheric pressure (TEA) lasers typically utilize a mixture of CO_2 - N_2 - He gases flowing through a pulsed discharge which is formed transverse to the axis of the tube. Experiments have also been conducted with other gases such as HF, DF, CO, and N_2O as well as with sealed tubes. A major advantage of these lasers is that they can provide high peak powers of greater than one Mw in a very lightweight compact machine. The devices are capable of operation at high repetition rates and appear to be useful for a number of communication and radar applications.

Pulsing of TEA lasers is achieved by either spark-gap circuitry or a thyratron. Thyratron life in this application has been found to be about 2000 hours of operation although it is only warranted by the manufacturer for 200 hours. It is possible to burn spots on the electrodes when the laser has been operated with a bad thyratron because an arc is struck instead of the usual glow discharge. Spark gaps require periodic maintenance of cleaning on the average of once a month after 50 to 300 hours of operation.

TEA laser life is dependent on the optics which typically require cleaning once a month and replacement after 1000 hours of operation. Because of this problem, optics warranties are restricted to a maximum of 10^5 pulses. Warranties for the rest of the machine range from 1000 hours to 1 year. It is possible to extend the life of the optics by lowering the high voltage level or adjusting the gas mixture. Charging capacitors occasionally fail, but this is to be expected because the lasers are being used for research applications in which the capacitors have little or no electrical stress derating and are subjected to high repetition rates. These highly stressed capacitors exhibit a failure rate that is two orders of magnitude (100 times) greater than identical charging capacitors conservatively derated.

4.11 Laser Power Supplies

Data on laser power supply part failures and operating hours were collected from several different sources during the course of this reliability study. Electronic part failure rates were calculated from this data. Although this data base was much smaller than is available from conventional electronic equipment, the failure rates fell into the same order of magnitude. As a further check, the observed failure rate of a statistically significant quantity of laser power supplies in operational use was compared with the predicted failure rate using MIL-HDBK-217B piece-part data. The result of this exercise (see Table 4.11-I) indicated that the observed and predicted values were in very close agreement. Therefore, it was decided not to utilize the collected power supply part failure rates from the smaller laser data base, but to employ the accepted MIL-HDBK-217B data as described in Section 6.0 and thus achieve a higher degree of confidence in the resulting predicted values.

TABLE 4.11-I

Laser Power Supply Observed versus Predicted Reliability

Part Type	Quantity	Base Failure Rate* (failures/10^6 hr)	Total Failure Rate (failures/10^6 hr)
Transistor, NPN	34	0.9800	32.3200
Transistor, PNP	8	1.6000	12.8000
Diode, general purpose	21	0.6800	14.2800
Diode, zener	4	0.8500	3.4000
Integrated circuit	9	1.2800	11.5200
Resistor, MIL-R-39008	34	0.0048	0.1632
Resistor, MIL-R-11	114	0.0240	2.7360
Resistor, MIL-R-26	3	0.3300	0.9900
Resistor, Var., MIL-R-22097	3	9.5000	28.5000
Capacitor, MIL-C-11015	48	0.4400	21.1200
Capacitor, MIL-C-39003	24	0.0005	0.0120
Capacitor, MIL-C-14157	1	0.0012	0.0012
Transformer	6	0.0560	0.3360
Choke	2	0.0600	0.1200
Relay	3	4.5000	13.5000
Connector	13	0.5100	6.6300
Predicted totals	324		149.4284
Predicted MTBF (hours)*			6,692
Observed MTBF (hours)**			6,081

* Source: Section 3.0 of MIL-HDBK-217B

** Source: Best estimated based on actual field data in airborne inhabited environment

A majority of investigators agree that the charging capacitor is the laser power supply part with which they experience the most trouble. As discussed in Section 4.10, the major reason for this problem is the fact that many power supply designs do not provide adequate derating for this part. Several designers have commented that they believe that the charging capacitor failure rate increases with very high repetition rates. Actual data to quantify and support this contention could not be collected. Figure 2.6.1-1 of MIL-HDBK-217B does contain information on temperature increase effects caused by pulsing plastic film capacitors. One manufacturer for the military market subjects storage capacitors to an environmental laboratory altitude test to screen marginal parts, and this procedure has greatly decreased the failure rate observed in the field. In another early airborne military laser system, a charging capacitor cyclic failure rate in the order of 10^7 shots has been documented.

The second most frequent laser power supply malfunction is associated with high voltage cables and connectors. A significant portion of this problem appears to be related to improper cable routing. MIL-STD-810 tests in both the humidity and altitude environments are a valuable aid to achieving product improvement and high reliability laser power supply designs.

4.12 Limited Use Items

There are a number of different kinds of limited use gas lasers for which it was not possible to collect sufficient reliability data to construct realistic failure rates, failure modes, or mathematical models. In general, these lasers are used for fusion studies and other laboratory research projects where the characteristic wave length is of interest. The helium/selenium, nitrogen, xenon, DF, and HF gas lasers are typical of the machines which fall into the limited-use category. Many of the failure modes peculiar to other gas lasers, such as gas cleanup, solarization, envelope integrity, and diffusion should be expected to occur and to be observed as experience is gained.

For reliability prediction purposes, estimates can be made either by using the component building-block approach or by choosing a math model based on similarity to other lasers. The helium/selenium laser is similar to helium/cadmium while the other limited-use lasers listed are perhaps closest to the argon ion or CO_2 systems.

4.13 Laser Components

Recent failure mode and mechanism data on major laser components are discussed in this section as they pertain to typical usage in operating commercial and military laser systems. Materials damage information from very high power research applications has been omitted since this area is outside the scope of the study. Several investigators have stated that there are perhaps five orders of magnitude between damage thresholds and nominal energy levels being used in the lasers for which reliability predictions are required. Most researchers are unanimous in their opinion that the quality of laser components has improved significantly in the last 5 years.

4.13.1 Crystals

Crystals are used in a wide variety of laser applications including frequencer doublers or second harmonic generators (SHG). In the case of YAG lasers, deuterated cesium dihydrogen arsenate (CD*A) is used to go from the 1.06 to the 0.532 micron wave length. Other crystals in common usage are deuterated potassium dihydrogen phosphate (KD*P), lithium iodate ($LiIO_3$), and lithium niobate ($LiNbO_3$). With adequate derating, there is no evidence that these crystals themselves wear out; however, the coatings may degrade if subjected to excessive heat. There have been examples of fractures of CD*A crystals when operated at 100°C. The problem has been solved by substituting CDA for CD*A and reducing the operating temperature to 40°C.

4.13.2 Mirrors

Laser mirrors being used in the late 1960's exhibited a large number of quality control problems associated with improper coatings. In recent years, the major vendors have improved their manufacturing process controls and the currently available production mirrors are highly reliable.

Mirror coatings fall into two general categories, TR and PR. The TR type is typically prepared by depositing either a gold or multilayered dielectric or both types of material on a silicon or other metallic substrate. Dielectric materials in common usage are magnesium fluoride (MgF_2), cadmium telluride (CdTe), and zinc sulfide (ZnS). As many as 25 layers of these materials may be required to get 0.999 reflectivity. The PR coating can be made of the same construction except that fewer layers are used, and a transmitting material is substituted as the substrate.

To achieve lowest loss and least impurities, vacuum deposition methods are employed with either a resistance heater or an electron beam to evaporate high temperature material. The electron beam approach is preferred by many manufacturers because it provides good adhesion at the molecular level and minimizes scattering. Dust contamination is the major cause of mirror coating failure, and substrate heating must also be avoided. There have also been reports of coating damage caused by inadvertent contact with leaking liquid fluorocarbon coolants. Certain unsealed laser designs require that maintenance action to clean mirror coatings be done on a periodic basis.

4.13.3 "Q" Switches

In order to provide the function described in Section 4.9, early solid-state layers employed the spinning mirror "Q" switch. The mirror was mounted on the end of a miniature electric motor shaft and was found to be unreliable because of bearing wearout, dust contamination, misalignment and balancing problems.

The next generation "Q" switch was the E/O Pockels cell. Crystal materials used for this purpose include ammonium dihydrogen phosphate (ADP), KD*P, potassium dihydrogen phosphate (KDP), LiNbO3. The KD*P is perhaps most commonly employed, and it is often immersed in a liquid fluorocarbon for index matching and hygroscopic protection. An alternative design for KDP Pockels cells utilizes a hermetic seal and desiccant approach. The desired E/O "Q" switching is caused by varying the refractive index of the crystal axes with an impressed electric field, thus modulating the light beam. Typical Pockels cell failure modes are leakage of the index matching fluid, coating damage from misalignment, and bubbles in the cell caused by filamenting or hot spots in the beam. In some applications, LiNbO3 may require a gaseous oxygen bleed as the crystal loses oxygen with time.

A major Pockels cell manufacturer has recently switched production entirely to A/O "Q" switches because of the improved reliability advantage of this new design. The typical A/O type "Q" switch utilizes a transducer to introduce a sound wave to a prism in the laser's optical train. The elastic wave acts to deflect the light beam off the mirrored surface, thus alternately achieving reflection and transmission. Early designs experienced occasional bond failures between the transducer and the quartz prism. At present, grease bonds are being used with great success, and a large quantity of part hours have been accumulated with no failures. Solid-state YAG laser scribers, with A/O "Q" switches, have operated reliably 24 hours per day for more than 30 months. As long as dust contamination is kept off the component, no "Q" switch failures are observed.

4.13.4 Rods

Solid-state laser rods consist primarily of one of three materials, ruby, Nd:Glass, or Nd:YAG. Early lasers experienced rod failures, but the major reason for this problem was minute impurities which were introduced during manufacturing. Very pure rods are now available and rod failures are rarely observed in low and medium power applications such as military designators, rangefinders, and commercial semiconductor scribers.

The typical laser rod uses antireflective (AR) coatings on both ends which may consist of a single layer of magnesium fluoride (MgF_2) dielectric material. Dust must be kept off the rod ends. For high-power lasers, rod coating damage can result from hitting a reflective target. Optics misalignment can also cause reflected energy which will burn the rod coating.

Amino compounds are not compatible with ruby rods and they should be avoided. One user of a YAG laser reported no rod problems in over 3 years field experience with daily operation. Ruby rods which were not kept clean required replacement between 5 x 10^5 and 5 x 10^6 shots.

4.13.5 Brewster Windows

Brewster windows are utilized on gas lasers to isolate the mirrors from the discharge. Orientation at the proper Brewster angle prevents reflections which would result in power loss. The actual AR angle employed varies with the refractive index of the material used for the window, and with sodium chloride (NaCl) and most glasses the angle is about 56 degrees. Any material which transmits the particular laser radiation involved can be used as a Brewster window. Glass or quartz are usually employed as long as the wavelength is within its transmission range which extends through the visible to the near infrared (IR). Beyond this range, some other material must be used. Salt is a good window material for infrared lasers, but it has a very short life in humid environments. Even with average relative humidities below 50 percent, NaCl window replacements may be required after approximately 5 weeks. Potassium chloride (KCl) is more commonly used for Brewster windows, because it is not as hygroscopic as NaCl. Zinc selenide (ZnSe) and GaAs have also been used with success. Metallic gold/indium compounds have been used as a reliable method to attach Brewster windows to the laser tube.

5.0 DATA ANALYSIS

5.1 Statistical Methods, Assumptions, and Ground Rules

Operational failure data on laser devices have been collected, analyzed, and summarized in the form of failure rates for individual laser item types. The following sections describe the basic ground rules and assumptions used in this analysis and define the statistical tests used in combining the data. The methods used for calculating failure rate confidence limits are included. Numerical examples are given for the statistical tests and for confidence limit calculations.

5.1.1 Assumption of Exponential Distribution

It is generally accepted that failure times for most electronic parts are exponentially distributed. Although this acceptance does not extend to some laser items, the assumption and use of the exponential failure distribution has ordinarily been extended to performing reliability calculations for these items. Two primary factors are involved in the widespread use of this assumption:

1 It greatly simplifies the reliability prediction techniques;

2 There is a pronounced lack of time-to-failure data on most laser items, so that a more descriptive failure distribution cannot be established.

The second factor was evident during the data collection phase of this study program. Many sources could provide only the total quantity of item-hours and failures rather than time-to-failure data. It was, therefore, necessary to assume the exponential distribution during the calculation of failure rates for this program.

Based on the exponential distribution, failure rates with respect to functional and environmental applications have been calculated for the items for which data were available.

5.1.2 Calculation of Confidence Limits

Two-sided limits of a 90 percent confidence interval have been derived for the failure rates in this report with one exception:

> When the item type under evaluation had zero failures, the failure rate point estimate was calculated as a function of total item-hours, and the chi-square (χ^2) value obtained from

the upper single-sided 60 percent confidence level at 2 degrees of freedom. Therefore, no confidence limits are given for failure rates calculated in this manner.

Before calculating the 90 percent two-sided confidence limits it was first necessary to determine whether the item data were time or failure truncated. As far as could be determined, no known instances of failure truncated information were reported, received, or documented; therefore, it was assumed that the data were time truncated. The upper confidence limit was obtained by using the component item-hours and the upper 95 percent chi-square value at 2r + 2 degrees of freedom. The lower limit value was likewise obtained using the component item-hours and the lower 5 percent chi-square value at 2r degrees of freedom. If the data had been failure truncated, the value for the upper limit would still have been obtained at the 95 percent level, but at the 2r degrees of freedom coordinate. The lower confidence limit value would not have changed.

The general equations used for obtaining the upper and lower confidence limits on the item failure rates in this report are as follows:

$$\frac{\chi^2\ (\alpha/2,\ 2r)}{2T} = \text{Lower confidence limit}$$

$$\frac{\chi^2\ (1-\alpha/2,\ 2r+2)}{2T} = \text{Upper confidence limit.}$$

where:

r = the number of failures which determines the degree-of-freedom coordinate used in determining chi-square (χ^2)

$\alpha/2$ = the 5 percent percentile coordinate used to determine the χ^2 value at the lower confidence limit

$1-\alpha/2$ = the 95 percent percentile coordinate used to determine the χ^2 value at the upper confidence limit

T = the total number of component item-hours.

As an example, three failures on helium/cadmium lasers occurred during 0.0398×10^6 item-hours of operation. To calculate the failure rate and associated 90 percent two-sided confidence limits, a table of χ^2 values from Reference 5 is used to establish the values of the upper and lower 90 percent confidence limits. The results are as follows:

$$\text{Failure rate} = \frac{\text{Failures}}{\text{Item-Hours}} = \frac{3}{0.0398 \times 10^6} = 75.37 \frac{\text{Failures}}{10^6 \text{ Item-Hours}}$$

$$\text{Lower confidence limit} = \frac{\chi^2\ (0.05,\ 6)}{2T} = \frac{1.64}{0.0796\text{x}10^6} = 20.60 \frac{\text{Failures}}{10^6 \text{ Item-Hours}}$$

$$\text{Upper confidence limit} = \frac{\chi^2\ (0.95,\ 8)}{2T} = \frac{15.5}{0.0796\text{x}10^6} = 194.72 \frac{\text{Failures}}{10^6 \text{ Item-Hours}}$$

5.1.3 Test of Homogeneity of Data

When billions of item-hours of data are collected from many different sources, the analyst is faced with the task of determining how the data should be combined. Obviously, it is imperative that homogeneity of item populations be maintained. If not, the introduction of bias and loss of precision in item failure rates would result. Therefore, all line items of failure rate data were carefully studied and evaluated. These data items were then reordered and categorized on the basis of laser item type, item subgroup type, functional application, and environmental application.

Before the data could be combined, an additional evaluation was also necessary; a statistical test for homogeneity. The Dixon Criterion test was chosen to statistically detect and identify those data entry failure rates which might significantly deviate from the family of failure rate entries under analysis. The ground rules and statistical assumptions used for this Dixon Criterion testing are as follows:

1 Failure rate observations derived from each line entry come from a single normal population.

2 Population mean and standard deviation of the failure rate observations are unknown. The data sample, consisting of the failure rate line entries, is the only source of information.

3 The probability of risk (α) for rejecting an observation that truly belongs in the group is 10 percent. Line items significantly different at either end of a 90 percent two-sided confidence interval are culled from the sample before a final combined failure rate estimate is calculated. (See Section 5.1.2 for a discussion of the method used for calculating confidence intervals.)

4 A minimum of three line entries of failure rate data are necessary in testing the homogeneity of the samples.

5 When a data line entry has zero failures, one failure has been assumed in calculating the data entry failure rate. Such an entry is tested only to determine whether its failure rate is significantly lower than the others in the sample. Extremely low failure rates may indicate overzealous censoring of failures by the data collecting activity. A failure rate calculated by assuming one failure is not included in the Dixon Criterion test if it is ranked at the high end of the ordered failure rate data entries, since a high failure rate with no actual failures is meaningless. The item-hours, however, of that entry are combined in the final failure rate calculation.

As an example, Table 5.1.3-I contains the three lowest and the three highest ordered line items of failure data received on mirrors and the equations for identifying outliers at the upper and lower ends for a data base of 25 observations.

To test acceptability of sample X_1 at the low-end, the applicable failure rates in failures/10^6 item-hours are substituted into the corresponding formula, and the result obtained is:

$$\frac{X_3 - X_1}{X_{23} - X_1} = \frac{15.385 - 5.882}{3954.306 - 5.882} = 0.002.$$

This value is less than 0.406; therefore, the lowest ordered failure rate is within the acceptable boundary. To test acceptability of sample entry X_{25} at the high end, the applicable values are again substituted into the corresponding formula, and the result obtained is:

$$\frac{X_{25} - X_{23}}{X_{25} - X_3} = \frac{12082.601 - 3954.306}{12082.601 - 15.385} = 0.674.$$

This value is greater than 0.406. Therefore, the failure rate of 12,082.601 and its associated item-hours and failures must be rejected. These would not be combined in the final failure rate estimate.

This iterative testing process using the Dixon Criterion is continued until all unrealistic outliers have been eliminated. The data and tables used for determining equations and statistics to be applied were obtained from Reference 6.

TABLE 5.1.3-I

Example of
Combination of Failure Data Line Entries

MIRRORS, GENERAL

Failure Rate (Failures/10^6 Item-Hours)		Item-Hours	Failures
X_1 =	5.882	170,000	1
X_2 =	13.699	73,000	1
X_3 =	15.385	65,000	1
X_{23} =	3,954.306	2,276	9
X_{24} =	7,029.877	2,276	16
X_{25} =	12,082.601	4,552	55

For a sample of 6 from a data base of 25 observations, if the low end is suspect,

$$\text{reject } X_1 \text{ if } \frac{X_3 - X_1}{X_{23} - X_1} \geq 0.406.$$

For a sample of 6 if the high end is suspect,

$$\text{reject } X_{25} \text{ if } \frac{X_{25} - X_4}{X_{25} - X_3} \geq 0.406.$$

5.2 Item Classes and Failure Rates

The purpose of this program has been to construct models and assemble failure rate data that are suitable for future revision of Section 2.4 of MIL-HDBK-217B. This was done through the collection, study, and analysis of laser item reliability data and information. These data, collected, studied, and analyzed, have been categorized by specific item type and environmental application. The results are presented in Table 6.2-I. No laser devices were tested to obtain data, but rather an extensive data survey and collection effort was undertaken to locate and obtain necessary data. Appendix A lists the sources from which the data were collected.

The equipment studied were typical of those used in military ground and airborne environments, as well as in commercial applications. Most of the failure rate data are in the form of failures/10^6 item-hours of operation; however, some failure rates are in terms of failures/10^6 item-pulses. These failure rates are annotated in Table 6.2-I by an asterisk (*) in the Item-Hour column. The pulses are dynamic rather than static.

A limited amount of qualitative failure mode and mechanism data were obtained during the data collection effort. These data are summarized in Section 4.0 for several general classes of lasers. No significant amount of quantitative data was obtained.

5.3 Weibull Analysis

In September 1951, the Swedish professor Waloddi Weibull published a distribution function which is most general inform and capable of completely describing the three classical reliability periods of decreasing, constant, and increasing failure rates.

While the distribution was apparently first conceived for the solution of mechanical engineering wearout problems, it has more recently been recognized as a powerful tool for the statistical analysis of life tests involving both electronic and mechanical component parts and equipment. It has been used for analyzing life tests of vacuum tubes and is coming into more general use for studying the reliability of semiconductors and capacitors.

Because of its versatility, the distribution which bears Professor Weibull's name continues to find increasing practical application in the electronics and aerospace industries.

The Weibull distribution is a three parameter distribution defined as follows:

$$F(X:\alpha,\ \beta,\ \gamma) = \frac{\beta}{\alpha}\ (x-\gamma)^{\beta-1}\ \exp\ \frac{(X-\gamma)^{\beta}}{\alpha} \quad \text{for:}\quad \begin{array}{l} x \geq \gamma \\ \gamma \geq 0 \\ \alpha > 0 \\ \beta > 0 \end{array}$$

$$= 0 \text{ otherwise}$$

where:

α = scale parameter

β = shape parameter

γ = location parameter

The Weibull shape parameter (β) is of extreme importance because it describes the region of failure; that is:

When β=1, the failure rate is said to be constant with time. This is the random failure region.

When β<1, the failure rate is said to be decreasing with time. This is normally the burn-in region.

When β>1, the failure rate is said to be increasing with time. This is normally the wearout region.

The parameter $\alpha^{\frac{1}{\beta}}$ is called the characteristic life and denotes the point where approximately 63 percent of the population has failed.

The gamma parameter (γ), which can also be interpreted as a warranty period, is called the location parameter or minimum life below which no failures should occur. In the following analysis, the assumption is made that all items placed on test are subject to failure from the instant they are put on test; hence, the location parameter equals zero.

5.3.1 Helium/Neon Laser Weibull Analysis

A limited amount of test-to-failure data were collected on helium/neon laser from several different sources. Initial inspection revealed that a deeper mathematical investigation was necessary to categorize and define with a greater degree of accuracy the reliability parameters of these devices. It appeared that the data would fall into two distinct quality levels as described in Section 2.0 (b), Part Quality, of MIL-HDBK-217B. It was not immediately obvious whether these two quality levels were attributable to infant mortality stemming from manufacturing variations as opposed to end-of-life wearout inherent in the device design. To resolve this question, Weibull analyses, as described in Reference 7, were employed.

5.3.1.1 Quality Level 1 Data

A statistically significant amount of quality level 1 data were received from two different sources and were coded Group 1 and Group 2. The times-to-failures for each of these groups were independently subjected to a Weibull analysis. The results are depicted in Figures 5.3-1 and 5.3-2. Surprisingly, both groups' initially exhibited a sharply increasing failure rate ($\beta \approx 4.32$ and 5.32) during early operation of up to approximately 13,000 hours (12,000 for Group 1 and 14,000 for Group 2). This first period was followed by a second period marked by a slightly increasing failure rate ($\beta \approx 2.25$ and 2.23) for both groups out to beyond 30,000 hours of useful operation. In other words, those units which survived 13,000 hours were very good units and, on the average, tended to last a very long time.

The mean life for the Weibull distribution depends on both the scale parameter (α) and the shape parameter (β). The mean life is termed the characteristic life (η) and is expressed by:

$$\eta = \alpha^{\frac{1}{\beta}}.$$

The characteristic life for Group 1 and Group 2 are also shown on Figures 5.3-1 and 5.3-2, respectively. During the first period, η was found to be approximately 17,300 hours and 17,600 hours. For the second period, η was observed to be about 26,000 and 22,000 hours.

Because of the apparent similarity in the reliability parameters exhibited by both groups of quality level 1 data, a Kolmogorov-Smirnoff test, Reference 8, was performed on Groups 1 and 2 as shown in Figure 5.3-3. This test revealed that there is no significant difference in the two groups at the 95 percent level, and they can, therefore, be combined without undue bias. Figure 5.3-4 displays the combined quality level 1 data which exhibit a characteristic life of about 20,000 hours. It should be noted that for a true exponential distribution ($\beta \approx 1$), the characteristic life (η) is equal to the mean-time-between-failure (MTBF - α). When $\beta \approx 3.25$, the distribution becomes normal. The analysis of the combined quality level 1 data (Figure 5.3-4) indicates that failures are normally distributed through a large portion of the useful life. The remaining devices are very good units and exhibit a constant or slightly decreasing failure rate until end-of-life. The failure mechanisms which contribute to this phenomenon are discussed in Section 4.0.

5.3.1.2 Quality Level 2 Data

Quality level 2 data were received from two different sources and were subjected to Weibull analyses as shown in Figures 5.3-5 and 5.3-6. This quality level is neither typical nor suitable for laser devices specified or required for military applications.

Group 1 data exhibited a distribution which might be expected of the exponential distribution or constant failure rate hardware. Group 2 data approximated the normal distribution throughout their life and did not show the decreasing failure rate observed in Group 1 later life.

5.3.1.3 Observations

Quality level 1 helium/neon lasers use higher cost construction and have better manufacturing process controls than quality level 2 devices, and are generally applied to military applications. Quality level 2 applies for commercial use.

The total amount of helium/neon laser data is small. So when the data from quality level 1 were combined as described in Section 6.0, it was determined that use of the constant failure rate would best fit the overall situation for laser predictive modeling purposes.

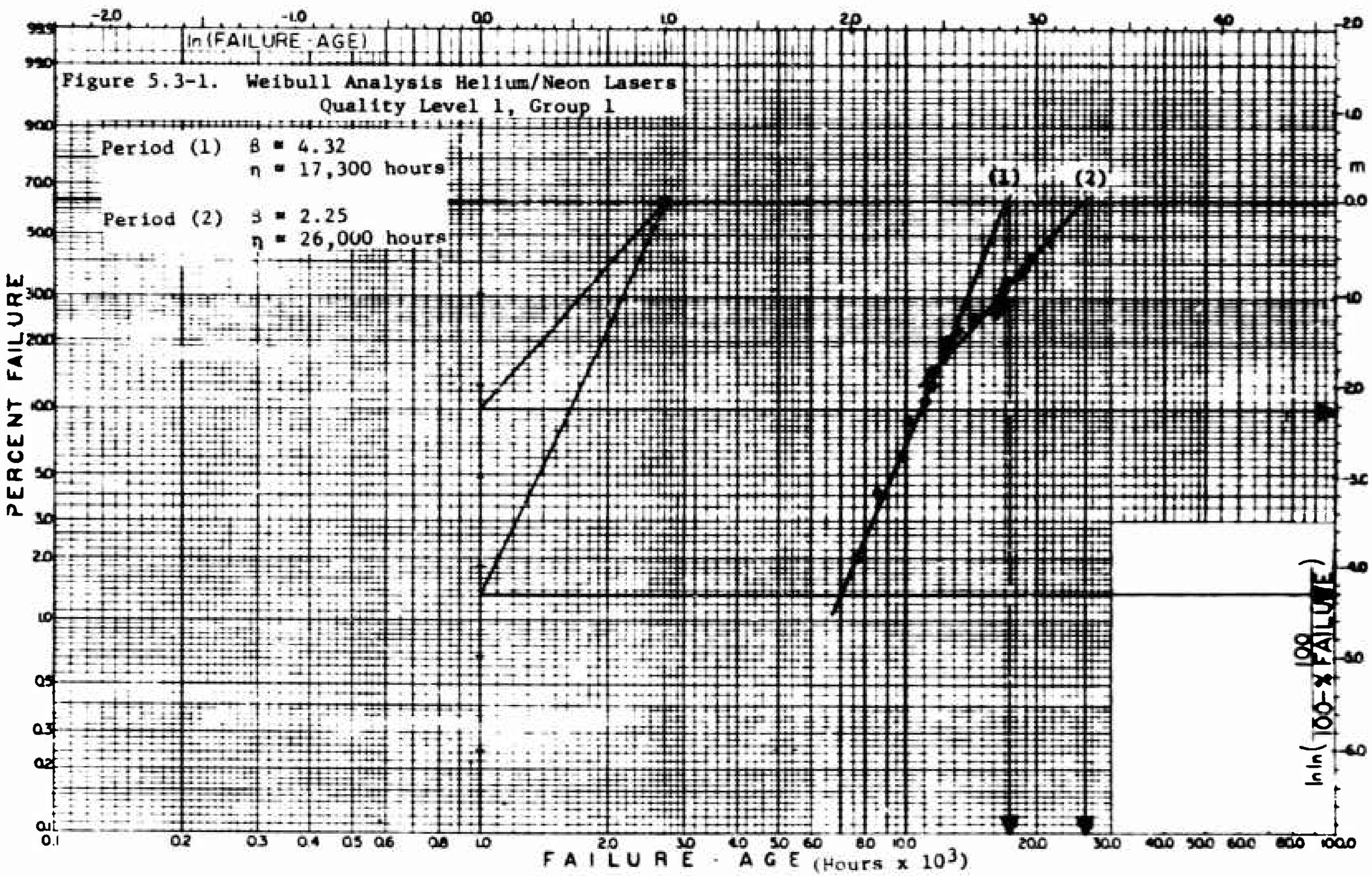


Figure 5.3-1. Weibull Analysis Helium/Neon Lasers Quality Level 1, Group 1

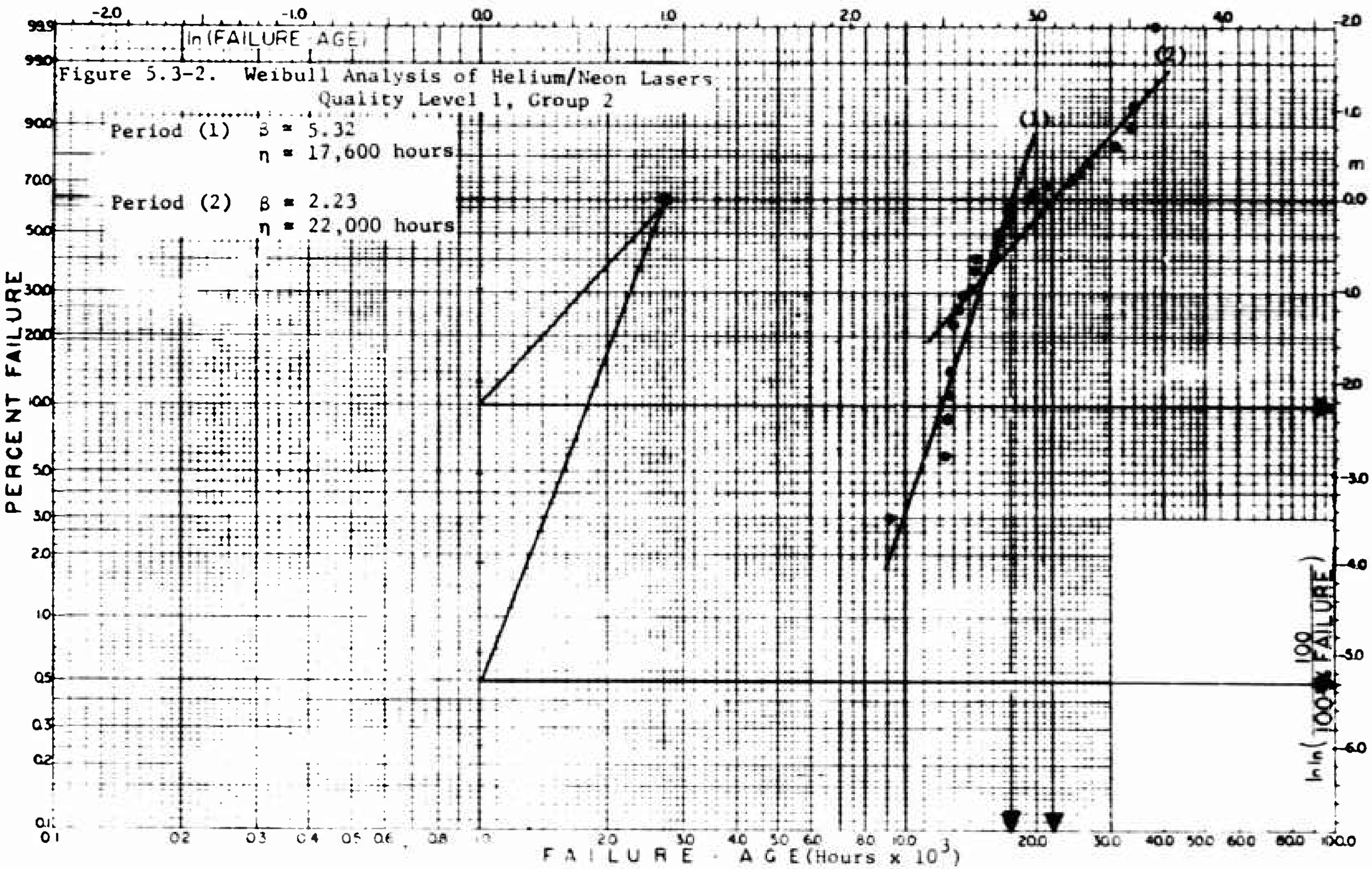
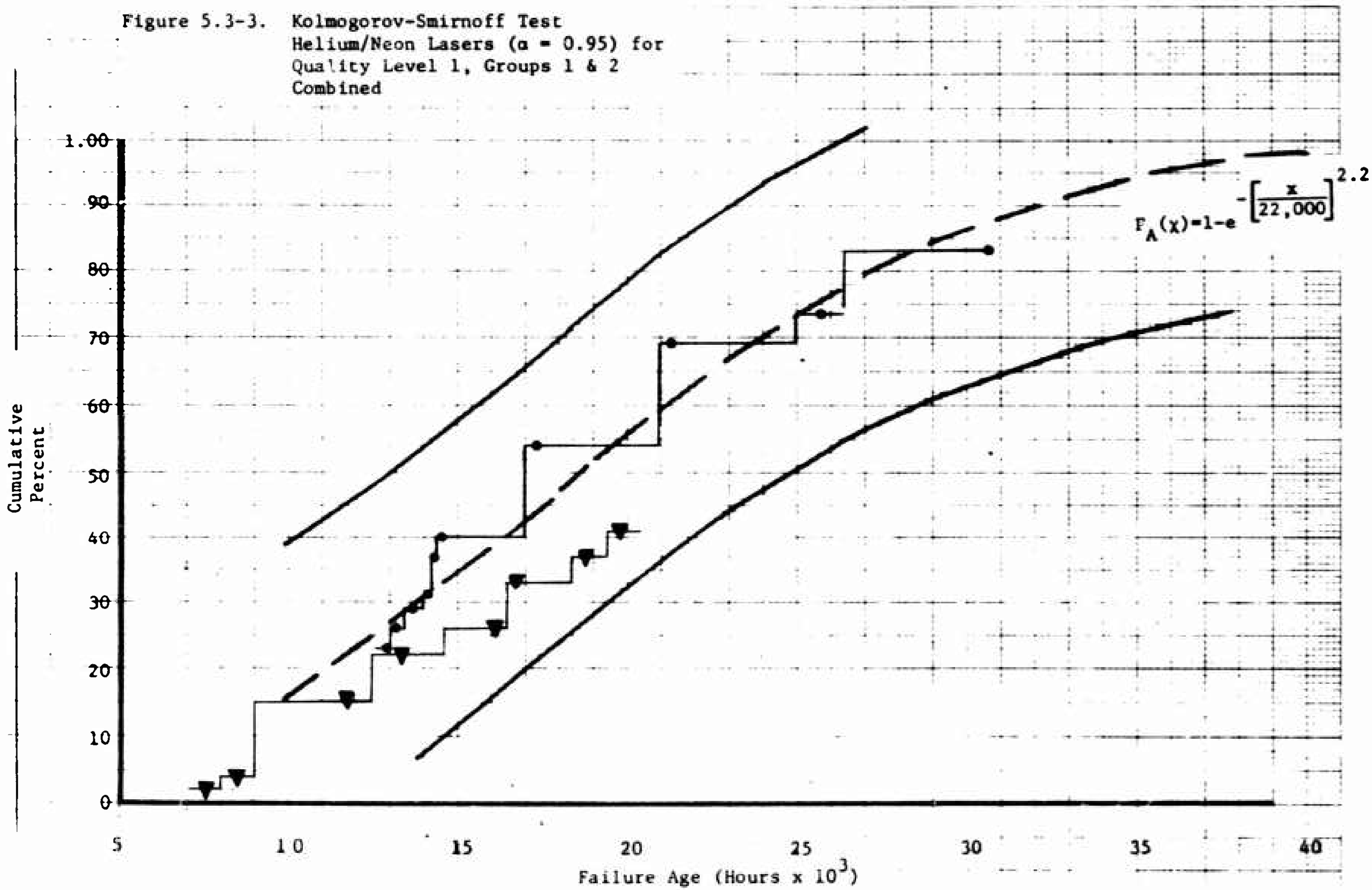


Figure 5.3-2. Weibull Analysis of Helium/Neon Lasers Quality Level 1, Group 2

Figure 5.3-3. Kolmogorov-Smirnoff Test
Helium/Neon Lasers (α = 0.95) for
Quality Level 1, Groups 1 & 2
Combined



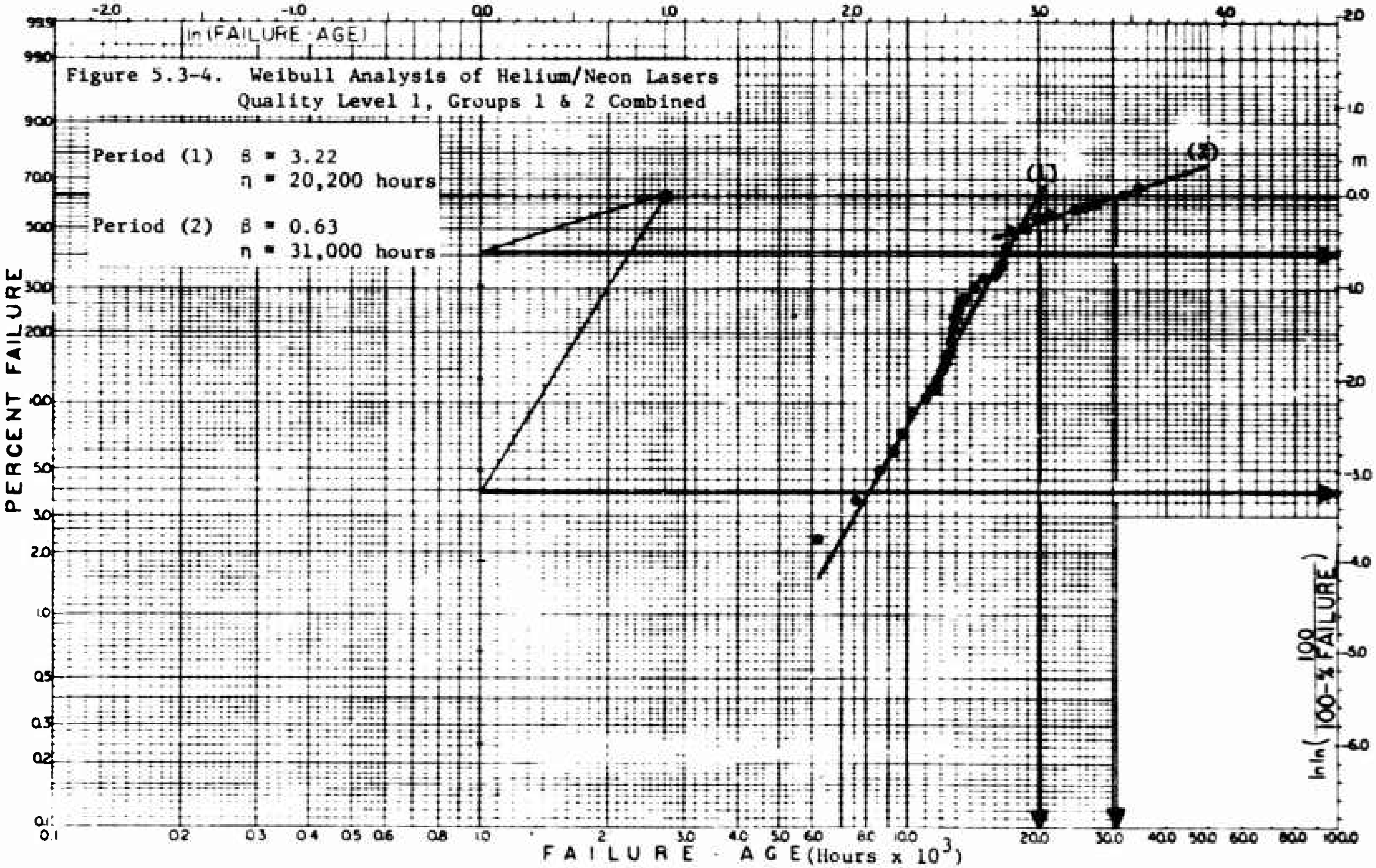


Figure 5.3-4. Weibull Analysis of Helium/Neon Lasers Quality Level 1, Groups 1 & 2 Combined

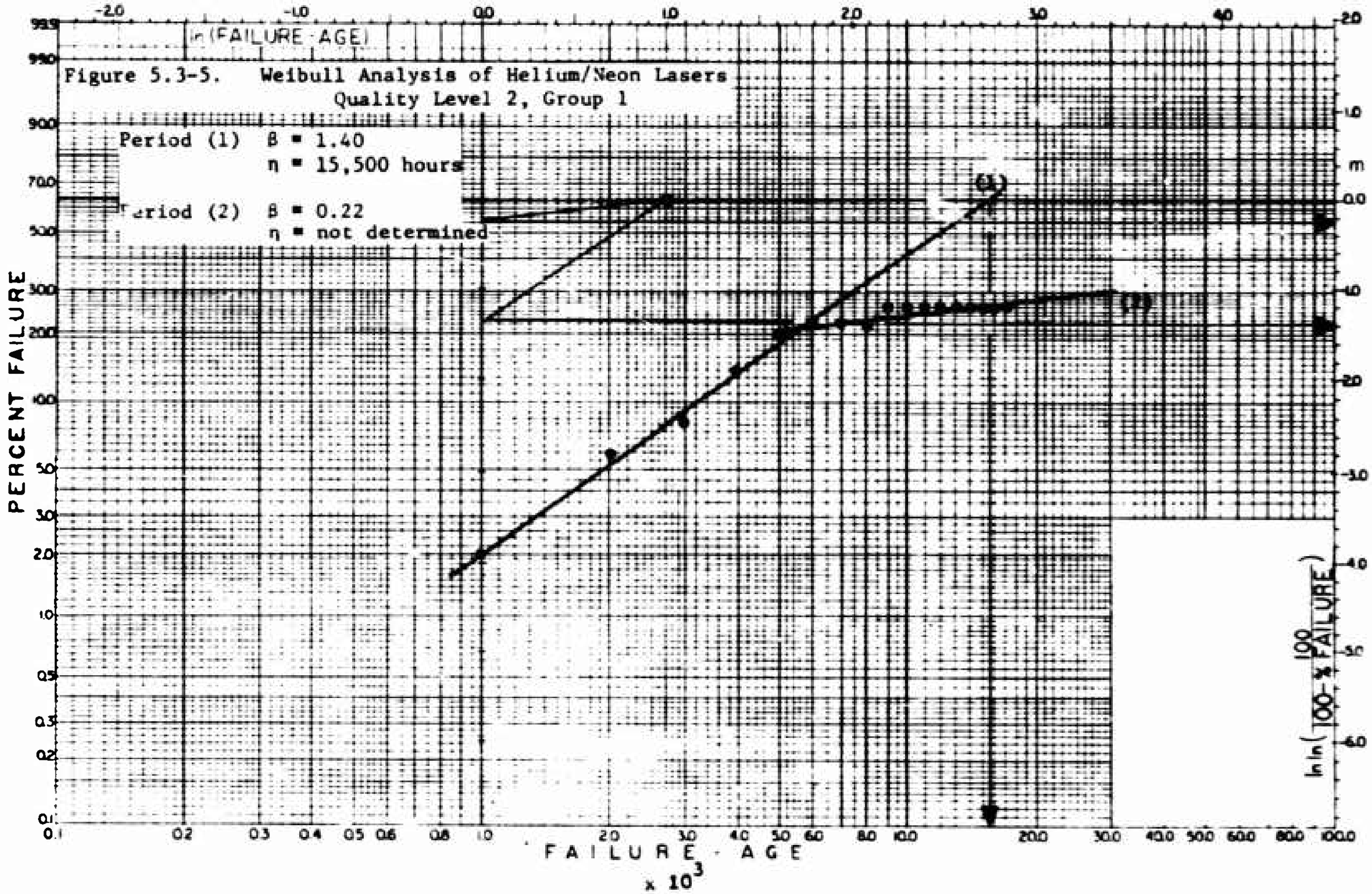


Figure 5.3-5. Weibull Analysis of Helium/Neon Lasers Quality Level 2, Group 1

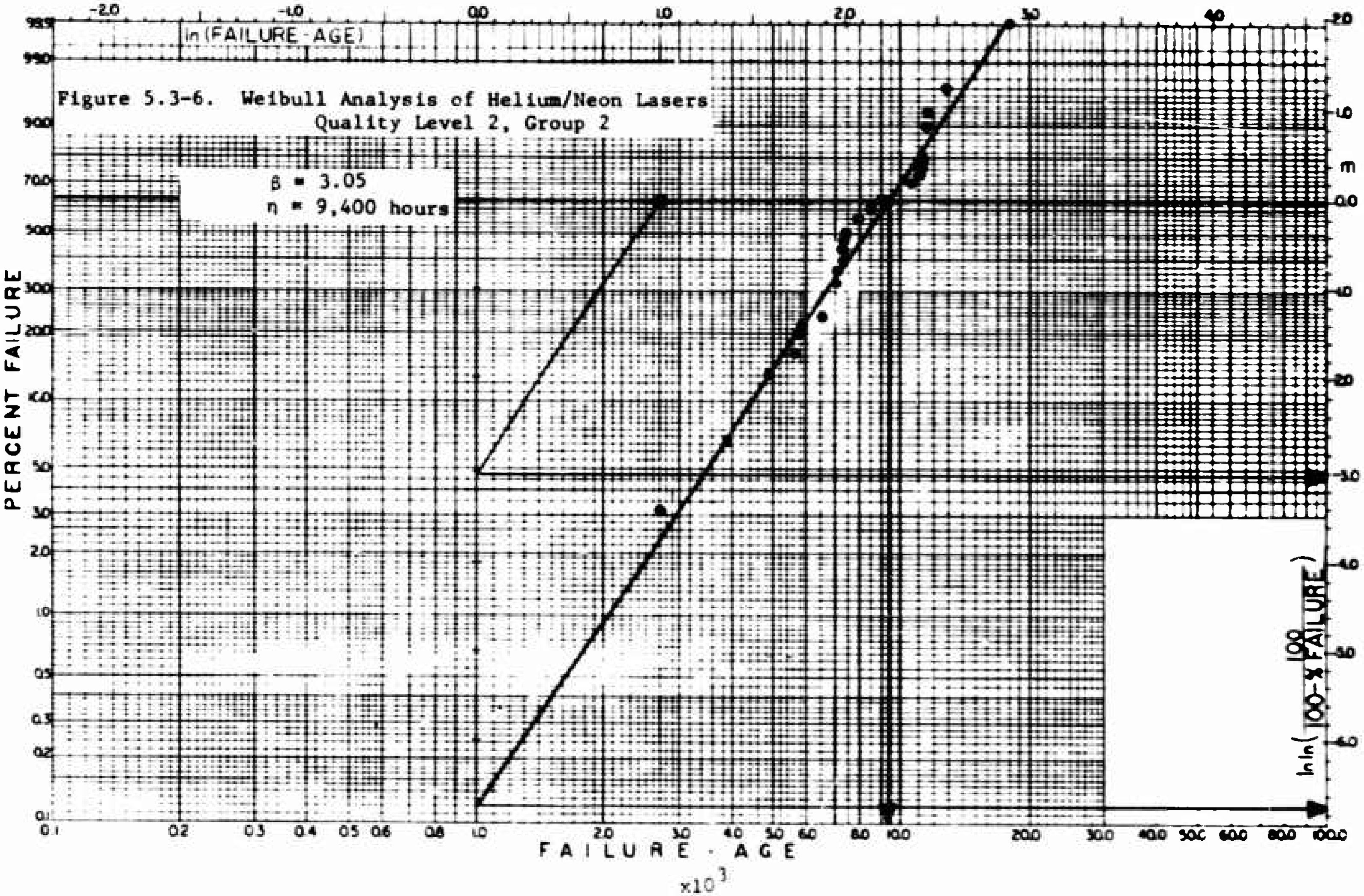


Figure 5.3-6. Weibull Analysis of Helium/Neon Lasers Quality Level 2, Group 2

6.0 LASER RELIABILITY PREDICTION

This section contains failure rate models and failure rate data suitable for predicting reliability of operational laser systems. System models are provided for six major laser types. This encompasses greater than 90 percent of the hardware presently in use.

In addition, laser device and component data are also presented. These data may be used to facilitate predictions for new, limited-use research lasers and require the conventional building block approach to perform a reliability assessment.

Finally, updated laser life characteristics have been included to allow users to estimate the time range when wearout might be expected and better plan for those equipments that are life limited.

6.1 Laser System Failure Rate Prediction Models

This section presents failure rate prediction models for six major classes of laser systems:

Helium/Neon	Sect.6.1.1
Argon Ion	Sect.6.1.2
Carbon Dioxide, Sealed	Sect.6.1.3
Carbon Dioxide, Flowing	Sect.6.1.4
Solid State, Nd:YAG Rod	Sect.6.1.5
Solid State, Ruby Rod	Sect.6.1.6

Because each laser family can be designed using a variety of approaches, the system failure rate prediction models have all been structured on four basic laser functions or categories which are common to all laser families, but may differ in the hardware implementation of a given function. Three of the categories are mandatory and must be considered for every laser type. They are identified as the lasing media, the pumping mechanism, or pump, and the coupling method. In addition to these mandatory ones, an auxiliary category must be considered in order to include peripheral laser subsystems that may be required for cooling or for gas flow regulation purposes. This functional approach to system failure rate prediction for lasers ensures completeness, but allows flexibility so that all major laser elements, environmental application factors, or hardware pecularities within a family can be accounted for and systematically evaluated.

In order to clarify this system failure rate prediction approach, the general laser model is an additive model concept; i.e.

$$\lambda_{LASER} = \lambda_{MEDIA} + \lambda_{PUMP} + \lambda_{COUPLING} + \lambda_{AUXILIARY}$$

The individual values and expressions within each additive term have been iteratively derived and validated from laser device field experience. The initial terms and expressions utilized were obtained either from system engineering judgements based on a review of the data or from suggestions in the literature for special cases.

Examples of media-related hardware and influence factors are the solid state rod, the gas, the gas pressure, the vacuum integrity, the gas mix, any outgassing, and the tube diameter. The electrical discharge, the flashlamp, the power supply, and the energy level are examples of pump-related hardware and influence factors. The coupling category contributors are the "Q" switch, mirrors, windows, crystals, substrates, coatings, and level of dust protection afforded. The auxiliary functional grouping includes coolants, de-ionizers, filters, heat exchangers, seals, O-rings, pumps, pressure regulators, gas flowmeters, tubes, fittings, vacuum valves, and degree of contamination control afforded.

6.1.1 Helium/Neon Lasers

$$\lambda_{He/Ne} = \pi_E \; \lambda_{MEDIA} + \lambda_{PUMP} + \pi_E \; \lambda_{COUPLING} + \lambda_{AUXILIARY}$$

where:

$\lambda_{He/Ne}$ is the helium/neon laser failure rate in failures/10^6 operating hours.

π_E is the environmental application factor, and its value is determined from Table 6.1.1-I.

λ_{MEDIA} is the failure rate contribution of the lasing media, and its value is 84 failures/10^6 operating hours for helium/neon lasers.

λ_{PUMP} is the failure rate contribution of the pumping mechanism which, for helium/neon lasers, is the power supply. The power supply failure rate is to be calculated by the detailed part stress analysis prediction method prescribed for electronic devices in the appropriate sections of MIL-HDBK-217.

$\lambda_{COUPLING}$ is the failure rate contribution of the laser coupling hardware, and its value is 0.1 failures/10^6 operating hours for helium/neon lasers.

$\lambda_{AUXILIARY}$ is the failure rate contribution of the auxiliary equipment. Since helium/neon lasers do not normally have auxiliary equipment, its value is normally zero.

It should be noted that the helium/neon laser failure rate prediction model can be simplified and rewritten as:

$$\lambda_{He/Ne} = 84.1 \; \pi_E + \lambda_{POWER\ SUPPLY}$$

Based on test-to-failure data, the failure rate for helium/neon lasers also appears to be constant over the major portion of the laser's expected life range or span. Reliability, therefore, of helium/neon lasers cannot be improved by preventive maintenance replacement; i.e., no limited life items.

TABLE 6.1.1-I

Application Environmental Factor, π_E

APPLICATION ENVIRONMENT	SYMBOL	π_E	Helium/Neon	Argon Ion	CO_2 Sealed	CO_2 Flowing	Solid State Nd:YAG	Solid State Ruby
Ground, Benign	G_B	0.2	X	X	X	X	X	X
Space Flight	S_F	0.2	X					
Ground, Fixed	G_F	1.0	X	X	X	X	X	X
Airborne, Inhabited	A_I	5.0	X				X	X
Naval, Sheltered	N_S	5.0	X				X	X
Ground, Mobile	G_M	5.0	X				X	X
Naval, Unsheltered	N_U	5.0	X				X	X
Airborne, Unihabited	A_U	8.0	X				X	X
Satellite or Missile Launch	M_L	8.0	X					

Note:

X Indicates current or past application. These data were derived from operational systems such as the ground mobile AN/VVS-1 and the airborne AN/AVQ-9.

6.1.2 Argon Ion Lasers

$$\lambda_{AI} = \pi_E \lambda_{MEDIA} + \lambda_{PUMP} + \pi_E \lambda_{COUPLING} + \lambda_{AUXILIARY}$$

where:

λ_{AI} is the argon ion laser failure rate in failures/10^6 operating hours.

π_E is the environmental application factor and its value is determined from Table 6.1.1-I.

λ_{MEDIA} is the failure rate contribution of the lasing media, and its value is 457 failures/10^6 operating hours for argon ion lasers.

λ_{PUMP} is the failure rate contribution of the pumping mechanism which, for argon ion lasers, is the power supply. The power supply failure rate is to be calculated by the detailed part stress analysis prediction method prescribed for electronic devices in the appropriate Sections of MIL-HDBK-217.

$\lambda_{COUPLING}$ is the failure rate contribution of the laser coupling hardware, and its value is 6 failures/10^6 operating hours for argon ion lasers. It should be noted that the predominant argon laser failure mechanism is related to the gas media (as reflected in λ_{MEDIA}); however, when the tube is refilled periodically (preventive maintenance) the mirrors (as part of $\lambda_{COUPLING}$) can be expected to deteriorate after approximately 10^4 hours of operation if in contact with the discharge region.

$\lambda_{AUXILIARY}$ is the failure rate contribution of the auxiliary cooling equipment, and its value is to be calculated from the appropriate item failure rates listed in Table 6.2-I and the parts count method described in Section 3.0 of MIL-HDBK-217.

It should be noted that the argon ion failure rate prediction model can be simplified and rewritten as:

$$\lambda_{AI} = 463 \pi_E + \lambda_{POWER\ SUPPLY} + \lambda_{AUXILIARY}$$

6.1.3 Carbon Dioxide, Sealed Lasers

$$\lambda_{CO_2\ SEALED} = \pi_E \pi_O \pi_B \lambda_{MEDIA} + \lambda_{PUMP} + \pi_E \pi_{OS} \lambda_{COUPLING} + \lambda_{AUXILIARY}$$

where:

$\lambda_{CO_2\ SEALED}$ is the carbon dioxide sealed laser failure rate in failures/10^6 operating hours.

π_E is the environmental application factor, and its value is determined from Table 6.1.1-I.

π_O is the gas overfill factor, and its value is determined from Table 6.1.3-I.

π_B is the ballast factor, and its value is determined from Table 6.1.3-II.

λ_{MEDIA} is the failure rate contribution of the lasing media, and its value is determined from Table 6.1.3-III which is based on the empirical expression:

$$\lambda_{MEDIA} = \left[\frac{69\ I - 450ma}{1ma}\right]\left[\frac{\text{failures}}{10^6\ \text{operating hours}}\right]$$

where: I = Current in milliamperes and $\geq$ 10ma and $\leq$ 150 ma.

λ_{PUMP} is the failure rate contribution of the pumping mechanism which, for carbon dioxide sealed lasers, is the power supply. The power supply failure rate is to be calculated by the detailed part stress analysis prediction method prescribed for electronic devices in the appropriate Sections of MIL-HDBK-217.

π_{OS} is the active optical surface application factor, and its value is determined from Table 6.1.3-IV and Figure 6.1.3-1.

$\lambda_{COUPLING}$ is the failure rate contribution of the laser coupling hardware; that is, lenses, mirrors, prisms, exit windows, etc. Its value is 10 failures/10^6 operating hours for carbon dioxide sealed lasers

$\lambda_{AUXILIARY}$ is the failure rate contribution of the auxiliary cooling equipment, and its value is to be calculated from the appropriate item failure rates listed in Table 6.2-I and the parts count method described in Section 3.0 of MIL-HDBK-217.

TABLE 6.1.3-I
GAS OVERFILL FACTOR, π_O

CO_2 OVERFILL PERCENT *	π_O
0	1.00
25	0.75
50	0.50

*Overfill percent is based on the percent increase over the optimum CO_2 partial pressure which is normally in the range of 1.5 to 3 Torr for most sealed CO_2 lasers.

TABLE 6.1.3-II
BALLAST FACTOR, π_B

PERCENT OF BALLAST VOLUMETRIC INCREASE	π_B
0	1.0
50	0.5
100	0.3
150	0.2
200	0.1

TABLE 6.1.3-III

λ_{MEDIA} Values for CO_2 Sealed Lasers

Current, I* (in milliamperes)	λ_{MEDIA} (failures/10^6 hours)
10	240
20	930
30	1,620
40	2,310
50	3,000
100	6,450
150	9,900

* The current I is tube current, and the values for I must be equal to or greater than 10 and equal to or less than 150 milliamperes.

TABLE 6.1.3-IV

Optical Surface Factor, π_{OS}

Number of Active* Optical Surfaces	π_{OS}
1	1
2	2
3	3
4	4
5	5
6	6
7	7
8	8

* ONLY ACTIVE OPTICAL SURFACES ARE COUNTED. AN ACTIVE OPTICAL SURFACE IS ONE WITH WHICH THE LASER ENERGY OR BEAM INTERACTS. See Figure 6.1.3-1 for descriptions.

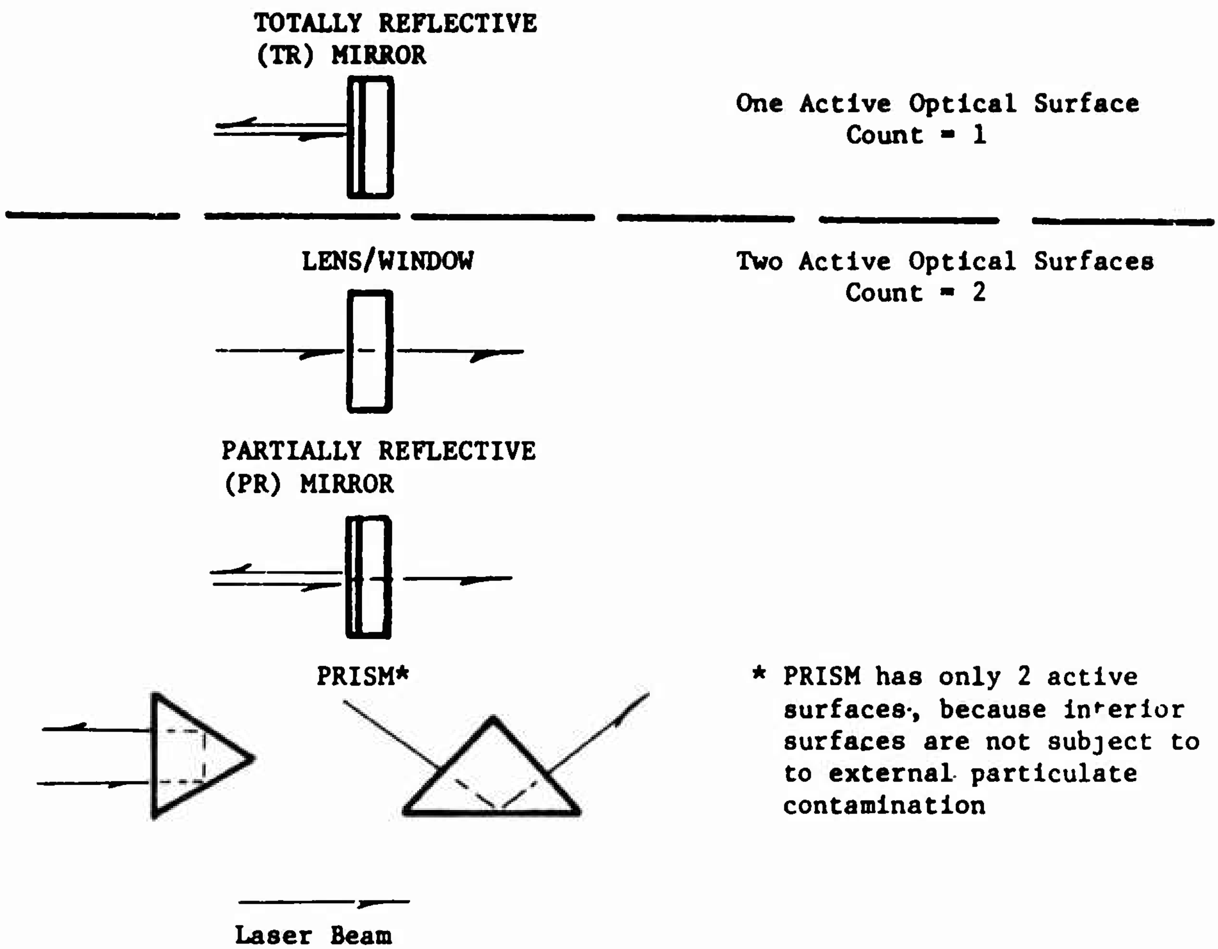


FIGURE 6.1.3-1. Examples of Active Optical Surfaces and Count

6.1.4 Carbon Dioxide, Flowing Lasers

$$\lambda_{CO_2\ FLOWING} = \pi_E\ \lambda_{MEDIA} + \lambda_{PUMP} + \pi_E\ \pi_{OS}\ \lambda_{COUPLING} + \lambda_{AUXILIARY}$$

where:

$\lambda_{CO_2\ FLOWING}$ is the carbon dioxide flowing laser failure rate in failures/10^6 operating hours.

π_E is the environmental application factor, and its value is determined from Table 6.1.1-I.

λ_{MEDIA} is the failure rate contribution of the lasing media and its value approaches zero for carbon dioxide flowing lasers. This is because this type of laser is much less susceptible to leaks and long term gas decomposition than a sealed system. The flowing gas also acts as a purge in removing contamination and precluding its entrapment. Therefore, except for tube breakage (which has rarely been observed) optics deterioration appears the predominant failure mechanism and this is accounted for under $\lambda_{COUPLING}$.

λ_{PUMP} is the failure rate contribution of the pumping mechanism which for carbon dioxide flowing lasers is the power supply. The power supply failure rate is to be calculated by the detailed part stress prediction method prescribed for electronic devices in the appropriate Sections of MIL-HDBK-217.

π_{OS} is the active optical surface application factor, and its value is determined from Table 6.1.3-IV.

$\lambda_{COUPLING}$ is the failure rate contribution of the laser coupling hardware; that is, lenses, mirrors, prisms, exit windows, etc. Its value is determined from Table 6.1.4-I which is based on the empirical expression:

$$\lambda_{COUPLING} = \left[\frac{300\ P}{1Kw}\right]\left[\frac{\text{failures}}{10^6\ \text{operating hours}}\right]$$

where P = average power in kilowatts

$\lambda_{AUXILIARY}$ is the failure rate contribution of the auxiliary cooling equipment and the gas flow regulation equipment, and their values are to be calculated from the appropriate item failure rates listed in Table 6.2-I and the parts count method described in Section 3.0 of MIL-HDBK-217.

It should be noted that the carbon dioxide flowing laser failure rate prediction model can be simplified and rewritten as:

$$\lambda_{CO_2\ FLOWING} = \lambda_{POWER\ SUPPLY} + (300\ P)\ \pi_E\ \pi_{OS} + \lambda_{AUXILIARY}$$

TABLE 6.1.4-I

$\lambda_{COUPLING}$ Values* for CO_2 Flowing Lasers

Power (kilowatts)	$\lambda_{COUPLING}$ (failures/10^6 hours)
0.01	3
0.1	30
1.0	300

*Note: The values shown are valid only for power levels up to one kilowatt. Beyond this range other glass failure mechanisms begin to predominate and alter the $\lambda_{COUPLING}$ values. It should also be noted that CO_2 flowing laser optical devices are the primary source of failure occurrence. A preventive maintenance program on optical devices would greatly extend laser life; however procedures must be tailored to the individual design of each system. Typical optical cleaning methods are as follows:

1. Use dry, pressurized air and a camel hair brush to remove dust, particulates, etc.
2. Rub with high quality lens tissue using moisture from breath (if necessary).
3. Flush with distilled water and a mild laboratory detergent (if necessary).
4. Cautions -
   a. Use of special gloves for handling recommended.
   b. Careful use of 20 to 30 percent alcohol solutions with sterile cotton swabs (change swabs frequently).

6.1.5 Solid State, Nd:YAG Rod Lasers

$$\lambda_{Nd:YAG} = \pi_E \lambda_{MEDIA} + \lambda_{PUMP} + \pi_E \pi_C \pi_{OS} \lambda_{COUPLING} + \lambda_{AUXILIARY}$$

where:

$\lambda_{Nd:YAG}$ is the solid state neodymium doped yttrium-aluminum-garnet rod laser failure rate in failures/10^6 operating hours.

π_E is the environmental application factor, and its value is determined from Table 6.1.1-I.

λ_{MEDIA} is the failure rate contribution of the lasing media, and its value is 0.1 failures/10^6 operating hours for Nd:YAG lasers.

λ_{PUMP} is the failure rate contribution of the pumping mechanism which, for solid state lasers, is highly affected by the flashlamp or flash tube contribution as well as the power supply contribution and can be expressed as:

$$\lambda_{PUMP} = \pi_E \lambda_{PUMP\ HOURS} + \lambda_{POWER\ SUPPLY}$$

where:

π_E is the environmental application factor, and its value is determined from Table 6.1.1-I.

$\lambda_{PUMP\ HOURS}$ is the failure rate contribution of the flashlamp or flashtube in failures/10^6 operating hours, and its value is determined by converting pump pulses from failures per 10^6 pulses to failures/10^6 operating hours. The value for $\lambda_{PUMP\ HOURS}$ is determined as indicated in Figures 6.1.5-1 and 6.1.5-2.

$\lambda_{POWER\ SUPPLY}$ is the failure rate contribution of the laser power supply electronics, and its value is to be determined by the detail part stress analysis prediction method prescribed for electronic devices in the appropriate Sections of MIL-HDBK-217.

π_C is the coupling cleanliness factor, and its value is to be determined from Table 6.1.5-III.

π_{OS} is the active optical surface application factor and its value is determined from Table 6.1.3-V and Figure 6.1.3-1.

$\lambda_{COUPLING}$ is the failure rate contribution of the laser coupling hardware; that is, lenses, mirrors prisims, exit window, etc. Its value is 16.3 failures/10^6 operating hours for solid state Nd:YAG lasers.

$\lambda_{AUXILIARY}$ is the failure rate contribution of the auxiliary cooling equipment, and its values are to be calculated from the appropriate item failure rates listed in Table 6.2-I and in the parts count method described in Section 3.0 of MIL-HDBK-217.

It should be noted that the solid state Nd:YAG laser failure rate prediction model can be rewritten as:

$$\lambda_{Nd:YAG} + \pi_E \left(\lambda_{MEDIA} + \lambda_{PUMP\ HOURS} + \pi_C\, \pi_{OS}\, \lambda_{COUPLING}\right) + \lambda_{POWER\ SUPPLY} + \lambda_{AUXILIARY}$$

The empirical formula used to determine $\lambda_{PUMP\ HOURS}$ for xenon lamps is:

$$\lambda_{PUMP\ HOURS\ XENON} = \left[\pi_{REP}\right]\left[2000\left(\frac{E_j}{dL\sqrt{T}}\right)^{8.58}\right]\left[\pi_{COOL}\right]\left[\frac{\text{failures}}{10^6\ \text{operating-hours}}\right]$$

where:

$\lambda_{PUMP\ HOURS\ XENON}$ is the failure rate contribution of the xenon flashlamp or flashtube* in failures/10^6 operating hours. The flashlamps evaluated herein are standard, linear types used for conventional military solid state laser systems.

π_{REP} is the pulse or repetition rate factor used to convert from failures per 10^6 pulses to failures/10^6 operating hours, and its value is determined from Table 6.1.5-I.

E_j is the flashlamp or flashtube input energy per pulse in joules, and its value is determined from the actual or design input energy parameter except that for input energy levels equal to or less than 30 joules $E_j = 30$.

d is the flashlamp or flashtube inside diameter in millimeters, and its value is determined from the actual design parameter of the flashlamp utilized.

L is the flashlamp or flashtube arc length in inches, and its value is determined from the actual design parameter of the flashlamp utilized.

$\sqrt{T}$ is the truncated pulse width in microseconds, and its value is determined from the actual design parameter of the pulse forming network (PFN) used to pulse the flashlamp or flashtube. Pulse tails do not affect reliability, and the maximum value of T is 100 microseconds for any truncated pulse width exceeding 100 microseconds. For shorter duration pulses, pulse width is to be measured at 10 percent of the maximum current amplitude.

π_{COOL} is the cooling factor due to various cooling media immediately surrounding the flashlamp or flashtube, and its value is determined from Table 6.1.5-II.

*Note: Typical values for Xenon flashlamps in military Nd:YAG rangefinders and designators are $E_j = 40$ joules, d = 4 millimeters, L = 2 inches, and T = 100 microseconds. The repetition or pulse rate ranges from 1 to 20 pps, and the lamps are normally liquid cooled.

Figure 6.1.5-1 Determination of $\lambda_{PUMP\ HOURS}$ for Xenon Flashlamps

TABLE 6.1.5-I

Repetition Rate Factors, π_{REP}

Repetition or Pulse* Rate (pulses per second)	π_{REP}
1	3,600
5	18,000
10	36,000
15	54,000
20	72,000

*Note: Repetition rates for military solid state lasers are generally in the 1 to 20 pps range. Repetition rates other than shown have not been observed and corresponding π_{REP} values certified.

TABLE 6.1.5-II

Flashlamp Cooling Factors, π_{COOL}

COOLING MEDIA	π_{COOL}
Gas, Air	1.0
Gas, Inert	1.0
Liquid, Deionized Water	0.1
Liquid, Water-Glycol	0.1
Liquid, Fluorocarbon	0.1

TABLE 6.1.5-III

Coupling Cleanliness Factor

CLEANLINESS LEVEL*	π_C
Rigorous cleanliness procedures, equipment, and trained maintenance personnel. Plus bellows provided over optical train.	1
Minimal precautions during opening, maintenance, repair, and testing. Plus bellows provided over optical train.	30
Minimal precautions during opening, maintenance, repair, and testing. No bellows provided over optical train.	60

*NOTE: Although sealed systems tend to be reliable once compatible materials have been selected and proven, extreme care must still be taken to prevent the entrance of particulates during manufacturing, field flashlamp replacement, or routine maintenance/repair. Contamination is the major cause of solid state laser malfunction, and special provisions and vigilance must continually be provided to maintain the cleanliness level required. π_C values can vary from 1 up to 60.

The emperical formula used to determine $\lambda_{PUMP\ HOURS}$ for Krypton lamp is:

$$\lambda_{PUMP\ HOURS\ KRYPTON} = \left[625\right]\left[10^{(0.9\ \frac{P}{L})}\right]\left[\pi_{COOL}\right]\left[\frac{\text{failures}}{10^6\text{operating-hours}}\right]$$

where:

$\lambda_{PUMP\ HOURS\ KRYPTON}$ is the failure rate contribution of the krypton flashlamp or flashtube in failures/10^6 operating hours. The flashlamps evaluated herein are the continuous wave (CW) type and are most widely used for commercial solid state applications. They are approximately 7mm in diameter and 5 to 6 inches long. Average power is typically 4 KW.

P is the average input power in kilowatts, and its value is determined from the actual design parameter for the flashlamp utilized.

L is the flashlamp or flashtube arc length in inches, and its value is determined from the actual design parameter of the flashlamp utilized.

π_{COOL} is the cooling factor due to various cooling media immediately surrounding the flashlamp or flashtube, and its value is determined from Table 6.1.5-II.

Figure 6.1.5-2 Determination of $\lambda_{PUMP\ HOURS}$ for Krypton Flashlamps

6.1.6 Solid State, [illegible] y Rod Lasers

$$\lambda_{RUBY} = \pi_E \lambda_{MEDIA} + \lambda_{PUMP} + \pi_E \pi_C \pi_{OS} \lambda_{COUPLING} + \lambda_{AUXILIARY}$$

λ_{RUBY} is the solid state ruby rod laser failure rate in failure/10^6 operating hours

π_E is the environmental application factor, and its value is determined from Table 6.1.1-I.

λ_{MEDIA} is the failure rate contribution of the pumping mechanism in failures/10^6 operating hours, and its value is determined by converting from failures per 10^6 pulses to failures/10^6 operating hours. The value for λ_{MEDIA} is determined as indicated in Figure 6.1.6-1.

λ_{PUMP} is the failure rate contribution of the pumping mechanism which for solid state lasers is highly affected by the flashlamp or flashtube contribution as well as the power supply contribution and can be expressed as:

$$\lambda_{PUMP} = \pi_E \pi_{\substack{PUMP \\ HOURS}} + \pi_{POWER\ SUPPLY}$$

where:

π_E is the environmental application factor, and its value is determined from Table 6.1.1-I.

$\lambda_{\substack{PUMP \\ HOURS}}$ is the failure rate contribution of flashlamp or flashtube in failures/10^6 operating hours, and its value is determined by converting from failures per 10^6 pulses to failures/10^6 operating hours. The value for $\lambda_{\substack{PUMP \\ HOURS}}$ is determined as indicated in Figures 6.1.5-1 or 6.1.5-2 as applicable.

$\lambda_{POWER\ SUPPLY}$ is the failure rate contribution of the laser power supply electronics, and its value is to be determined by the detail part stress analysis prediction method prescribed for electronic devices in the appropriate Sections of MIL-HDBK-217.

π_C is the coupling cleanliness factor, and its value is to be determined from Table 6.1.5-III.

π_{OS} is the active optical surface application factor, and its value is determined from Table 6.1.3-IV and Figure 6.1.3-1.

$\lambda_{COUPLING}$ is the failure rate contribution of the laser coupling hardware; that is, lenses, mirrors, prisms, exit windows, etc. Its value is 16.3 failures/10^6 operating hours for solid state ruby lasers.

$\lambda_{AUXILIARY}$ is the failure rate contribution of the auxiliary cooling equipment, and its values are to be calculated from the appropriate item failure rates listed in Table 6.2-I and the parts count method described in Section 3.0 of MIL-HDBK-217.

It should be noted that the solid state ruby failure rate prediction model can be rewritten as:

$$\lambda_{RUBY} = \pi_E (\lambda_{MEDIA} + \lambda_{PUMP\ HOURS} + \pi_C \pi_{OS} \lambda_{COUPLING}) + \lambda_{POWER\ SUPPLY} + \lambda_{AUXILIARY}$$

The empirical formula used to determine λ_{MEDIA} is:

$$\lambda_{MEDIA} = \left[\pi_{REP}\right]\left[43.5 \quad F^{2.52}\right]\left[\frac{\text{failures}}{10^6 \text{ operating-hours}}\right]$$

where:

π_{REP} is the pulse or repetition rate factor used to convert from failures/10^6 pulses to failures/10^6 operating hours, and its value is determined from Table 6.1.5-I.

F is the energy density in Joules per centimeter^2 over the cross sectional area of the laser beam which is nominally equivalent to the cross sectional area of the laser rod, and its value is determined from the actual design parameter of the laser rod utilized.

Figure 6.1.6-1 Determination of λ_{MEDIA} for Solid State Ruby Lasers

6.1.7 Examples of Laser Failure Rate Prediction

6.1.7.1 Example of Failure Rate Calculation for He/Ne Lasers

Given. A helium neon laser device to be used in a military ground mobile application.

Step 1 - The failure rate model of Section 6.1.1 applies:

$$\lambda_{He/Ne} = 84.1\ \pi_E + \lambda_{POWER\ SUPPLY}.$$

Step 2 - From Table 6.1.1-I, $\pi_E = G_M = 5.0$.

Step 3 - Calculate $\lambda_{POWER\ SUPPLY}$:

Prepare a part stress failure rate estimate per appropriate Sections of MIL-HDBK-217 based on the detailed power supply parts list, including part description, quality, electrical stress, thermal stress, and other applicable influence factors and base failure rates. Such an analysis might yield a λ power supply of 165.6 failures/10^6 operating hours in a ground mobile application.

Step 4 - Calculate $\lambda_{He/Ne}$:

$$\lambda_{He/Ne} = 84.1\ \pi_E + \lambda_{POWER\ SUPPLY}$$

$$= 84.1\ (5) + 165.6$$

$= 586.1$ failures/10^6 hours in a ground mobile application.

6.1.7.2 Example of Failure Rate Calculation and Reliability Prediction for a Solid State, Nd:YAG Rod Laser

Given: A military aircraft carried Nd:YAG laser designator utilizing a Xenon flashlamp which is cooled by a eutectic water-glycol solution. Design parameters include:

Pulse or Repetition Rate	=	10 pps
Flashlamp input energy (per pulse)	=	30 joules
Flashlamp inside diameter	=	4 millimeters
Flashlamp arc length	=	2 inches
Pulse width (including both tails)	=	120 microseconds

Optical train enclosed in bellows.

In addition, strict field maintenance, repair, and test procedures will be written, validated, and provided for use by trained specialists in appropriately clean and controlled facilities.

Find: Airborne failure rate ($\lambda_{Nd:YAG}$) and probability of successfully completing a one hour operational mission.

Step 1 - The failure rate model of Section 6.1.5 applies:

$$\lambda_{Nd:YAG} = \pi_E(\lambda_{MEDIA} + \lambda_{PUMP\ HOURS} + \pi_C\ \pi_{OS}\ \lambda_{COUPLING}) + \lambda_{POWER\ SUPPLY} + \lambda_{AUXILIARY}.$$

Step 2 - From Table 6.1.1-I, $\pi_E = A_I = 5.0$.

Step 3 - From Paragraph 6.1.5, $\lambda_{MEDIA} = 0.1$ failures/10^6 operating hours for solid state Nd:YAG lasers.

Step 4 - Calculate $\lambda_{PUMP\ HOURS}$ for Xenon flashlamps from

$$\lambda_{PUMP\ HOURS\ XENON} = \pi_{REP}\left[2000\left(\frac{E_i}{dL\sqrt{T}}\right)^{8.58}\right]\pi_{COOL}$$

From the given design parameters and Figure 6.1.5-1 notes:

4_b - E_j = 30 joules

d = 4 mm

L = 2 in

T = 100 μs (refer to Figure 6.1.5-1)

4_c - From Table 6.1.5-II, π_{COOL} = 0.1 for Liquid, Water-Glycol cooling media.

4_d - $$\lambda_{\substack{PUMP\\HOURS\\XENON}} = (36{,}000)\left[2000\left(\frac{30}{4\times 2\sqrt{100}}\right)^{8.58}\right](0.1)$$

= 1,591 failures/10^6 operating hours

Step 5 - From Table 6.1.5-III, π_C = 1 for the most stringent cleanliness level (as is specified).

Step 6 - From Table 6.1.3-IV and Figure 6.1.3-1, 'etermine π_{OS}:

6_a - Make parts list and count of optical train:

(1) One totally reflective (TR) mirror
(2) One Prismatic "Q" Switch
(3) One partially reflective (PR) mirror
(4) One exit lens or win'ow

6_b - Determine active optical surfaces:

(1) One TR mirror = 1
(2) One "Q" Switch = 2
(3) One PR mirror = 2
(4) One exit lens = 2

Active Optical Surfaces = 7 total

6_c - From Table 6.1.3-IV, π_{OS} = 7

Step 7 - From Paragraph 6.1.5, $\lambda_{COUPLING}$ = 16.3 failures/10^6 operating hours for solid state Nd:YAG lasers.

Step 8 - Calculate $\lambda_{POWER\ SUPPLY}$:

Prepare a part stress failure rate estimate per appropriate Sections of MIL-HDBK-217 based on the detailed power supply parts list, including part description, quality, electrical stress, thermal stress, and other applicable influence factors and base failure rates. Table 4.11-I is just such an analysis for an airborne Nd:YAG laser power supply; utilizing this prediction $\lambda_{POWER\ SUPPLY}$ = 149.4 failures/10^6 operating hours.

Step 9 - Calculate $\lambda_{AUXILIARY}$

9_a - Make parts list and count of auxiliary items. (Cooling only; Gas regulation not applicable). Assign item failure rates obtained from Table 6.2-I or RADC-TR-74-268 and sum:

(1)	One Hydraulic Pump, Coolant	649.5/10^6
(2)	One Heat Exchanger	2.8/10^6
(3)	Tubes, Coolant	600.0/10^6
	Σ =	1,252.3/10^6

9_b - $\lambda_{COOLING\ SYSTEM}$ = 1,252.3 failures/10^6 operating hours

Step 10 - Calculate $\lambda_{Nd:YAG}$:

$$\lambda_{Nd:YAG} = \pi_E(\lambda_{MEDIA} + \lambda_{PUMP\ HOURS} + \pi_C\ \pi_{OS}\ \lambda_{COUPLING}) + \lambda_{POWER\ SUPPLY} + \lambda_{AUXILIARY}$$

$$= (5)\left[0.1/10^6 + 1{,}591/10^6 + (1)(7)(16.3/10^6)\right] + 149.6/10^6 + 1{,}252.3/10^6$$

$$= 9{,}927.9 \text{ failures}/10^6 \text{ operating hours}$$

Step 11 - Calculate reliability, assuming the exponential:

The probability of successfully completing a one hour mission would be:

$$P_{S(one\ hour)} = R = e^{-\lambda t} = e^{-(9{,}927.9/10^6)(1)}$$

$$= 0.990$$

Note: This value is in very close agreement with the observed operational reliability for a similar system.

6.2 Laser Item Failure Rates

System math models for the more commonly deployed laser systems are given in Section 6.1 and should be used for normal military applications. Reliability models, however, for some research type lasers or other special type lasers are not given in Section 6.1. Reliability predictions for these low population laser device types can be calculated using the item failure rate data in Table 6.2-I and the functional parts building block method described in Section 3.0 of MIL-HDBK-217.

The item failure rate information contained in Table 6.2-I is based on a composite average computed from field data observed in the ground and aircraft environments for several different kinds of lasers operated at various power levels. Predictions resulting from these generic type of data should not be completely expected to agree with the more rigorous methods given in Section 6.1.

The failure rate data of Table 6.2-I will also be useful for making preliminary estimates when complete stress data are not available, such as during concept formulation or early design phases. The initial prediction thus made should be updated and revised by the more rigorous methods of Section 6.1 as detailed design information is made available.

The failure rate for any items for which zero failures were observed is a point estimate calculated as a function of total item-hours and the Chi-Square (χ^2) value obtained from the upper single-sided 60 percent confidence level at two degrees of freedom. The 90 percent two-sided confidence limits have been calculated and shown for all items for which one or more failures were observed. This has been done because the magnitude (item-hours) of the laser data bases is much smaller than those available for conventional electronic parts and components.

When a failure rate cannot directly be established from field data on an laser item of special interest, a failure rate can be synthesized from another laser item which is similar in function, construction, and application. For instance, the general mirror failure rate is listed in Table 6.2-I as an average expected value of 18.4 failures per million hours. To establish a failure rate for an etalon mirror, one might assume item similarity in function, construction, and application and presume and assign a value of 18.4 also. This value may be adjusted because of mitigating stresses or conditions within the band of 10.9 and 29.2 failures per million hours as defined by the Lower Confidence Limit (LCL) and Upper Confidence Limit (UCL).

All observed failures in Table 6.2-I are catastrophic failures except lamps and lasers which are a mixture of catastrophic and end-of-life; i. e., degradation of a magnitude which precluded proper operation as defined by the system specification.

TABLE 6.2-I
SUMMARY OF DATA COLLECTED BY LASER ITEM

LASER ITEM DESCRIPTION	OBSERVED ITEM FAILURES	ITEM-HOURS OR ITEM-PULSES* (x10^6)	FAILURE RATE (λ) [FAILURES / 10^6 hours or pulses*] EXPECTED	LCL	UCL
Anode, gas laser	0	0.078	11.7	----	---
Bellows, dust protective	3	0.040	75.0	20.5	193.7
Cathode, gas laser	0	0.048	19.1	----	---
Cavity, elliptical	3	0.167	18.0	4.9	46.5
Crystals, various*	2	0.009* pulses	222.2*	39.5*	700.0*
De-Ionizer, coolant system	0	0.154	6.0	----	---
Dye, laser	2	0.001	1923.1	341.8	6057.7
Dye, laser*	0	0.450* pulses	2.0*	----	---
Electrode, general	0	0.093	9.8	----	---
Filament, gas laser	0	0.001	909.6	----	---
Filter, gaseous, coolant system	Use RADC-TR-75-22**				
Filter, liquid, coolant system	Use RADC-TR-75-22**				
Filter, exit	2	0.002	878.7	156.2	2768.0
Flowmeter, gas	2	0.033	60.6	10.6	190.9
Fitting, hydraulic	Use RADC-TR-75-22**				
Gasket, coolant system	Use RADC-TR-75-22**				
Grating, diffraction	0	0.065	14.1	-----	---
Heat exchanger	Use RADC-TR-75-22**				
Lamp, krypton linear	Refer to Table 6.3-I				

* Indicates Pulses
** AD-005657

TABLE 6.2-I (continued)
SUMMARY OF DATA COLLECTED BY LASER ITEM

LASER ITEM DESCRIPTION	OBSERVED ITEM FAILURES	ITEM-HOURS OR ITEM-PULSES* (x10^6)	FAILURE RATE (λ) [FAILURES / 10^6 hours or pulses*] EXPECTED	LCL	UCL
Lamp, tungsten halogen	Refer	to Table 6.3-I			
Lamp, xenon helical*	14	1.677* pulses	8.3*	5.0*	13.1*
Lamp, xenon linear	Refer	to Table 6.3-I			
Laser, argon	Refer	to Section 6.1			
Laser, CO_2, flowing	Refer	to Section 6.1			
Laser, CO_2, sealed	Refer	to Section 6.1			
Laser, gyro	1	0.027	36.5	1.9	173.0
Laser, helium/cadmium	3	0.040	75.4	20.6	194.7
Laser, helium/neon	Refer	to Section 6.1			
Laser, heterojunction GaAs	26	3.567	7.3	5.1	10.1
Laser, krypton ion	1	0.005	198.4	10.2	941.5
Laser, ruby	Refer	to Section 6.1			
Laser, TEA	10	0.039	256.4	139.7	434.6
Laser, YAG	Refer	to Section 6.1			
Lens, optical instrument	8	0.045	177.6	88.4	320.8

* Indicates Pulses

TABLE 6.2-I (continued)
SUMMARY OF DATA COLLECTED BY LASER ITEM

LASER ITEM DESCRIPTION	OBSERVED ITEM FAILURES	ITEM-HOURS OR ITEM-PULSES* $(x10^6)$	FAILURE RATE (λ) [FAILURES / 10^6 hours or pulses*] EXPECTED	LCL	UCL
Mirrors, general	13	0.706	18.4	10.9	29.2
Mounts, general	0	0.011	85.2	----	---
Optical devices, misc.	1	0.016	61.1	3.1	289.7
O-Ring, coolant system	Use RADC-TR-75-22**				
Pockels cell ("Q"-switch E/O)	2	0.003	579.5	103.0	1825.5
Prisms, general	10	0.010	1046.9	570.6	1774.5
Pumps, coolant	Use RADC-TR-75-22**				
Pumps, vacuum	Use RADC-TR-75-22**				
"Q"-switch, A/O	2	0.161	12.4	2.2	39.0
"Q"-switch, E/O	See Pockels cell				
"Q"-switch, rotating	3	0.002	1318.1	360.3	3405.1
Regulator, pressure, gas	Use RADC-TR-75-22**				
Rod, Nd:Glass*	0	0.100* pulses	9.2*	----	---
Rod, ruby*	10	3.260* pulses	3.1*	1.7*	5.2*
Rod, YAG, CW	0	0.164	5.6	----	---
Rod, YAG*	9	524.1* pulses	0.02*	0.01*	0.03*

* Indicates Pulses

** AD-005657

TABLE 6.2-I (continued)
SUMMARY OF DATA COLLECTED BY LASER ITEM

LASER ITEM DESCRIPTION	OBSERVED ITEM FAILURES	ITEM-HOURS OR ITEM-PULSES* (x10^6)	FAILURE RATE (λ) [FAILURES / 10^6 hours or pulses*] EXPECTED	LCL	UCL
Seal, coolant system	Use RADC-TR-75-22**				
Seal, epoxy	2	0.078	25.6	4.6	80.8
Spark gap*	4	144.986* pulses	0.03*	0.01*	0.06*
Tube, gas general	44	0.260	169.1	129.6	217.5
Tubes, coolant system (hose and fittings)	9	0.015	600.0	313.0	1046.7
Valve, pneumatic, vacuum	Use RADC-TR-75-22**				
Window, Brewster	30	0.691	43.3	31.2	58.9

* Indicates Pulses
** AD-005657

6.3 Laser Life Characteristics

The laser life characteristics summarized in Table 6.3-1 have been obtained basically from users who operated lasers in field environments. This table has been supplemented to include manufacturers' information derived from lasers returned for warranty repairs or replacement.

Failure definition has been expressed as a percent of output power degradation. A range has been shown because of the variation within laser device families, and certain applications are not as sensitive to degradation as are others. The reliability models in Section 6.1 are derived from the average of this range. The data base from controlled experiments was not sufficiently large to construct curves of degradation versus derating or the several other pertinent influence factors which effect end-of-life.

Sealed gas lasers are typically operated at from 100 to 50 percent of rated power. CW laser lamps are usually operated at full power, while the xenon flashlamps in military designators/rangefinders are derated to between 10 to 20 percent of the energy which will cause the tube to explode. Additional tests-to-failure would be necessary to determine mean-operating-life for laser diodes and TEA lasers.

The mean-life values for lasers were derived primarily from manufacturer test-to-failure data and warranty information. Lamp life was calculated from user operational data and from manufacturer's life tests. The reliability models are valid for the entire useful life span of a laser system; however, they do not attempt to predict the effect of preventive maintenance such as flashlamp replacement prior to wearout. In actual military practice, flashlamps are not replaced unless a preflight checkout indicates that this maintenance action is required because of low output power.

TABLE 6.3-I

Laser Life Characteristics

Laser or Flashlamp Type	Sample Size	Failure Definition (percent of degradation)	Typical Derating (percent of rated)	Life Range (hours)	Mean Life (hours)
Argon ion	56	20 to 40	100 to 50	1,350 to 6,000	2,056
CO_2 sealed	137	10 to 40	100 to 50	200 to 11,000	3,041
Helium/cadmium	105	N.A.	N.A.	800 to 2,100	1,975
Helium/neon	216	20 to 50	N.A.	1,224 to 44,000	12,270
Heterojunction GaAs injection	2206*	20 to 25	N.A.	*	4,000 (n)
TEA	36*	N.A.	100 to 50	*	>2,000++ (n)
CW linear krypton flashlamp	545	10 to 30	100 to 50	174 to 432	188.43
CW tungsten halogen flashlamp	158	10 to 30	100 to 50	65 to 800	232
Pulsed linear xenon flashlamp	771	20 to 50	30 to 10	$5.4x10^5$ to $5x10^8$ pulses	$5.32x10^6$ pulses

n = nominal

* = Insufficient units tested to failure to determine end-of-life (refer to Table 6.2-I for λ_b)

N.A. = Not applicable

++ = Excluding optics failures, typical optics life = 10^5 pulses at high energy levels

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Martin Marietta has thoroughly conducted and successfully concluded the RADC sponsored program, "Laser Reliability Prediction," Contract F30602-74-C-0091.

More than 10 million item-hours and 4 billion item-pulses of operating data have been collected from all sources. This data base has been used to prepare a future update for the existing laser information in Section 2.4 of MIL-HDBK-217B.

Laser reliability characteristics (Table 4.0-I) have been summarized in one convenient report. This includes design parameters, manufacturing burn-in and warrantee information, application notes, and common failure modes. Additionally, in depth discussions on Argon Ion, Flowing CO_2, Sealed CO_2, Dye, Helium/Cadmium, Helium/Neon, Heterojunction GaAs Injection, TEA, Solid State Lasers, and their major components have been provided.

It has been necessary to assume an exponential failure distribution for the components covered by this study. This is due to a pronounced lack of time-to-failure data on most lasers thus precluding determination of the exact failure distribution of each device.

Quality grades are not well defined for most laser components. Therefore, to categorize these components to some quality grading scale would require extensive searching through component specifications and drawings. Data contributors are generally reluctant to incur large expenditures to further refine the data and information that they provide free of charge. They are also hesitant to allow visitors unrestricted access to their detailed records. Therefore, quality levels for most laser items have not been included in this study. The basic assumption made is that the combined data reflects average failure rates for items over the quality grade spectrum specified for and used in most military equipment.

Using the limited quantity of time-to-failure data available, Weibull analyses were performed to obtain estimates of the failure distributions. The results indicated that some helium/neon tubes may exhibit a constant failure rate, and, in some cases, a decreasing failure rate prior to the wearout (increasing failure rate) period. Therefore, the assumption of an exponential distribution may provide reasonable estimates of the reliability. More effort is needed in this area before definite conclusions can be drawn as this analysis was based on only a small amount of data.

Laser system failure rate prediction models have been defined, quantified, and validated on six laser families -- helium/neon, argon ion, CO_2 sealed, CO_2 flowing, solid-state Nd:YAG, and solid-state ruby. Section 6.1 presents these models and explains their use and limitation.

For low population and research type lasers, laser item failure rates have been provided. Thus, by utilizing these data and a part count reliability prediction method, failure rate estimates on these one or two-of-a-kind lasers can be made. Section 6.2 contains this information.

The laser life characteristic data of Table 6.3-I, which have been collected during this study, were compared to the existing information in Section 2.4 of MIL-HDBK-217B. Significant increases in average lifetime have been noted for both helium/cadmium and sealed CO_2 lasers. These data indicate that reliability growth has been taking place, and the state-of-the art is still improving.

7.2 Recommendations

The following recommendations are submitted for consideration and possible implementation:

1 A concerted effort should be made to generate and collect more time-to-failure data on laser components. Consideration should be given to the feasibility of restructuring or of incorporating the means by which large quantities of time-to-failure data can be collected through existing military data collection systems. This type of data is required to more fully understand laser failure distributions.

2 Additional studies should be made to determine the failure rate versus stress relationships for applicable laser components. In many cases the data collected during this study were not complete enough to accurately determine these relationships. Extensive research and study would be required to obtain such data.

3 Section 2.4 of MIL-HDBK-217B should be updated and revised approximately every two years. This would promote retention and analysis of field data on a current basis. Much data that are over two years old are either lost or thrown away, and the data of this vintage which can be obtained are sometimes difficult to trace. In addition, changes in the state-of-the-art would be reflected on a timely basis.

4 The benefits of a low key effort to collect laser reliability data, when and as it is generated, should be investigated. In the study just completed, a growing tendency has been noted. This tendency is a reluctance, on the part of major military systems contractors, to furnish uncontracted for data free of charge. This is due to material and manpower costs incurred

by them in reconstructing or resorting past or present applicable data and not receiving monetary compensation for the added scope. This reluctance is further heightened by current cutbacks in military defense spending which directly results in purse-string tightening on the part of private contractors.

5 A separate effort should be initiated to update the proposed failure rate prediction models for laser components to be incorporated in MIL-HDBK-217B. This effort would include a specialized data collection program, data analysis, and mathematical modeling.

8.0 REFERENCES

1. Webb, J. P., et al., "Sixteen New Infrared Laser Dyes Excited by a Simple Linear Flashlamp," International Quantum Electronics Conference, Paper F.3, San Francisco, CA, June 1974.

2. Drexhage, K. H., "What's Ahead in Laser Dyes," Laser Focus, March 1973.

3. Storme, F. C., "The Dye Laser," Eastman Organic Chemical Bulletin, Vol. 46, No. 2, Eastman Kodak Company, Rochester, N. Y., 1974.

4. Kressel, H., et al., "GaAs Degradation," Technical Report AFAL-TR-71-83, AFSC, Wright-Patterson AFB, Ohio, April 1971.

5. Hald, A., "Statistical Tables and Formulas," John Wiley and Sons Inc., New York, 1952.

6. Natrella, Mary G., "Experimental Statistics," National Bureau of Standards Handbook 91, pp. 17-1 through 17-3, August 1963.

7. Bauer, J. A., "The Weibull Distribution, Its Advantages and Practical Application with Tables of Confidence Limit Multiplers," OR 6206, Martin Marietta Corporation, September 1964.

8. Massey, Frank J., "The Kolmogorov-Smirnoff Test," J. Am. Statist. Assoc., Vol. 51, pp. 68-78, March 1956.

APPENDIX A

LIST OF DATA SOURCES

UNITED STATES

NONGOVERNMENT

Advanced Kinetics, Inc.
Costa Mesa, CA

American Laser Corporation
Winter Park, FL

American Laser Systems
Goleta, CA

American Optical Company
Keene, NH

American Optical Corporation
Buffalo, NY

Apollo Lasers
Los Angeles, CA

Aremco Products
Ossining, NY

ARO, Incorporated
Arnold Air Force Station, TN

Atomergic Chemical
Carle Place, NY

AVCO - Everett
Everett, MA

Bell Telephone Laboratories
Murray Hill, NJ

Bell Telephone Laboratories
Holmdel, NJ

Block Engineering, Incorporated
Cambridge, MA

Britt Corporation
Los Angeles, CA

Burleigh Instruments, Inc.
East Rochester, NY

Carson Astonomical Instruments, Inc.
Valencia, CA

Ceramaseal, Incorporated
New Lebanon, NY

Chromatrix
Mountain View, CA

Cleveland Crystals
Euclid, OH

Coherent Radiation
Palo Alto, CA

Colorado State University
Fort Collins, CO

Consolidated Ceramics
Hampton, NJ

Cordin Company
Salt Lake City, UT

Corning Glass Works
Corning, NY

Crystal Technology, Incorporated
Mountain View, CA

Data Optics
Yipsilanti, MI

Datalight
Bloomfield, CT

Davidson Optronics, Inc.
West Covina, CA

Dement Labs
Portland, OR

Denton Vacuum
Cherry Hill, NJ

Digalab
Cambridge, MA

Ditric Optics, Incorporated
Marlboro, MA

Donnelly Mirrors
Holland, MI

Dow Chemical Corporation
Freeport, TX

EG&G, Incorporated
Salem, MA

Electro Optical Industries
Santa Barbara, CA

Electrophysics Corporation
Nutley, NJ

Energy Sciences, Incorporated
Burlington, MA

Energy Technology, Inc.
San Luis Obispo, CA

ESCO Products
Oakridge, NJ

Evaporated Coatings, Inc.
Huntington Valley, PA

Evaporated Metal Films, Inc.
Ithaca, NY

Fairchild Semiconductor
Mt. View, CA

Fraser-Volpe Corporation
Warrington, PA

GCO, Incorporated
Plymouth, MI

General Electric Company
Cincinnati, OH

General Laser Corporation
Natick, MA

General Photonics Corporation
Santa Clara, CA

Grayco Optical Corporation
Lindhurst, NY

GTE Sylvania
Mountain View, CA

GTE Sylvania
Waltham, MA

Hadron, Inc.
Yonkers, NY

Hallicrafters Company
Rolling Meadows, IL

Harris Electronics
Melbourne, FL

Harris Manufacturing Company
North Billerica, MA

Harshaw Chemical Company
Solon, OH

Heliotek
Valencia, CA

Holobeam, Incorporated
Paramus, NJ

Honeywell Incorporated
St. Paul, MN

Honeywell Incorporated
Waltham, MA

Hoya Optics USA
Menlo Park, CA

Hughes Aircraft Company
Culver City, CA

Hughes Research Labs
Malibu, CA

Hughes Industrial Products Division
Oceanside, CA

Hughes Aircraft Company
Torrance, CA

Hutson Corporation
Arlington, TX

IBM Corporation
Gaithersburg, MD

ILC Technology, Inc.
Sunnyvale, CA

Illumination Industries, Inc.
Sunnyvale, CA

International Laser Systems, Inc.
Orlando, FL

Image Information
Monsey, NY

Ionics, Incorporated
Watertown, MA

Isomet Corporation
Oakland, NJ

Itek Corporation
Lexington, MA

Jodon Engineering
Ann Arbor, MI

Kemlite Labs, Incorporated
Chicago, IL

Klinger Scientific
Applications Corp.
Jamaica, NY

KMS Industries
Van Nuys, CA

Korad
Santa Monica, CA

Laboratory Optical Company
Plainfield, NJ

Laser Comp. Systems Corporation
Hamden, CT

Laser Consultants, Incorporated
Huntington, NY

Laser Diode Labs
Metuchen, NJ

Laser Energy, Incorporated
Rochester, NY

Laser Image Systems
Mountain View, CA

Lasermation, Incorporated
Philadelphia, PA

Laser Optics, Incorporated
Danbury, CT

Laser Precision Corporation
Yorkville, NY

Lansing Research Corporation
Ithaca, NY

Laser Sciences
Bethel, CT

Lawrence Livermore Laboratory
Livermore, CA

Lenox Instrument
Philadelphia, PA

Lexel Corporation
Palo Alto, CA

Liberty Mirror
Brackenridge, PA

Liconix
Mountain View, CA

Lockheed MSD
Huntsville, AL

Lockheed Palo Alto Research Lab
Palo Alto, CA

Lockheed SSD
Sunnyvale, CA

Martin Marietta Aerospace
Denver, CO

Martin Marietta Aerospace
Orlando, FL

Maxwell Labs
Sandiego, CA

McCowan Laboratories
Tempe, AZ

McDonnell Douglas
St. Louis, MO

McDonnell Douglas Electronics Co.
St. Charles, MO

McDonnell Douglas Research Lab
Huntington Beach, CA

MERET Incorporated
Santa Monica, CA

Metrologic Instruments, Inc.
Bellmawr, NJ

Microcoatings, Incorporated
Burlington, MA

MIT Lincoln Labs
Lexington, MA

Motorola I/C Center
Mesa, AZ

Neslab Instruments, Inc.
Portsmouth, NH

New England Laser Corporation
North Billerica, MA

J. A. Noll Company
Monroeville, PA

Northeast Scientific Corporation
Acton, MA

Optical Coating Lab., Inc.
Santa Rosa, CA

Optical Industries
Costa Mesa, CA

Optical Systems & Technology, Inc.
Bedford, MA

Optics International
Tenafly, NJ

Optics Technology, Inc.
Redwood City, CA

Optimation, Incorporated
Concord, MA

Owens-Illinois Technical Center
Toledo, OH

Pacific Optical
Los Angeles, CA

Perkin Elmer Corporation
Norwalk, CT

Philips Metalonics
Lewiston, ME

Photon Sources
Livonia, MI

Pratt & Whitney Aircraft
West Palm Beach, FL

Precision Instruments
Santa Clara, CA

Precision Optics, Inc.
Eatontown, NJ

PSR, Incorporated
Oak Ridge, TN

Quantronix Corporation
Smithtown, NY

Raytheon Laser Development Center
Waltham, MA

RCA Laboratories
Lancaster, PA

Recognition Systems, Inc.
Van Nuys, CA

Reich Associates, Inc.
Plans, TX

Republic Lens Company
Bronx, NY

Rockwell International
Anaheim, CA

Sandia Laboratories
Albuquerque, NM

Sandia Laboratories
Livermore, CA

Santa Barbara Research Center
Goleta, CA

Schott Optical Glass, Inc.
Duryea, PA

Science Spectrum
Santa Barbara, CA

SCI-METRICS
Tullahoma, TN

Semi Elements, Incorporated
Saxonburg, PA

Servo Corporation of America
Hicksville, NY

Space Optics Labs
Chelmsford, MA

Spawr Optical Research
Corona, CA

Spectra-Mat, Inc.
Watsonville, CA

Spectra Optics
La Crescenta, CA

Spectra Physics, Inc.
Mountain View, CA

Technological Research, Inc.
Ann Arbor, MI

Texas Instruments
Dallas, TX

Thermal American Fuzed Quartz, Co.
Montville, NJ

Three B Optical, Co., Inc.
Gibsonia, Pa

Tropel
Fairport, NY

TRW Systems
Redondo Beach, CA

II-IV Incorporated
Glenshaw, PA

United Aircraft Research Labs
East Hartford, CT

University of California
Santa Barbara, CA

University of Chicago
Chicago, IL

University of Cincinnati
Cincinnati, OH

University of Maryland
College Park, MD

University of Minnesota
Minneapolis, MN

University of Southern California
Los Angeles, CA

U. S. Scientific Instruments
Watertown, MA

Valpey Corporation
Holliston, MA

Westinghouse Electric
Baltimore, MD

Whittaker Corporation
Waltham, MA

Xenon Corporation
Medford, MA

Xerox Corporation
Palo Alto, CA

Xerox Electro Optical Systems
Pasadena, CA

Zenith Radio Corporation
Melrose Park, IL

Zenith Research Laboratory
Menlo Park, CA

UNITED STATES
GOVERNMENT

U. S. AIR FORCE

Air Force Weapons Lab
Kirtland AFB, NM

Armament Development & Test Center
Eglin AFB, FL

Headquarters AFSC
Andrews AFB, DC

Robins Air Logistics Center
Robins AFB, GA

Headquarters AFLC
Wright-Patterson AFB, OH

Ogden Air Logistics Center
Hill AFB, UT

Air Force Avionics Lab
Wright-Patterson AFB, OH

Rome Air Development Center
Griffiss AFB, NY

Aeronautical Systems Division
Wright-Patterson AFB, OH

U. S. ARMY

Aberdeen Proving Ground
Aberdeen, MD

Watervliet Arsenal
Watervliet, NY

Frankford Arsenal
Philadelphia, PA

U. S. ARMY (cont.)

Harry Diamond Labs
Washington, DC

Electronics Command
Ft. Monmouth, NJ

USAMERDC
Fort Belvoir, VA

Missile Command
Redstone Arsenal, AL

Tank Automotive Command
Warren, MI

DCSI-ED
Ft. Ord, CA

Headquarters MASSTER
Ft. Hood, TX

U. S. NAVY

Naval Electronics Lab
San Diego, CA

Naval Research Laboratory
Washington, DC

Naval Weapons Center
China Lake, CA

USN Naval Sea Systems Command
Washington, DC

U. S. MARINES

Marine Corps Development Center
Quantico, VA

OTHER

Bureau of Radiological Health
Rockville, MD

Los Alamos Scientific Lab
Los Alamos, NM

National Bureau of Standards
Washington, DC

National Bureau of Standards
Boulder, CO

National Oceanic & Atmospheric Administration
Boulder, CO

NASA-AMES Research Center
Moffett Field, CA

NASA-Goddard SFC
Greenbelt, MD

NASA/LRC
Cleveland, OH

Waterways Experiment Station
Vicksburg, MS

CANADA

NONGOVERNMENT

Gen-Tec, Incorporated
Quebec, Canada

Lumonics Research Limited
Ottawa, Canada

Quantum Technology Limited
Toronto, Canada

RCA Limited
Quebec, Canada

CANADA

GOVERNMENT

Defense Research Establishment Valcartier
Courcelette, Canada

FOREIGN

Siemens AG
St. Martenstr
West Germany

BIBLIOGRAPHY

1. Abrams, R. L., and Bridges, W. B., "Characteristics of Sealed - Off Waveguide CO_2 Lasers," IEEE Journal of Quantum Electronics, Vol. QE-9, No. 9, September 1973.

2. Agostinelli, Nereo, "High Energy Density Capacitors," Sprague Electric Co., North Adams, Mass., AD 856-930, January, 1969.

3. Ahmed, S. A., et al., "RF Inductively Excited Ion Laser With Aperture-Magnetic Confinement," IEEE Journal of Quantum Electronics, Vol. QE-5, No. 5, June, 1969.

4. Alcock, A. J., et al., "Continuously Tunable High-Pressure CO_2 Laser With uv Photopreionization," Division of Physics, National Research Council of Canada, Ottawa, Canada, Applied Physics Letter, Vol. 23, No. 10, 15 November 1973.

5. Allen, Jr., "Preparation of Gold Coated Stainless Steel Reflecting Surfaces for Use as Laser Optical Components for 10.6 Micrometers Radiation," Defense Standards Labs., Maribyrnong, Australia, AD 904-329, May 1972.

6. Anon., "Advanced Electron Device Technology," Office of the Director of Defense Research and Engineering, Washington, D. C.; Advisory Group on Electron Devices, Status Report No. 137, AD 914-117L, October, 1973.

7. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

8. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

9. Anon., "Check Test of Laser Range Finder, XM23E1," Development and Proof Services, Aberdeen Proving Ground, Md., AD 369-013L, January, 1966.

10. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

11. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

12. Anon., "Laser Rangefinders," Army Test and Evaluation Command, Aberdeen Proving Ground, Md., AD 720-579, October, 1969.

13. Anon., "Laser Rangefinders," Army Test and Evaluation Command, Aberdeen Proving Ground, Md., AD 718-610, February, 1968.

14. Anon., "Laser Rangefinder for M60A1E1 Tank," Control Data Corp., Melville, N. Y., TRG Division, TRG-0105A, AD 829-775L, March, 1968.

15. Anon., "Laser Reproducibility," Martin Marietta Corporation, Orlando, Fla., OR 8758, May, 1967.

16. Anon., "Laser Tank Gunnery Trainer," Army Test and Evaluation Command, Aberdeen Proving Ground, Md., AD 729-844, August, 1971.

17. Anon., "Lasers," Army Test and Evaluation Command, Aberdeen Proving Ground, Md., AD 718-621, November, 1968.

18. Anon., "Low Noise, Long Life, Helium-Neon Laser," Ferranti Ltd., Dundee, Scotland, AD 906-939, November, 1972.

19. Anon., "Martin Marietta Model 1970 Designator/Rangefinder Product Line," Martin Marietta Corporation, Orlando, Fla., OR 10,460-1, May, 1970.

20. Anon., "Night Acquisition/Laser Designation, Subsystem (Pave Lance) Phase 1, Vol. I, Recommended Susbsystem Design, Book," Bell Aerospace Co., Buffalo, N. Y., AD 529-051, April, 1971.

21. Anon., "Night Acquisition/Laser Designation Subsystem (Pave Lance) Phase I, Vol. III, Appendices, Book 1," Bell Aerospace Co., Buffalo, N. Y., AD 529-054, April, 1971.

22. Anon., "Production Engineering Measure for Moderate Power Fiber Optic Laser Arrays," RCA Electronic Components, Lancaster, Pa., AD 911-188L, May, 1973.

23. Anon., "Service Test of Laser Rangefinder XE-6," Army Artillery Board, Ft. Sill, Okla., AD 357-816, October, 1964.

24. Anon., "Service Test of Laser Rangefinder XM23," Army Artillery Board, Ft. Sill, Okla., AD 357-815, October, 1964.

25. Anon., "Study of Gas Lasers," Ferranti Ltd., Edinburgh, Scotland, AD 457-386, November, 1964.

26. Anon., "The Guidance of High-Voltage Electrical Breakdown Streamers by Lasers Induced Ionization in Air," Versar Inc., Springfield, Va., AD 763-827, June, 1973.

27. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

28. Babcock, Gary D., and Vescial, Fredrick, "RF Cleaning - Ring Laser Gyro," Rockwell International Corp., Anaheim, Calif., AD 911-373L, June 1973.

29. Backhouse, G. H., "Room Temperature Gas Laser," Standard Telecommunication Labs., Ltd., Harlow (England), DRIC BR-27737, AD 890-710, 1971.

30. Backhouse, G. H., "Room Temperature GaAs Laser," Standard Telecommunication Labs., Ltd., Harlow, England, AD 915-056, 1973.

31. Baker, Charles E., and Fournier, Gerald R., "Large-Angle Deflection Technique for Laser Display," AD 481-154, Texas Instruments Inc., Dallas, Texas, April 1966.

32. Bass, Michael, "Nd:YAG Laser Radiation-Induced Damage to $LiNbo_3$ and KDP," IEEE Journal of Quantum Electronics, July 1971.

33. Bass, Michael, and Barrett, H. H., "Avalanch Breakdown and the Probabilistic Nature of Laser-Induced Damage," IEEE Journal of Quantum Electronics, Vol. QE-8, No. 3, March 1972.

34. Bayless, John R., "Plasma Cathode for E-Beam Lasers," Hughes Research Labs, Malibu, Calif., AD 764-079, May 1973.

35. Beaulieu, A. J., "Transverse Excitation Atmospheric Pressure Lasers," IEEE/OSA Conference on Laser Engineering and Applications, Washington, D. C., June 2-4, 1971, Defense Research Establishment Valcartier, Courcelette, Canada.

36. Bell, William Earl, and Goldsborough, John P., "Ion Laser Device Research," Spectra-Physics Inc., Mountain View, Calif., AD 484-466, July 1966.

37. Belyaiev, V. P., et al., "High-Power Single-Frequency Argon Ion Laser," IEEE Journal of Quantum Electronics, Vol. QE-5, No. 12, December 1961.

38. Benard, D. J., et al., "N_2O Pure Chemical CW Flame Laser," Applied Physics Letters, Vol. 23, No. 2, The Johns Hopkins University, Applied Physics Laboratory, Silver Spring, Md., 15 July 1973.

39. Benedict, W. S., et al., "The Water-Vapor Laser," IEEE Journal of Quantum Electronics, Vol. Qe-5, No. 2, February 1969.

40. Bergmann, E. E., and Edberhardt, N., "A Start High-Power TE Nitrogen Laser," IEEE Journal of Quantum Electronics, August 1973.

41. Bickert, C. J., et al., "A Study of Gaseous Reactions in Passive CO_2 Laser Cells as Indicated by Emission in the Visible Region," Army Electronics Command, Fort Monmouth, N. J., June 1970.

42. Bickert, C. J., et al., "Long Life Sealed CO_2 Laser," Army Electronics Command, Fort Monmouth, N. J., AD 881-927L, January 1971.

43. Blaszczak, Z., "Small Portable Gas Laser Designed for Alignment of Optical Systems," Foreign Technology Division, Wright-Patterson AFB, Ohio, AD 882-057, November 1970.

44. Boling, N. L., and Dube, G., "Laser-Induced Inclusion Damage at Surfaces of Transparent Dielectronics," Corporate Technology, Owens-Illinois Technical Center, Toledo, Ohio, Applied Physics Letters, Vol. 23, No. 12, 15 December 1973.

45. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

46. Bovee, W. B., "Integrated Observation System (IOS) AN/GVQ-10," Marine Corps Development and Education Command, Quantico, Va., AD 522-729L, October 1972.

47. Brandenberg, W. M., et al., "Supersonic Transverse Electrical Discharge Laser," IEEE Journal of Quantum Electronics, Vol. QE-8, No. 4, April 1972.

48. Bridges, W. B., and Mercer, G. N., "CW Operation of High Ionization States in a Xenon Laser," IEEE Journal of Quantum Electronics, September 1969.

49. Brown, R. T., and Smith, D. C., "Optically Pumped Electric-Discharge UV Laser," Applied Physics Letters, Vol. 24, No. 5, United Aircraft Research Laboratories, East Hartford, Conn., March 1, 1974.

50. Bullock, C. K., "Effect of Gas Composition on Power Output of Sealed-Off CO_2 Laser," Naval Weapons Center, China Lake, Calif., AD 863-080L., November 1969.

51. Burch, Jack J., and Geikas, G. I., "Coherent Rear Projection Viewer," Texas Instruments Inc., Dallas, Tex., TI-UI-963401-F, AD 873-237, August 1970.

52. Burlamacchi, P., and Pratesi, R., "High-Efficiency Coaxial Waveguide Dye Laser With Internal Excitation," Instituto di Fisica Superiore, and Laboratorio di Elettronica Quantistica, Firenze, Italy, Applied Physics Letters, Vol. 23, No. 8, 15 October 1973.

53. Burlamacchi, P., and Pratesi, R., "Waveguide Superradiant Dye Laser," Applied Physics Letters, Vol. 22, No. 7, 1 April 1973.

54. Byer, N., et al., "Production Engineering Measure on Gallium Arsenide Laser Diode," RCA Electronic Components, Somerville, N. J., AD 843-784L, June 1968.

55. Byron, S. R., et al., "Chemically Pumped Laser System," Aeroneutronic Division, Philco Corporation, Newport Beach, Calif., AD 479-017, November 1965.

56. Byron, S. R., et al., "HF and DF Lasers by Direct Electrical Discharge Excitation," Applied Physics Letters, Vol. 23, No. 10, 15 November 1973.

57. Carbone, R. J., "Continuous Operation of a Long-Lived CO_2 Laser Tube," Massachusetts Institute of Technology, Lexington Lincoln Lab., AD 673-595, January 1968.

58. Carbone, R. J., "Long-Term Operation of a Sealed CO_2 Laser," Massachusetts Institute of Technology, Lexington Lincoln Lab., AD 668-195, June 1967.

59. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

60. Chang, T. Y., and Wood, O. R., "Optically Pumped 33-atm CO_2 Laser," Bell Telephone Labs., Holmdel, N. J., Applied Physics Letters, Vol. 23, No. 7, 1 October 1973.

61. Chen, C. J., et al., "Double-Discharge Copper Vapor Laser With Copper Chloride as a Lasant," Jet Propulsion Lab., Pasadena, Calif., Applied Physics Letters, Vol. 23, No. 9, 1 November 1973.

62. Cheng, David, "Instability of Cavity-Dumped YAG Laser Due to Time-Varying Reflections," IEEE Journal of Quantum Electronics, Vol. QE-9, No. 6, June 1973.

63. Chester, R. B., and Draegert, D. A., "Miniature Diode-Pumped Nd:YAG Lasers," Bell Telephone Labs., Murray Hill, N. J., Applied Physics Letters, Vol. 23, No. 5, 1 September 1973.

64. Chicklis, Evan P., and Naiman, Charles S., "Studies of the Sensitization Mechanisms of Rare Earth Detection and Laser Materials," AD 757-520, February 1973.

65. Christiansen, W. H., and Greenfield, E., "Analysis of a Collisionally Induced Dipole Laser," Aerospace Research Lab., University of Washington Seattle, Wash., Applied Physics Letters, Vol. 23, No. 11, 1 December 1973.

66. Church, C. H., et al., "Optical Pumps for Lasers -- Phase II," Westinghouse Research Labs., Pittsburgh, Pa., AD 829-852, February 1968.

67. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

68. Clark, P. O., "Ten Watt CW CO_2 Box Laser," Hughes Research Labs, Malibu, Calif., AD 836-778L, July 1968.

69. Clark, P. O., and Smith, M. R., "Ten Watt, CW CO_2 Gas Laser," Hughes Research Labs., Malibu, Calif., AD 801-846L, October 1966.

70. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

71. Cochran, Albert L., "Check Test of Rangefinder, AN/GVS-3 (SM23E2)," Army Field Artillery Board, Ft. Sill, Okal., USAF ABD-FA-2861-3, AD 503-881, July 1969.

72. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441

73. Contini, Daniel A., et al., "Optical Transponder Reliability Mathematical Model," Martin Marietta Aerospace, Orlando, Fla., OR 12,805, October 1973.

74. Cool, T. A., "MDI-The Transfer Chemical Laser: A Review of Recent Research," IEEE Journal of Quantum Electronics, Vol. QE-1, No. 1, January 1973.

75. Cubeddu, R., and Curry, S. M., "A Simple High-Power Pulsed Nitrogen Laser," IEEE Journal of Quantum Electronics, April 1973.

76. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

77. Damen, T. E., et al., "NdLa Pentaphosphate Laser Performance," Applied Physics Letters, Vol, 23, No. 9, Bell Telephone Laboratories, Holmdel, N. J., November 1973.

78. Damon, W. E., "Research on Laser Balancing of Rotating Turbine Components," General Motors Corporation, Indianapolis, Ind., AD 857-672, August 1969.

79. Day, G. W., et al., "Investigation of a Q-Switched Pulsed Discharge CO_2 Laser," IEEE Journal of Quantum Electronics, August 1969.

80. Degnan, J. J., et al., "Gain and Saturation Intensity Measurements in a Waveguide CO Laser," IEEE Journal of Quantum Electronics, April 1973.

81. Demaria, A. J., et al., "Research Investigation of Laser Line Profiles," United Aircraft Corporation, East Hartford, Conn., Research Labs., AD 665-780, February 1968.

82. DeShazer, L. G., et al., "Role of Coating Defects in Laser-Induced Damage to Dielectric Thin Films," Center for Laser Studies, Univ. of Southern California, Los Angeles, Calif., Applied Physics Letters, Vol. 23, No. 11, 1 December 1973.

83. Deutsch, T., "High Power Gas Lasers for CS/NV Applications," Raytheon Co., Waltham, Mass., AD 826-467, January 1968.

84. Deutsch, T., "High Qower Gas Laser For CS/NV Applications," Raytheon Co., Research Division, Waltham, Mass., ECOM-0478-F, AD 839-970, September 1968.

85. Deutsch, T., and Bass, M., "Laser-Pumped Dye Lasers Near 4000 Å," IEEE Journal of Quantum Electronics, May 1969.

86. Dierschke, Eugene G., "Semiconductor Pumps for the Nd:YAG Laser," Texas Instruments, Inc., Dallas Components Group, Dallas, Texas, June 1973.

87. Djeu, N., "CW Single-Line CO Laser on the $V = 1 \rightarrow V = 0$ Band," Laser Physics Branch, Optical Sciences Division, Naval Research Lab., Washington, D. C., Applied Physics Letters, Vol. 23, No. 6, 15 September 1973.

88. Djeu, N., and Wolga, G. J., "Observation of New Laser Transitions in N_2O," Cornell University, Ithaca, N. Y., IEEE Journal of Quantum Electronics, January 1969.

89. Draegert, D. A., "Single-Diode End-Pumped, Nd:YAG Laser," IEEE Journal of Quantum Electronics, Vol. QE-9, No. 12, December 1973.

90. Draggoo, V. G., et al., "Effects of Laser Mode Structure on Damage in Quartz," IEEE Journal of Quantum Electronics, Vol. QE-8, No. 2, February 1972.

91. Duston, D. K., "Interaction Studies of Laser Beams Intersecting in an Active Medium (Crossed Beam Laser)," General Electric Co., Schenectady, N. Y., AD 847-026, July 1968.

92. Duthler, C. J., "Explanation of Laser-Damage Cone-Shaped Surface Pits," Xonics, Inc., Van Nuys, Calif., Applied Physics Letters, Vol. 24, No. 1, 1 January 1974.

93. Eales, B. A., and Selway, P. R., "Freon Cooled Gas Lsaer," Standard Telecommunication Labs., Ltd., Harlow (England), AD 908-211, 1972.

94. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

95. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

96. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

97. Emmony, D. C., et al., "Laser Mirror Damage in Germanium at 10.6 μm," Loughborough University of Technology, Leicestershire, United Kingdom, Applied Physics Letters, Vol. 23, No. 11, 1 December 1973.

98. Erickson, L. E., and Szabo, A., "Effects of Saturable Absorber Lifetime on the Performance of Giant-Pulse Lasers," Journal of Applied Physics, Vol. 37, No. 13, Radio and Electrical Engineering Division, Owttawa, Canada, December 1966.

99. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

100. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

101. Evtuhov, Viktor, "Laser Devices Exploratory Investigation," Hughes Research Labs., Malibu, Calif., AD 468-754, July 1965.

102. Fahlen, Ted S., "High Average Power Liquid Laser," GTE Sylvania Inc., Mountain View, Calif., Electro-Optics Organization, AFAL TR-72-225, AD 902-579L, July 1972.

103. Fahlen, T. S., et al., "Life Testing of Metal-Ceramic CO_2 Lasers," GTE Sylvania, Inc., Mountain View, Calif., N72-13440, November 1971.

104. Feldman, Albert et al., "Mechanisms for Self-Focusing in Optical Glasses," IEEE Journal of Quantum Electronics, Vol. QE-9, No. 11, November 1973.

105. Ferrar, C. M., "Mode-Locked Flashlamp-Pumped Coumarin Dye Laser at 4600 A," IEEE Journal of Quantum Electronics, United Aircraft Research Labs., East Hartford, Conn., November 1969.

106. Ferrar, C. M., "Spark Pumped Dye Laser With High Repetition Rate and Low Threshold," United Aircraft Research Labs., East Hartford, Conn., Applied Physics Letters, Vol. 23, No. 10, 15 November 1973.

107. Ferrar, C. M., "Wavelength Variations of a Flashlamp-Pumped Sodium Fluorescein Dye Laser," IEEE Journal of Quantum Electronics, United Aircraft Research Labs., East Hartford, Conn., December 1969.

108. Ferrario A., and Sona, A., "An Argon-Ion Laser with a Mercury Pool Cathode," IEEE Journal of Quantum Electronics, February 1969.

109. Fleck, Jr., J. A., and Layne, C., "Study of Self-Focusing Damage in a High-Power Nd:Glass-Rod Amplifier," Lawrence Livermore Lab., Livermore, Calif., Applied Physics Letters, Vol. 22, No. 9, 1 May 1973.

110. Forbes, N., and Dyson, D. J., "Study of Gas Lasers," Ferranti, Ltd., Edinbrugh, (Scotland), No. 142/64, AD 457-386, November 1964.

111. Forest, Harvey, et al., "Liquid Laser Parameters," General Precision, Inc., Little Falls, N. J., Aerospace Research Center, AD 488-248, August 1966.

112. Fortin, R., et al., "Double Discharge TEA Laser Beams," Defense Research Establishment Valcartier, Quebec, Canada, AD 780-840, March 1974.

113. Fowler, V. J., and Watson, S. R., "Optical Properties of Binary Gas Plasmas," General Telephone and Electronics Labs., Inc., Bayside, N. Y., AD 477-752L, January 1966.

114. Fox, Jay A., and Barr, Dallas N., "Laser-Induced Shock Effects in Plexiglas and 6061-T6 Aluminum," Applied Physics Letters, Vol. 22, No. 11, 1 June 1973.

115. Fradin, D. W. and Bass, Michael "Comparison of Laser-Induced Surface and Bulk Damage," Applied Physics Letters, Vol. 22, No. 4, 15 February 1973.

116. Fradin, D. W., and Bass, M., "Electron Avalanch Breakdown Induced by Ruby Laser Light," Gordon McKay Lab., Haward University, Cambridge, Mass., Raytheon Research Div., Waltham, Mass., Applied Physics Letters, Vol. 22, No. 5, 1 March 1973.

117. Free, John "High Power Laser Techniques," Korad Corp., Santa Monica, Calif., AD 470-898, July 1965.

118. Free, John "High Power Laser Techniques," Korad Corp., Santa Monica, Calif., AD 480-271, October 1965.

119. Freed, Charles, "Sealed-Off Operation of Stable CO Lasers," Mass. Institute of Technology, Lexington Lincoln Lab., AD 729-613, April 1971.

120. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

121. Freudenthal, Jedidja, "Deposits in a Sealed-Off CO_2 Laser-Type Discharge," IEEE Journal of Quantum Electronics, Vol. QE-6, No. 8, August 1970.

122. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

123. Friesem, A. A., et al., "Simultaneous Multiple-Wavelength Operation of a Tunable Dye Laser," Applied Physics Letters, Vol., 23, No. 5, The Weizmann, Institute of Science, Department of Electronics, Rehovot, Israel, September 1973.

124. Gampel, Leonard "Space Laser Design," Hughes Aircraft Co., Culver City, Calif., AD 907-213L, December 1972.

125. Gerardo, J. B., and Johnson, A. W., "High-Pressure Xenon Laser at 1730 A," IEEE Journal of Quantum Electronics, Vol. QE-9, No. 7, July 1973.

126. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

127. Gilmour, A. S., and Clark, R., "Laser Triggered Switch Study," Cornell Aeronautical Labs., Inc., Buffalo, N. Y., CAL-RM-2169-E-2, AD 810-505, February 1967.

128. Giuliano, Concetto R., "Laser-Induced Damage in Transparent Dielectrics: The Relationship Between Surface Damage and Surface Plasma," IEEE Journal of Quantum Electronics, Vol. QE-8, No. 9, September 1972.

129. Goetzke, J. A., and Chittenden, J. W., "Expanded Service Test of Anti-Laser Goggles," Army Armor and Engineering Board, Ft. Knox, Ky., June 1972.

130. Goldsborough, J. P., and Bloom, A. L., "Near-Infrared Operation Characteristics of the Mercury Ion Laser," IEEE Journal of Quantum Electronics, Vol. QE-5, No. 9, September 1969.

131. Goldsborough, J. P., and Hodges, E. G., "Stable, Long-Life Operation of Helium-Cadmium Lasers at 4416 A and 325 A," IEEE Conference on Laser Engineering and Applications, Spectra-Physics, Inc., Mountain View, Calif.

132. Gonda, Tibor, "Production Engineering Measure on Gallium Arsenide Laser Diode," RCA Electronic Components, Somerville, N. J., AD 865-578L, December 1969.

133. Gonda, Tibor and Gill, Robert "Production Engineering Measure on Gallium Arsenide Laser Diode," RCA Electronic Components, Somerville, N. J., AD 871-918L, May 1970.

134. Grant, N. J., et al., "Research on Materials for High Power Laser Windows," Massachusetts Institute of Technology, AD 909-162L, January 1973.

135. Gregg, David W., and Thomas, S. J., "New Lasing Organic Dyes Flash-lamp-Pumped," IEEE Journal of Quantum Electronics, June 1969.

136. Greiner, N. Roy, "Submicrosecond Pulses from a Hydrogen-Fluorine Laser With High Energy Density and Quantum Efficiency," IEEE Journal of Quantum Electronics, Vol. QE-8, No. 12, December 1972.

137. Hacker, M. P., et al., "Low-Pressure Gas Breakdown With CO_2 Laser Radiation," Francis Bitter National Magnet Lab., Massachusetts Institute of Technology, Cambridge, Mass., Applied Physics Letters, Vol., 23, No. 7, 1 October 1973.

138. Hacker, M. P., and Cohn, D. R., "Low-Pressure Gas Breakdown With CO_2 Laser," Massachusetts Institute of Technology, Cambridge Francis Bitter National Magnet Lab., AD 772-413, July 1973.

139. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

140. Halpin, Joseph J., "A Progress Report on the Transient Radiation Effects on Laser Materials FY 1971," Naval Research Lab., Washington, D. C. AD 888-249L, June 1971.

141. Halsted, A. S., "Gaseous Ion Laser Research," Hughes Research Labs., Malibu, Calif., AD 825-772, December 1967.

142. Halsted, A. S., et al., "Gaseous Ion Laser Research," Hughes Research Laboratories, Malibu, Calif., AD 815-371, May 1967.

143. Halsted, A. S., et al., "Gaseous Ion Laser Research," Hughes Research Laboratories, Malibu, Calif., AD 819-127, August 1967.

144. Halsted, A. S., et al., "Gaseous Ion Laser Research," Hughes Research Laboratories, Malibu, Calif., December 1967.

145. Halsted, A. S., et al., "Gaseous Ion Laser Research," Hughes Research Laboratories, Malibu, Calif., AD 841-834, July 1968.

146. Hanna, D. C., et al., "Q-Switched Laser Damage of Infrared Nonlinear Materials," IEEE Journal of Quantum Electronics, Vol. QE-8, No. 3, March 1972.

147. Hartman, R. L., and Hartman. A. R., "Strain-Induced Degradation of GaAs Injection Lasers," Bell Labs., Murray Hills, N. J., Applied Physics Letters, Vol. 23, No. 3, 1 August 1973.

148. Hartter, D. R., et al., "Laser Initiation of Thin Explosive Wafers," Harry Diamond Labs., Washington, D. C. AD 502-744, April 1969.

149. Hercher, Michael and Pike, H. Alan, "Technology of Continuous Dye Lasers," IEEE/OSA Conference on Laser Engineering and Applications, Washington, D. C., June 2-4, 1971, Institute of Optics, University of Rochester, Rochester, N. Y.

150. Hernqvist, Karl G., "He-Cd Lasers Using Recirculation Geometry," IEEE Journal of Quantum Electronics, Vol. QE-8, No. 9, September 1972.

151. Herriott, D. R., "Applications of Laser Light," Scientific American, Vol. 219, No. [illegible], pp. 140, September 1968.

152. Hirose, Yasuo et al., "TA1-A CW-CO Chemical Laser from the Reaction of Active Nitrogen With O_2 + CS_2," IEEE Journal of Quantum Electronics, Vol. QE-9, No. 1, January 1973.

153. Hodges, D. T., and Hartwick, T. S., "Waveguide Laser for the Far Infrared (FIR) Pumped by a CO_2 Laser," Electronics Research Lab., The Aerospace Corp., El Segundo, Calif., Applied Physics Letters, Vol. 23, No. 5, 1 September 1973.

154. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

155. Holst, G. C., and Carver, C. T., "Airborne Laser Range Finder for Multiweapon Fire Control System," Frankford Arsenal, Philadelphia, Pa., AD 876-979, April 1970.

156. Holst, G. C., and Dallas, A. G., "Laser Range Finder AN/VVS-1 for M60A1E2 Tank." Frankford Arsenal, Philadelphia, Pa., AD 876-980, April 1970.

157. Holst, G. C., and Stuebing, E. W., "Luminous Transmittance of Anti-Laser Eye Protection Devices Under Various Light Conditions," AD 905-800L, Frankford Arsenal, Philadelphia, Ap., August 1972.

158. Husain, S. A., "Resonance-Radiation-Trapping Effects in a Pulsed-ion Laser," Oxford University, England, AD 677-955, May 1968.

159. Itzkan, I., and Cunningham, F. W., "Oscillator-Amplifier Dye-Laser System Using N_2 Laser Pumping," IEEE Journal of Quantum Electronics Vol. Qe-8, No. 2, February 1972.

160. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

161. Johnson, T. J., et al., "Wideband Electronics for High Speed Digital Laser Communications," TRW Systems Group, Redondo Beach, Calif., AFAL TR-72-155, AD 902-097L, May 1972.

162. Johnston, T. J., et al., "Wideband Electronics for High Speed Digital Laser Communications," TRW Systems Group, Redondo Beach, Calif., May 1972.

163. Johnston, Thomas F., and Halsted, A. Steven, "Manufacturing Methods Program 5 w CW Argon Ion Laser," Hughes Aircraft Co., Torrance, Calif., AD 912-889L, June 1973.

164. Johnston, Jr., W. D., and Miller, B. I., "Degradation Characteristics of CW Optically Pumped Al Ga_{1-x} As Heterostructure Lasers," Bell Labs., Holmdel, N. J., Applied Physics Letters, Vol. 23, No. 4, 15 August 1973.

165. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

166. Kannelaud, J., and Peterson, J. E., "Efficient Frequency-Doubled Single-Frequency Nd:YAG Laser," Lockheed Missiles and Space Co., Inc., Palo Alto, Calif., IEEE Journal of Quantum Electronics, Vol. QE-8, August 1971.

167. Kembry, K., MacPherson, R. W., "CO_2 Laser Induced Breakdown and Damage to Surfaces of Laser Optical Materials," Defense Research Establishment, Valcartier, Quebec, AD 903-868, July 1972.

168. Kent, G. S., et al., "A Study of the Feasibility of Measuring Atmospheric Densities by Using a Laser-Search Light Technique," University of the West Indies, Kingston, Jamaica, AD 741-875, February 1972.

169. Kessler, E. G., et al., "The Detonation of Explosives Using Pulsed Laser Systems As A Stimulus," Picatinny Arsenal, Dover, N. J., AD 905-512L, October 1972.

170. Killick, D. E., et al., "A High Power Frequency Doubled Neodymium-In-Glass Laser," Royal Aircraft Establishment, Farnborough (England), RAE-TR-67-47, AD 823-972L, February 1967.

171. Klose, Jules Z., "Transition Probabilities and Mean Lives of the 352 Laser Level in Neon I," National Bureau of Standards, Washington, D. C., AD 703-356, December 1968.

172. Kochner, R., et al., "Repetitively Pulsed Inorganic Liquid Lasers," Bayside Research Center, GTE Labs., Bayside, N. Y., Applied Physics, Vol. 41, 1970.

173. Koechner, Walter, et al., "Characteristics and Performance of High-Power CW Krypton Arc Lamps for Nd:YAG Laser Pumping," IEEE Journal of Quantum Electronics, Vol. 3, March 1972.

174. Kressel, H., et al., "High-Average-Power Room-Temperature Large Optical Cavity (LOC) Lasers," RCA, Labs., Princeton, N. J., PRRL-72-CR-35, AD 905-545L, October 1972.

175. Kressel, H., et al., "Production Engineering Measure on Gallium Arsenide Laser Diode," RCA Electronic Components, Somerville, N. J., AD 843-784L, 1 April - 30 June 1968.

176. Kressel, Henry et al., "(ALGA) As Laser Study," RCA Labs., Princeton, N. J., AD 882-978L, October 1969.

177. Kressel, Henry et al., "(GAAL) As Electroluminescent Diodes and Injection Lasers," RCA Labs., Princeton, N. J., AD 871-228L, June 1970.

178. Kressel, Henry et al., "Gas Degradation," RCA Labs., Princeton, N. J., AFAL TR-71-83, AD 882-976, April 1971.

179. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

180. Landry, Murphy J., "A Pulsed Ruby Laser With Individual Q-Switched Multiple Cavities," IEEE Journal of Quantum Electronics, June 1973.

181. Lam, M. F., et al., "Transverse-Excitation HCN Laser," IEEE Journal of Quantum Electronics, August 1973.

182. Laurie, K. A., and Hale, M. M., "A Pin-Electrode Atmospheric-Pressure CO_2 Laser," IEEE Journal of Quantum Electronics, November 1971.

183. Lechevalier, R., et al., "Three-Axis Laser Angular Rate Sensor," Honeywell Inc., Minneapolis, Minn., AD 374-565, July 1966.

184. Lechevalier, R., and Pekkarinen, M., "Three-Axis Laser Angular Rate Sensor," Honeywell Inc., Minneapolis, Minn., AD 385-558L, November 1967.

185. Leib, K. G., et al., "Activation of Gaseous Lasers by Diffusion," Grumman Aircraft Engineering Corp., Bethpage, N. Y., AD 807-326, February 1976.

186. Lempicki, A., and Samelson, H., "Liquid Lasers," Scientific American, Vol. 216, No. 6, pp. 80, June, 1967.

187. Lencioni, Donald E., "The Effect of Dust on 10.6 Micrometers Laser-Incuded Air Breakdown," Massachusetts Institute of Technology, Lexington Lincoln Lab., AD 771-895, April 1973.

188. Lesnick, J. P., "High Energy Coaxial Laser Pumps," Westinghouse Research Labs., Pittsburgh, Pa., AD 484-453, February 1966.

189. Lesnick, J. P., "Development Study of High Energy Coaxial Laser Pumps," Westinghouse Research Labs., Pittsburgh, Pa., AD 476-554, May 1965.

190. Loiacono, G. M., and Anafi, D., "Advanced Production Engineering for Lithium Niobate Crystals for Laser Q-Switch," Isomet Corporation, Oakland, N. J., AD 909-608L, January 1973.

191. Lopolito, Angelo L., "Engineering Test of Simulator, Weapon Firing (aser) 3A102B," Development and Proof Services, Aberdeen Proving Ground, Md., DPS-2788, AD 844-616L, July 1968.

192. Lopolito, Angelo, L., "Check Test of Laser Range Finder, XM23E1," Development and Proof Services, Aberdeen Proving Ground, Md., AD 369-013L, January 1966.

193. Lopolito, Angelo L., "Check Test of Range Finder AN/GVS-3 (Engineering Phase)," Materiel Test Directorate, Aberdeen Proving Ground, Md., AD 503-670, August 1969.

194. Mack, M. E., "Vortex Stabilizer Flashlamps for Dye Laser Pumping," Applied Optics, Vol. 13, No. 1, January 1974, United Aircraft Research Laboratories, East Hartford, Conn.

195. MacNair, Donald "Study of Electron Emitters for Use in Gas Lasers," IEEE Journal of Quantum Electronics, Vol. QE-5, No. 9, September 1969.

196. Macpherson, R. W., and Gravel, M., "Sequential Dielectric Breakdown of Air By The Focussed Radiation From a Mode Locked CO_2 Tea Laser," Defense Research Establishment, Valcartier, Quebec, AD 743-735, August 1971.

197. Magyar, G., "Dye Lasers--A Classified Bibliography 1966-1972," Applied Optics, Vol. 13, No. 1, January 1974, European Space Research Institute, European Space Research Organization, Frascati, Rome, Italy.

198. Mannewurf, C. R. and Motamedi, M. E., "A Pulsed GaAs Laser System for Semiconductor Carrier Lifetime Measurements," Northeastern University, Evanston, Ill., AD 714-397, July 1969.

199. Marantz H., et al., "The Singly Ionized Krypton Ion Laser," IEEE Journal of Quantum Electronics, Vol. QE-5, No. 1, January 1969.

200. Marker, Douglas L., "A Review of Laser Safety Eyewear," Naval Weapons Lab., Dahlgren, Va., AD 889-055L, June 1971.

201. Markiewicz, J. P., and Emmitt, J. L., "Design of Flashlamp Driving Circuits," IEEE Journal of Quantum Electronics, Vol. QE-2, No. 11, November 1966.

202. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

203. Marshall, Albert H., et al., "Laser Weapon Fire Simulator Using Retro-reflective Targets," Naval Training Equipment Center, Orlando, Fla., AD 749-951, September 1972.

204. Massey, Gail A., "ND:YA103 Laser Device Development," GTE Sylvania Inc., Mountain View, Calif., AD 903-864L, June 1972.

205. Massone, C. A., et al., "New IR Laser Lines in a N_2 Pulsed Discharge," IEEE Journal of Quantum Electronics, Universidad Nacional de La Plata, La Plata, Argentina, November 1969.

206. Mauer, Paul B., "Laser Material Study," Eastman Kodak Co., Rochester, N. Y., AD 604-443, June 1964.

207. May, Frank D., "Laser Rangefinder XM23, Military Check Test," Army Artillery Board, Ft. Sill, Okla., AD 368-965L, December 1965.

208. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

209. McKenney, L. E., "Pave Spike IOT and E," Tactical Air Warfare Center, Eglin AFB, Fla., AD 525-057L, March 1973.

210. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

211. Milam, David and Bradbury, R. A., "Laser Damage Threshold for Dielectric Coatings As Determined by Inclusions," Air Force Cambridge Research Labs., Laser Physics Branch, L. G. Hanscom Field, Bedford, Mass., Applied Physics Letters, Vol. 23, No. 12, 15 December 1973.

212. Moffat, Jack P., Jr., "Disc Laser Amplifier," ILC Technology, Inc., Sunnyvale, Calif., AD 760-707, April 1973.

213. Monchamp, R., et al., "High Quality ND:YAG Laser Materials," Raytheon Co., Waltham, Mass., AD 861-732L, October 1969.

214. Morehead, Jr., F. F. "Light-Emitting Semiconductors," Scientific American, Vol. 216, No. 5, pp. 108, May 1967.

215. Nerenberg, L. P., Christian, W. J., "Laser-Photochromic Large-Screen Display System," Naval Electronics Lab. Center, San Diego, Calif., AD 907-495L, October 1972.

216. Neuman, Don B., "Effects of Laser Radiation on Guidance and Control Systems of Missiles," Air Force Avionics Lab., Wright-Patterson AFB, Ohio, AD 349-918, April 1964.

217. Nevares, Henry Jr., Leary, Richard L., "Expanded Service Test of Anti-Laser Goggles," Army Tropic Test Center, APO New York, AD 910-021L, October 1972.

218. Newman, D. H., "Experimental Tests of Proposed Mechanisms for Gradual Degradation of Gas Double-Heterostructure Injection Lasers," Post Office Research Department, London (England), No. 299, AD 753-752, July 1972.

219. Newman, David H., and Ritchie, Simon, "Gradual Degradation of GaAs Double-Heterostructure Lasers," IEEE Journal of Quantum Electronics, Vol. QE-9, No. 2, February 1973.

220. Newman, D. H., "Experimental Tests of Proposed Mechanisms for Gradual Degradation of GaAs Double-Heterostructure Injection Lasers," Post Office Research Department, London, England, AD 753-752, July 1972.

221. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

222. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

223. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

224. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

225. Okoomian, H. J., "Feasibility of an Undersea Laser Communications Link," Radio Corporation of America, Burlington, Mass., AD 377-665L, April 1974.

226. Oliver, J. R., and Barnes, F. S., "A Comparison of Rare - Gas Flash-lamps," IEEE Journal of Quantum Electronics, Vol. QE-5, May 1969.

227. Oliver, J. R., and Barnes, F. S., "Rare-Gas Pumping Efficiences for Neodymium Lasers," IEEE Journal of Quantum Electronics, Vol. QE-5, No. 5, May 1969.

228. Ornstein, M. H., and Derr, V. E., "Prepulse Enhancement of the Flash-lamp Pumped Dye Laser," Applied Optics, Vol. 13, No. 9, September 1974.

229. Packard J. R., et al., "Standing Waves and Single-Mode Room-Temperature Laser Emission from Electron-Beam-Pumped Cadmium Sulfide," IEEE Journal of Quantum Electronics, Vol. QE-5, No. 1, January 1969.

230. Panish, M. B., and Hayashi, Izuo, "A New Clash of Diode Lasers," Scientific American, Vol. 225, No. 1, pp. 32, July 1971.

231. Parker, J. V., and Stephens, R. R., "Pulsed HF Chemical Laser With High Electrical Efficiency," Applied Physics Letters, Vol. 22, No. 9, Hughes Research Lab., Malibu, Calif., 1 May 1973.

232. Patel, C. K. N., "High-Power Carbon Dioxide Lasers," Scientific American, Vol. 219, No. 2, pp. 22, August 1968.

233. Paul, Anthony J., et al., "Component Engineering Test of Tank, Combat, Full-Tracked, 152mm Gun, M60A1E2, Army Armor and Engine Board, Ft. Knox, Ky., AD 851-415L, May 1969.

234. Paul, Anthony J., "Service Test of Tank, Combat, Full-Tracked, 152MM Gun, M60A1E2 with Closed Breech Scavenger System and Laser Range Finder," Army Armor and Engineer Board, Ft. Knox, Ky., AD 852-327, April 1969.

235. Pearson, R. K., et al., "Pressure Dependency The NF_3 - H_2 Transverse-Discharge Pulse-Initiated HF Chemical Laser," IEEE Journal of Quantum Electronics, Vol. QE-9, No. 7, July 1973.

236. Pearson, R. K., and Cowles, J. O., "Relative Performance of a Variety of NF_3 + Hydrogen-Donor Transverse-Discharge HF Chemical Laser Systems," IEEE Journal of Quantum Electronics, Vol. QF-9, No. 9, September, 1973.

237. Pekkarinen, M., "Three-Axis Laser Angular Rate Sensor," Honeywell, Inc. Minneapolis, Minn., AD 391-380L, May 1968.

238. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

239. Pekkarinen, Michael O., "Development and Evaluation of a Laser Angular Rate Sensor for Use in Severe Environmental Applications, Volume III," Honeywell Inc., Minneapolis, Minn., AD 504-205, February 1969.

240. Petroff P., and Hartman, R. L., "Defect Structure Introduced During Operating of Heterojunction GaAs Laser," Bell Telephone Labs., Murray Hill, New Jersey, Applied Physics Letters, Vol. 23, No. 8, 15 October 1973.

241. Picus, G. S., "Far Infrared Laser Receiver Investigation," Hughes Research Labs., Malibu, Calif., AD 810-764L, March 1967.

242. Pimentel, G. C., "Chemical Lasers," Scientific American, Vol. 214, No. 4, pp. 32, April 1966.

243. Plante, T. K., et al., "New Optically Pumped Far - Infrared Lasers, IEEE Journal of Quantum Electronics, September 1973.

244. Powell, F. X., and Djeu, N. I., "CW Atomic Oxygen Laser at 4.56 μ," Naval Research Lab., Washington, D. C., IEEE Journal of Quantum Electronics, April 1971.

245. Prindle, W. R., "Preparation of Platinum-Free Laser Glass," AD 457-331, American Optical Corp., Southbridge, Mass., December 1964.

246. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

247. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

248. Rice, Robert R., et al., "Laser Modulator," McDonnell Douglas Astronautics Co., East, St. Louis, Mo., AD 901,023, May 1972.

249. Rice, W. W., and Jensen, R. J., "Aluminum Fluoride Exploding-Wire Laser," Applied Physics Letters, Vol. 22, No. 2, Las Alamos Scientific Laboratory, University of Calif., Las Alamos, New Mexico, 15 January 1973.

250. Ripper, J. E., "Comments on the Reliability of GaAs Strip-Geometry Junction Lasers," IEEE Journal of Quantum Electronics, Vol. QE-6, June 1970.

251. Riseberg, L. A., et al., "New Class of Intermediate-Gain Laser Materials: Mixed Garnets," Texas Instruments Inc., Dallas, Texas, Applied Physics Letters, Vol. 23, No. 3, 1 August 1973.

252. Ritchie, S., "The Reliability of Gallium Arsenide Double Heterojunction Injection Lasers," Post Office Research Dept., London, England, AD 911-760L, September 1972.

253. Roess, Dieter and Zeidler, Guenter, "Pumping New Life Into Ruby Lasers," Industrial Electronics, Central Laboratories, Siemens & Halske AG, Munich, West Germany, September 1966.

254. Rosen, David I., et al., "WB4-A Spectroscopic Study of CW Chemical Lasers," IEEE Journal of Quantum Electronics, Vol. QE-9, No. 1, January 1973.

255. Ross, M., et al., "Space Data Relay Subsystem Laser Communications Preliminary Subsystem Design," AD 889-322L, McDonnell Douglas Astronautics Co., E. St. Louis, Mo., November 1971.

256. Sabotinov, N. V., and Qelbizov, P. K., "He-Cd-Se Gas Laser," IEEE Journal of Quantum Electronics, August 1973.

257. Sarjeant, W. J., and Brannen, Eric "Enhancement of Laser Action in H_2O by the Addition of Helium," IEEE Journal of Quantum Electronics, December 1969.

258. Sasser, T., et al., "1.06 Micron Laser Technology,: Martin Marietta Corporation, Orlando, Fla., OR 9926, December 1968.

259. Scarlet, Richard I., et al., "Direct Measurement of Picosecond Lifetimes," Cornell University, Ithaca, N. Y., Materials Science Center, MSC-TR-24, MSC-938, AD 677-775, June 1968.

260. Schawlow, A. L., "Laser Light," Scientific American, Vol. 219, No. 3, pp. 120, September 1968.

261. Schiel, Ernest J., et al., "Large Area (Quadrant) Germanium Detectors," Army Electronics Command, Fort Monmouth, N. J., ECOM-3381, AD 881-750, January 1971.

262. Schmitt, George F., Jr., and Hall, Richard C., "Effects of a Rain Erosive Environment on the Transmission of Optically Transparent Plastic Materials," Air Force Materials Laboratory, Wright Patterson Air Force Base, Ohio, AFML-TR-73-136, AD 916-696L, August 1973.

263. Schneegans, M., "The Use of Glass in Lasers," Foreign Technology Division, Wright-Patterson AFB, Ohio, AD 890-902L, November 1971.

264. Schroeder, J. B., et al., "Crystals for Optical Laser Applications," Perkin-Elmer Corp., Norwalk, Conn., AD 484-276, June 1966.

265. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

266. Sherman, Glenn H., and Coleman, Paul D., "Absolute Measurement of the Second-Harmonic Generation Nonlinear Susceptibility of Tellurium at 28.0 μm," IEEE Journal of Quantum Electronics, Vol. QE-9, No. 3, March 1973.

267. Shirahata, H., and Fujisawa, A., "Aerodynamic Mixed Electric Discharge CO_2 Lasers," Applied Physics Letters, Vol. 23, No. 2, 1st Research Center, Tokyo, Japan, 15 July 1973.

268. Simorda, Josef, "New Possibilities of Non-Destructive Testing of Tires by Laser Holography," Foreign Technology Division, Wright-Patterson AFB, Ohio, AD 734-916, October 1971.

269. Smith, David C., "Q-Switched CO_2 Laser," IEEE Journal of Quantum Electronics, June 1969.

270. Smith, P. W., and Maloney, P. L., "A Self-Stabilized 3.5-μm Waveguied He-Xe Laser," Applied Physics Letters, Vol. 22, No. 12, Bell Telephone Laboratories, Holmdel, N. J., 15 June 1973.

271. Smith P. W., et al., "Waveguide TEA Laser," Applied Physics Letters, Vol. 23, No. 9, Bell Telephone Laboratories, Holmdel, N. J., 1 November 1973.

272. Sommers, H. S., et al., "High Pulse Power Injection Laser," RCA Labs., Princeton, N. J., AD 844-211L, November 1968.

273. Sorokin, Peter, "Organic Lasers," Scientific American, Vol, 220, No. 2, pp. 30, February 1969.

274. Southward, H. D., and Noel, B., "Fast Neutron Effects on Diffused Gallium," New Mexico University, Albuquerque, N. M., AD 912-532L, EE-201(73)AFWL-092.

275. Srinivasan, R., "New Materials for Flash-Pumped Organic Lasers," IEEE Journal of Quantum Electronics, IBM Thomas J. Watson Research Center, Yorktown, N. Y., November 1969.

276. St. Peters, R. L., and Taylor, D. J., "Face-Pumped High-Average-Power Low-Distortion Dye Laser," Applied Physics Letters, Vol. 23, No. 2, General Electric Corporate Research and Development, Schenectady, New York, 15 July 1973.

277. Stafsudd, O. M., and Yeh, Y. C., "The CW Gain Characteristics of Several Gas Mixtures at 337 μ," IEEE Journal of Quantum Electronics, Vol. QE-5, No. 7, July 1969.

278. Stone, J. and Burrus, C. A., "Neodymium-Doped Silica Lasers in End-Pumped Fiber Geometry," Bell Telephone Labs., Crawford Hill Lab., Holmdel, N. J., Applied Physics Letters, Vol. 23, No. 7, 1 October 1973.

279. Strome, Jr., F. C., "Transient Gain Measurements on Laser Dyes," IEEE Journal of Quantum Electronics, No. 2, February 1972.

280. Strome, Jr., F. C., "Transient Gain Measurements on Laser Dyes," IEEE/OSA Conference on Laser Engineering and Applications, Washington, D. C. June 2-4, 1971, Research Laboratories, Eastman Kodak Co., Rochester, N. Y.

281. Stullenbarger, L. G., "Engineering Test of Laser Range Finder for Tank, Combat, Full-Tracked, 152-MM Gun, M60A1E1 (Comparative Selection Phase)," Development and Proof Services, Aberdeen Proving Ground, Md., AD 390-623L, June 1968.

282. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

283. Sweet, R. M., et al., "Research and Development of a Prototype Laser Point Marking Instrument," Optomechanisms Inc., Plainview, N. Y., AD 673-291, June 1967.

284. Targ, Russell, "Pulsed Nitrogen Laser at High Repetition Rate," IEEE Journal of Quantum Electronics, August 1972.

285. Tedrow, Ronald G., and Adamczyk, Walter F., "Military Potential Test of Simulator, Weapon Firing, Helium-Neon Laser," Army Armor and Engineering Board, Ft. Knox, Ky., AD 848-199L, January 1969.

286. This reference will be made available to qualified military and government agencies on request from RADC (OCTM) Griffiss AFB NY 13441.

287. Triplett, J. R., and Boni, A. A., "The Interaction of Suspended Atmospheric Particles With Laser Radiation," Systems Science and Software, La Jolla, Calif., AD 757-517, November 1972.

288. Tullis, B. J., et al., "Development, Application, and Design Specifications of a Laser-Doppler Particle Sensor for the Measurement of Particle Velocities in Two-Phase Rocket Exhausts," Stanford Univ., Calif., AD 845-191, September 1968.

289. Wall, B., and Jones, E., "Research on Flash Tubes," English Electric Valve Company, Ltd., Chelmsford, Essex, England, AD 844-110, October 1968.

290. Walpole, J. N., et al., "Single Heterojunction Pb_{1-x} Sn_x Te Diode Lasers," Lincoln Lab., Massachusetts Institute of Technology, Lexington, Mass., Applied Physics Letters, Vol. 23, No. 11, 1 December 1973.

291. Ward, Kevin B., "Low Power CW Alkali Vapor Lamps," Holobeam, Inc., Paramus, N. J., AFAL TR-72-40, AD 894-695L, May 1972.

292. Warr, P. D., and Rouse, R. L., "Investigation of Dielectric Optical Coatings for Lasers," General Electric Co., Ltd., Wembley, England, AD 879-376, November 1970.

293. Weber, Marvin J., et al., "Laser Action From Ho^{3+}, Er^{3+}, and Tm^{3+} in $YAlO_3$," IEEE Journal of Quantum Electronics, Vol., QE-9, No. 11, November 1973.

294. Wiberg, Lloyd W., "Category I Final Test Report for Compass Look System," Cubic Corporation, San Diego, Calif., TR/299-1A, AD 872-862L, July 1970.

295. Wilson, Leroy E., et al., "New Gas Lasers Committee Report on Electronic Transition Chemically and Electrically Excited Lasers," Air Force Weapons Lab., Kirtland AFB, New Mexico, 22 September 1972.

296. Woodcock, Richard F., "Multiple Doped Erbium Glasses," American Optical Co., Southbridge, Mass., AD 843-780, 15 April - 15 July 1968.

297. Woodcock, Richard F., and Siegmund, Walter P., "Neodymium Laser Glass Improvement Program," American Optical Co., Southbridge, Mass., AD 431-641, 1964.

298. Woodward, Benjamin W., "A Reliable, Repetitively Pulsed, High Power Nitrogen Laser," Colorado Univ., Boulder, Colo., AD 764-023, March 1973.

299. Woodward, Jason H., "Laser Distance Measuring Equipment," Radio Corporation of America, Burlington, Mass., AD 377-278, October 1966.

300. Yeamans, Norman L., and Creedon, John E., "Long-Life High-Repetition-Rate Flash Tubes," Army Electronics Command, Fort Monmouth, N. J., ECOM-3043, AD 679-146, November 1968.

301. Yonezu, H., et al., "Degradation Mechanism of (Al-Ga) As Double-Heterostructure Laser Diodes," Nippon Electric Co., Ltd., Central Research Labs., Kawasaki, Japan, Applied Physics Letters, Vol. 24, No. 1, 1 January 1974.

302. Young, P. A., "Thermal Runaway in Germanium Laser Windows," Defense Standards Labs, Maribyrnong, Australia, AD 879-910, October 1970.

303. Zigler, Gilbert Lenk, "Laser Initiated Conduction of an Overvolted Liquid Dielectric," Air Force Institute of Technology, Wright-Patterson AFB, Ohio, School of Engineering, Master's Thesis, AD 857-481, June 1969.

304. Zirfas, Ewald "Check Test of Laser AN/GVS-3 (SM23E2)," Army Artillery Board, Ft. Sill, Okla., AD 378-606L, October 1966.

MISSION
of
Rome Air Development Center

RADC is the principal AFSC organization charged with planning and executing the USAF exploratory and advanced development programs for information sciences, intelligence, command, control and communications technology, products and services oriented to the needs of the USAF. Primary RADC mission areas are communications, electromagnetic guidance and control, surveillance of ground and aerospace objects, intelligence data collection and handling, information system technology, and electronic reliability, maintainability and compatibility. RADC has mission responsibility as assigned by AFSC for demonstration and acquisition of selected subsystems and systems in the intelligence, mapping, charting, command, control and communications areas.

Printed by
United States Air Force
Hanscom AFB, Mass. 01731