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# OPTICAL PUMPS FOR LASERS

## TRI-ANNUAL REPORT No. 1

By

LOWELL NOBLE AND C. B. KRETSCHMER

MARCH, 1972

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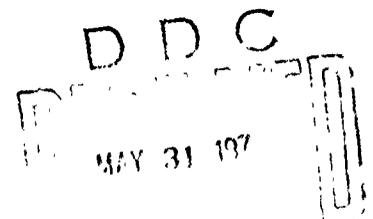CONTRACT DAAB07-71-C-0239

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### 17 May 1971 to 17 September 1971

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The objective of this program is to increase both the output efficiency and the reproducibility of optical pumps for Nd:YAG lasers. This report covers the work carried out during the first four months of the program.

Lamps with quartz envelopes doped with cerium, which converts ultra violet radiation to visible radiation, have been tested and found to emit 15% more light in the region between 0.4 and 0.65 $\mu m$ than lamps made of undoped quartz.

An analysis was made of the externally triggered mode and simmer mode of flashlamp operation. It is hypothesized that the lower electron temperature and the lower current density achieved in simmer mode operation are responsible for the enhanced light output obtained in the simmer mode.

A technique was devised to measure lamp arc growth during a pulse. A lamp of 4 mm bore diameter and 2.125 inch arc length, filled with 450 Torr of xenon, required a 20 joule pulse to fill the bore within a 100 $\mu s$ period.

Lamps have been manufactured to tolerances significantly tighter than normal; they may provide more reproducible light output than is provided by standard lamps.

| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Optical Pumps | | | | | | |
| Flash Lamps | | | | | | |
| Inert Gas Lamps | | | | | | |
| Lasers | | | | | | |
| Laser Pumping | | | | | | |

# TABLE OF CONTENTS

## FOREWORD

The work reported herein was accomplished under Contract Number
DAAB07-71-C-0239 for the Gaseous Electron Devices Team, Beam
and Plasma Device Technical Area of the Electronic Technology and
Devices Laboratory under the guidance of Mr. Norman Yeamans,
the contracting officer's designated representative.

The studies being carried out on this program are being performed in
the Engineering Division of ILC, which is under the direction of
Dr. L. Reed. Martin Marietta is responsible for the laser effort on
a sub-contract basis.

Mr. Lowell Noble is the principal investigator. Dr. Carl Kretschmer
developed the theory of simmer mode operation. Mr. B. Maynard
and Mr. Harry Flentz are carrying out the optical measurements and
data reduction. Mr. D. Alexander is responsible for flashlamp fa-
brication. Mr. D. Allen is responsible for the auxiliary digitizing
modification to the fluorescent analysis instrument and Mr. M. Grasis
designed the multiple lamp life testing unit.

Mr. P. M. Rushworth of Martin Marietta is responsible for laser
testing.

# ABSTRACT

The objective of this program is to increase both the output
efficiency and the reproducibility of optical pumps for Nd:YAG
lasers. This report covers the work carried out during the first
four months of the program.

Lamps with quartz envelopes doped with cerium, which converts
ultra violet radiation to visible radiation, have been tested and
found to emit 15% more light in the region between 0.4 and $0.65\mu$
than lamps made of undoped quartz.

An analysis was made of the externally triggered mode and simmer
mode of flashlamp operation. It is hypothesized that the lower
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simmer mode operation are responsible for the enhanced light output
obtained in the simmer mode.

A technique was devised to measure lamp arc growth during a pulse.
A lamp of 4 mm bore diameter and 2.125 inch arc length, filled with
450 Torr of xenon, required a 20 joule pulse to fill the bore within
a $100\mu$s period.

Lamps have been manufactured to tolerances significantly tighter
than normal; they may provide more reproducible light output than
is provided by standard lamps.

# LIST OF ILLUSTRATIONS

List of Illustrations - Continued

## LIST OF TABLES

## 1.0 SUMMARY AND CONCLUSIONS

Work is being carried out to increase the overall efficiency (to 4%) and reproducibility (to ±5%) of a pulsed Nd:YAG laser that uses a 1/4 inch by 2-1/2 inch laser rod and a 10 joule pump lamp. These results will then be applied to improving the overall efficiency and reproducibility of a laser that uses a 3 mm x 30 mm Nd:YAG laser rod and a 5 joule pump lamp. This performance is to be attained by improving lamps, their associated electronics and the related laser cavities. The best comparable laser efficiency previously achieved was 2.32%.[1] That laser was pumped with a 10 joule flashlamp of 2.125 inch arc length, 3 mm bore, filled with krypton to 1500 Torr. The flash duration was 80 microseconds.

The circuit analysis presently used for determining the L, C and V parameters of a single mesh flashlamp pulsing network assumes an arc that fills the bore. With more precision the arc growth may be described by an equation of the form

$$d_a = k \cdot \ell \cdot \frac{i^n}{v}$$

where $d_a$ is the varying arc diameter of length $\ell$ through which a current passes with a voltage drop v; k and n are constants, which can be determined experimentally. This equation is being used as a starting point to develop a more precise circuit analysis for flashlamp driving circuits for the case of a partially filled bore.

The values of $d_a$ throughout a 100$\mu$s pulse have been measured in 4 mm bore, 2.125 inch arc length, 450 Torr xenon flashlamps pulsed at 5 to 60 joules. An external trigger wire was used. A newly developed image intensifier photographic technique was applied to photograph the plasma and measure $d_a$. (The bore of the flashtube is found to be filled only with input energies above 20 joules.)

The normally erratic growth of the arc has been changed to a smooth radial arc growth by placing a thin metallic strip along the side of the flash tube for triggering. This improvement is expected to allow better imaging of the arc onto the laser rod.

Flashtubes with envelopes of cerium-doped quartz have been shown

to produce 15% more light output in the 0.4 to 0.65$\mu$m wavelength
band compared to normal quartz envelope lamps, by down converting
the UV energy of the arc.

Comparison of the externally triggered mode and the simmer mode of
lamp initiation has shown that the increase in light output obtained
with the simmer mode results from enhancement of line radiation
(which is in the Nd:YAG pump band) and depression of continuum radiation,
compared to that obtained with standard triggering. This phenomenon,
it is hypothesized, results from both lower electron temperatures
and lower current densities.

The main fabrication variation affecting the reproducibility of lamp
output is variation in the bore diameter of the lamp. 4mm bore
lamps were produced with bore diameter variations of only $\pm$ 0.05 mm.

In order to increase the reproducibility of light output, digial read-out
equipment has been constructed to measure the radiation in the excita-
tion bands of Nd:YAG. The digital read-out replaces the less accurate
oscilloscope procedures used previously. [1] A five-position station
has been constructed for measuring the reproducibility of these lamps
as they age.

The inferences that may be drawn from the work performed so far are:

1. Laser lamps with cerium-doped-quartz envelopes
produce more radiation in the 0.4 to 0.65$\mu$ region
than lamps with clear fused quartz envelopes.
Laser output efficiencies will probably be increased
through pumping of the 0.58$\mu$ band.

2. Lamps with a metal stripe trigger wire produce
more uniform discharges than lamps without the
stripe and probably increase laser efficiency through
improved imaging in the rod.

3. Improvements in lamp efficiency have been
achieved using the simmer mode of lamp operation,
which, it is suggested, modifies arc initiation processes
to decrease electron temperature and to decrease current
density.

4. Measurements of plasma diameter during arc growth
have been made that show that bores of 4mm lamps are
not filled during 5 and 10 joule pulsing. Improvements in

2

designing flashlamp driving circuits specifically for unfilled bore lamps may increase the pumping efficiency.

5.      Instrumentation has been developed with which the reproducibility (of the output within the Nd:YAG pumping bands) of a single lamp was found within 10 pulses to vary an average of 0.7% and a maximum of 1.4% of the mean value. How much of the measured variation are due to the lamp and how much to the instrumentation is not yet known.

## 2.0   INTRODUCTION

The purpose of this program is to increase both the efficiency and the reproducibility of Nd:YAG lasers through improvements in lamps, the their associated power supplies, and in laser cavities. This work follows a previous contract, [1] which was initiated to improve the performance of lightweight manportable laser illuminators and target designators.

### 2.1   Objectives

Improved laser performance is sought for two types of laser operating modes, each of which requires the development of a distinctly different pump lamp. A feasibility study of "Optical Pumps for Holmium Lasers" was substituted for a third mode of operation. Table I gives the specifications and performance goals for the two modes of operation.

### 2.2   Approach

The execution of this program is divided into two tasks. The first task is to increase laser output efficiency and, if necessary, lamp life. The second task is to determine the reproducibility of lamp and laser output before and during life tests and, if necessary, improve lamp reproducibility.

3

## TABLE I

## Nd:YAG LASER PROGRAM GOALS

|  | Mode I | Mode II |
|---|---|---|
| **Operating Conditions** | | |
| Energy Input (joules) | 5 | 10 |
| Repetition Rate (pps) | 1 | 20 |
| **Dimensional Constraints** | | |
| Laser Rod OD (mm) | 3 | 6 |
| Laser Rod Length (mm) | 30 | 63.5 |
| Lamp Overall Length (mm) | 63.5 | open |
| **Performance Objectives** | | |
| Lamp Life (pulses)* | $10^6$ | $10^7$ |
| Initial Lamp-to-Lamp Reproducibility (Laser Output) | ±5% | ±5% |
| Overall Laser Efficiency | 2.5% | 4% |
| Cooling | None | Liquid |

*Laser life is defined as the number of pulses at which the output has dropped by 20% of its initial value.

4

The approach to increasing laser efficiency involves:

1. Obtaining a more detailed understanding of the plasma discharge process in the pump lamp.

2. Incorporating new envelope materials, fabrication processes and trigger wire fabrication techniques into the manufacture of lamps. Each may incrementally add to pump lamp efficiency.

3. Improving the energy delivery from the PFN (pulse forming network) by:

   a) Improving PFN-to-lamp matching design techniques that are applicable when the arc does not fill the bore.

   b) Developing new matching circuits.

4. Modifying the laser cavity designs to accept:

   a) the new lamps

   b) new triggering techniques

   c) other cavity improvements.

The second task, lamp reproducibility, requires very precise measurements of lamp light output. Such measurements require improvements in existing instrumentation.

The reproducibility of laser output may be improved by:

1) Using lamp materials that are manufactured to closer dimensional tolerances.

2) Maintaining a close control over the gas filling and other manufacturing processes.

5

3)     Introducing new triggering methods, power supply concepts and laser cavity changes that can improve reproducibility.

The laser output measurements are being made principally by Martin-Marietta. Additional laser output measurements are also being made in cooperation with other laser manufacturers. The amount of expensive in-laser testing required is reduced by the use of a recently developed instrument that directly measures the "useful" light that a pump lamp emits, i.e., the light that can be used to pump the excitation bands of the Nd:YAG laser.[1] This device is called a differential fluorescence analysis instrument, and the useful light output is measured in terms of a fluorescent output voltage (FOV). The useful light output must be measured with a high degree of precision in order to determine the lamp-to-lamp light output reproducibility. Consequently the existing differential fluorescence analysis instrument is being improved to provide greater precision.

A statistical approach to the measurement of lamp light output reproducibility is being undertaken. Flash lamp life test equipment, capable of testing five lamps at a time, has been constructed for this purpose.

## 3.0   BACKGROUND

Work carried out under a previous optical pump contract[1] resulted in the efficiency improvements shown in Table II and Figure 1. The baseline for the efficiency comparisons was the performance of the standard lamp employed for target designator and illumination applications prior to this investigation: a 450 Torr xenon-filled lamp having a 4mm bore diameter and 2.125 inch arc length , which uses an external trigger wire for initiation and does not employ simmering.

The simmering of the lamp at a low power level between pulses was first introduced by Yeamans and Creedon as a means of improving lamp life[2]; however, it was later found to significantly increase laser output efficiency.[1] A "pseudo-simmer mode" of operation was subsequently developed by ILC in order to reduce the weight of the power supply required.

This technique involves prepulsing the lamp for a period of approx-

6

imately 100$\mu$s before the main pulse is initiated.[1] The increase
in laser efficiency that resulted from employment of the simmer mode
of operation is shown in Table II and Figure 2. The pseudo-simmer
mode is being further investigated during this program.

Figure 1 shows the laser output for two lamps operating between
4 and 10 joules energy input. In the case of the 3000 Torr krypton,
3mm bore lamp the laser efficiency is 1.7% at 5 joules and 2.05%
at 10 joules, using the full simmer mode of operation. Subsequent
laser data obtained at International Laser Systems, Inc. gave a laser
efficiency of 2.32% at the 10 joules level, with a 1500 Torr krypton,
3mm bore lamp and external trigger initiation.[1] Accordingly it
would appear that with full simmer operation approaching 3% efficiency
should be realized at the 10 joule lamp energy input level with a 3mm
bore 3000 Torr krypton lamp.[1]

Further improvements in flash lamp efficiency may be obtained by
analyzing the requirements of the driving circuit more closely for
the 5 joule and 10 joule modes of flashlamp operation, as it has
been found that at these energy levels the plasma does not completely
fill the lamp bore. Prior analyses have assumed that the plasma does
fill the bore for substantially the whole pulse.[3]

The match of the PFN to a flashlamp has been optimized in prior work
using a driving circuit analysis due to Markiewicz and Emmett.[3]
These authors used the relationship

$$v = \pm K_o |i|^{1/2} \tag{1}$$

to develop their analysis, where $v$ is the instantaneous flashlamp
voltage corresponding to the instantaneous current $i$ through the
flashlamp. $K_o$, the impedance characteristic, is in units of ohm-
amps$^{1/2}$. The units of $K_o$ are derived from the relationship

$$v = R \cdot |i| \tag{2}$$

where R is the varying resistance of the flashlamp at a given value
of v and i.

## TABLE II

## IMPROVEMENTS IN LAMP USEFUL LIGHT OUTPUT
## AND LASER OUTPUT

### Averaged Values @ 60 Microsecond Lamp Pulses*

| Modification | Lamp Useful Light Output Increase | | Laser Output Increase | |
|---|---|---|---|---|
| | 5 Joule+ | 10 Joule+ | 5 Joule+ | 10 Joule+ |
| Xe to Kr | 10% | 0%** | 29% | 10% |
| 450 Torr to 3000 Torr | 43% | 17% | 26% | 12% |
| 4mm to 3mm | 4% | 4% | 23% | 12% |
| External Trigger to Simmer Mode | 63% | 25% | 62% | 30% |
| Expected Improvement if all effects are independent | 168% | 52% | 225% | 81% |
| Measured Improvement | (Not measured) | 56% | 240% | 72% |

*The comparison is made at this pulse length because this is the pulse length at which the laser data was taken.

**Improvements (of up to 20%) are noted for longer pulse lengths.

+Level of energy level input to lamp.

NOTE: Lamp arc length is 2.125 inches.

8

Equation 1 is based on earlier experimental work due to Goncz[4] who found that for the high current region and with the plasma filling the flashlamp bore the equation

$$v = v_e + |i| \cdot \frac{\gamma \ell}{A}$$ (3)

holds, where $\gamma$ is the specific resistivity of the xenon or krypton plasma, and is a function of the current density. The voltage drop at the electrodes, $v_e$, is of the order of 20V and so can be neglected in comparison with total lamp voltage drop. A is the cross-sectional area of the tube and $\ell$ is its length.

Goncz experimentally found for xenon at 450 Torr that

$$\gamma = 1.13/J^{1/2} . \text{ohm-cm}$$ (4)

where J is the current density, in $\text{amps/cm}^2$.

From equations 2 and 3:

$$R = \frac{\gamma \ell}{A}$$ (5)

$$v = 1.27 \frac{\ell}{d} \cdot \frac{1}{i^{1/2}}$$ (6)

where d is the diameter of the flashlamp bore.

Thus

$$v = 1.27 \frac{\ell}{d} i^{1/2}$$ (7)

making

$$K_o = 1.27 \cdot \frac{\ell}{d}$$ (8)

9

The value of 1.27 holds for 450 Torr Xe lamps. It has been found from many flash lamp experiments run at ILC that equation (8) can be generalized for other pressures and expressed as

$$K_o = k \left(\frac{P}{450}\right)^{0.2} \cdot \frac{\ell}{d} \tag{9}$$

where P is the flash lamp pressure in Torr. The value of k changes for different gases, and is 1.27 for xenon. The value obtained for krypton has been found to be slightly lower.[1]

Markiewicz and Emmett[3] begin their flash lamp driving circuit analysis by considering the nonlinear differential equation for a single mesh flashlamp LC driving circuit with a voltage $V_o$ across the capacitor. The nonlinear equation relating L, C and V is:

$$L \frac{di}{dt} \pm K_o \left| i \right|^{1/2} + \frac{1}{C} \int_o^T \left| i \right| dt = V_o \tag{10}$$

where t is the time in seconds.

If we make the substitutions and normalizations

$$Z_o = \sqrt{\frac{L}{C}}, \quad \left| i \right| = I \frac{V_o}{Z_o}, \quad \tau = \frac{t}{T}, \tag{11}$$

$$T = \sqrt{LC} \tag{12}$$

The equation becomes

$$\frac{dI}{d\tau} \pm (\alpha) \left| I \right|^{1/2} + \int_o^T \left| I \right| d\tau = 1 \tag{13}$$

where

$$\alpha = \frac{K_o}{(V_o Z_o)^{1/2}}$$

The quantity $\alpha$ is called the damping factor for the circuit. The optimum matching of the flashlamp circuit occurs when $\alpha = 0.8$.

Goncz has speculated that the experimental relationship determined in equation (6) might also hold during the initial portion of the pulse, with the effective instantaneous diameter of the arc replacing the bore diameter during the growth period. Thus equation (6) can be restated as

$$R = 1.27 \frac{\ell}{d_a} \cdot \frac{1}{i^{1/2}} \tag{14}$$

and

$$K_o = 1.27 \, \ell/d_a \tag{15}$$

where $d_a$ is the instantaneous diameter of the arc. Liberman, et al., furnished some experimental support for this hypothesis by applying a variation of equation (14) to the terminal case of arc growth for 0.75J, 20$\mu$s pulses in a 3mm bore xenon flash lamp. "At the peak of the current pulse the arc diameter was calculated to be 1.9mm. It appeared to be $\approx$ 2mm to the eye".[5] They further stated that there did not seem to be enough energy in the pulse to expand the arc to the wall. It should be noted that equation (15) makes $K_o$ time-dependent. Therefore the Markiewicz-Emmett solutions of equation (11) no longer apply exactly, when the bore is not completely filled.

We might further speculate that the 1/2 power relationship in equation (14) might be replaced by another power relationship during the growth period, and the more general relationship

$$v = K_o \, |i|^n \tag{16}$$

might apply. Indeed for pulsed non wall-confined alkali metal vapor lamps the value of n has been found to vary from 0.4 to 0.8 for various lamp fills and pressures,[5] and consequently

$$\alpha = \frac{K_o V_o^{n-1}}{(Z_o)^n} \tag{17}$$

11

These relationships can be experimentally tested on this program. Equipment has been designed to accurately measure v and i and also to record the change of $d_a$ throughout the pulse.

Data from ILC indicate that 100 to $120\mu s$ are required for the diameter of the arc, $d_a$, to reach the walls of a 4mm bore lamp. This time is much longer than that assumed by Goncz[4] based on earlier work reported by Le Compte and Edgerton.[7] Consequently, for the short pulse times of $60-200\mu s$ considered for pulsed laser applications, a more thorough analysis and experimental determination of the growth mode of the arc is in order, to assure that lamps are operated in the most efficient manner.

Surprisingly, though, it has been experimentally determined that xenon flash lamps operated with high current, short pulses (for example, as dye laser pumps), follow the Markiewicz and Emmett flash lamp model with good accuracy. The probable explanation can be best obtained by rewriting equation (10) as follows:

$$\left[ L + L_a (t) \right] \frac{di}{dt} \pm K_o i^{1/2} + i \frac{d L_a (t)}{dt} + \frac{1}{C} \int_o^t i \, dt = V_o, \qquad (18)$$

During the arc expansion process the arc has not yet entirely filled the bore, so $K_o$ is both higher than calculated and is changing in a fashion similar to that expressed in equation (15). The $K_o i^{1/2}$ term is, therefore, higher during the arc expansion process.

On the other hand, the $i \frac{d L_a (t)}{dt}$ term can have a very large negative value, since the inductance of the arc, initially high because of the small arc diameter, is rapidly changing to a low value as the arc expands. These two effects tend to cancel each other in the high current, short pulse regime.

The use of $\alpha$ = 0.8 (the PFN design criterion) often produces component values of L and C that are not readily obtainable, so that a departure from $\alpha$ = 0.8 is often obtained. The L and C components can be adjusted experimentally to give a value close to 0.8. The criteria used is that at 3 $\sqrt{LC}$ the normalized current is 20% of maximum and at 4 $\sqrt{LC}$ it is essentially zero. A slightly over-damped pulse ($\alpha$ greater than 0.9[3]) is aimed for rather than an

12

under-damped pulse as current reversals associated with under-damped pulses tend to shorten electrode, and hence, lamp life. The flash lamp circuit parameters for the most efficient 10J lamp developed to date is given in Table III.

## TABLE III

## OPTIMIZED FLASHLAMP-CIRCUIT PARAMETERS FOR THE MOST EFFICIENT LAMP DEVELOPED ON THE PRIOR PROGRAM

| | | |
|---|---|---|
| Lamp Number | 101 | |
| Bore Diameter | 3 | mm. |
| Arc Length | 2.12 | inches |
| Gas | | Krypton |
| Pressure | 1500 | Torr |
| Inside Wall Area | 5.1 | Sq.cm. |
| Cross Section Area | 0.07 | Sq.cm. |
| Volume | 0.38 | cc. |
| Lamp Impedance | 27.1 | Ohm $(Amp)^{0.5}$ |
| Input Energy | 10 | Joules |
| Pulse Width | 70 | Microseconds |
| Pulse Rep. Rate | 20 | Pulses/sec. |
| Capacitance | 20.4 | $\mu F$ |
| Inductance | 26.6 | $\mu H$ |
| Voltage | 989 | V |
| Circuit Impedance | 1.1 | $\Omega$ |
| Peak Current | 433.3 | A |
| Peak Current Density | 6129 | $A/cm^2$ |
| RMS Current | 11 | A |
| Init. Rate Current Rise | 37.1 | $A/\mu s$ |
| Peak Power | 214 | kW |
| Average Power | 200.0 | W |
| Peak Power Density | 562 | kW/cc |
| Ave. Power Density | 524.1 | W/cc |
| 1 Shot Explosion Energy | 192 | Joules |
| Fraction of Explosion Energy | 0.65 | |
| Expected Life | $>10^6$ | Pulses |
| Inside Wall Load | 39.3 | $W/cm^2$ |
| Alpha | 0.80 | |

*$K_o$ the lamp impedance is measured in ohms-amps$^{1/2}$.

## 4.0   IMPROVING LASER OPERATING EFFICIENCY

· Work was carried out during this reporting period toward development
of a 10J lamp that will pump a Nd:YAG laser with 4% overall efficiency.
A baseline lamp against which improvements have been measured is
the 10J, 4mm bore, 2.125 inch arc length, 450 Torr xenon lamp, which
is the standard lamp used in many laser systems including target de-
signator systems.  This lamp was also the base comparison lamp used
in a prior optical pump program.[1]  The base line for this program is a
modified version of this lamp, which is presently being used in field
tests.  It is the same lamp filled to 1500 Torr.  This modified lamp will
soon be used in target designator and illuminator systems.  The optimized
flashtube, lamp and circuit parameters for the best lamp developed on the
prior program are given in Table III.  It, too, can be used as a comparison
lamp.

Techniques to increase both the amount of effective light output
(effective irradiance) and effective brightness (effective radiance) are
required, as both quantities contribute to increase the efficiency of
laser pumping.  The work "effective" is used to denote that portion of
the light output of the lamp that can be used to pump the excitation bands
of the laser.  Therefore, differential fluorescence analysis measurements
(proportional to effective light output) and arc diagnostic tests are pro-
grammed.  Laser testing will provide confirmation of the improvements
obtained.

### 4.1   Lamps with Cerium Doped Quartz Envelopes

Quartz doped with cerium will absorb radiation below 0.31 $\mu$m
and will fluoresce at wavelengths between 0.4 and 0.65 $\mu$m
A sample of 4mm bore diameter cerium doped quartz became avail-
able and a lamp with a 2.0 inch arc length was constructed from
it.  A control lamp was constructed from clear fused quartz en-
velope material with the same dimensions.  Both lamps were filled
with 450 Torr of xenon.

Spectral data was taken on both lamps at 10 joules input energy
and are shown in Figure 3.  The cerium doped envelope lamp has
approximately 15% greater output over the spectral range from
0.4 to 0.65 $\mu$m.  Since Nd:YAG has a pump band in the wave-
length region from 0.57 to 0.60$\mu$m (Figure 4) the increased
output in the 0.57 to 0.60 $\mu$m region should increase the
pumping efficiency.

14

Laser tests will be conducted later to measure the efficiency improvement that can be obtained when using cerium doped quartz as an envelope material.

## 4.2 Operation of Lamps in Simmer Mode

Prior investigation[1] has shown that operation of lamps with a "simmer current" or "keep alive current" increases both the total light output and the useful light output from lamps. Comparative data of useful light output for simmer and external trigger modes of operation are shown in Figure 5 for a 450 Torr xenon filled lamp with 4mm bore diameter. Comparative laser data for the same lamp operated alternatively with external triggering and with simmer mode are shown in Figure 2. The useful light output at 10J input energy is increased approximately 29%, and the laser output is increased by 27%.

A theoretical investigation was undertaken to determine the reason for the increased efficiency of light production. As a part of this investigation an energy level diagram for krypton was constructed and is presented in Figure 6. The main lines that contribute to pumping of a Nd:YAG laser are indicated, and are seen to terminate on the metastable level.

A spectrum from a krypton lamp is shown in Figure 7, before and after going through a Nd:YAG filter. It is seen that the lines that pump Nd:YAG most effectively are at 0.7602, 0.8104 and $0.8113\mu$. (The latter two lines are not resolved in the spectra.) On the energy level diagram these lines terminate at the metastable level at 7.98 eV.

Simmer current can affect the light output of the main discharge by providing the presence, at the beginning of the pulse, of ions and electrons of the simmer discharge, and the resulting metastable and resonance-excited atoms. The metastable atoms in the gas outside the simmer discharge column increase the rate of growth of the arc when the main discharge is initiated. The arc grows by means of heat conduction to the gas at its boundary, and also by electron-impact ionization of neutral atoms in the boundary layer. If metastables are present, this ionization proceeds at a faster rate, and the boundary layer becomes ionized at a lower temperature than is the case when there are no metastables initially present. The result is that, in the simmer mode,

the arc is larger and has a lower impedance at any given
value of current during its growth, than is the case for non-
simmer operation. Since the voltage gradient is lower during
arc growth in simmer operation, the electron temperature is
also lower. And while the peak current is higher (because
of the lower voltage gradient) the current density is lower
(because of the larger arc diameter). The lower current density
and the lower electron temperature both reduce the relative im-
portance of continuum radiation as compared to line radiation.
Since the line radiation is in the Nd:YAG pumping band, the
effect of simmer mode operation is to increase the fraction of
the output energy that is within the Nd:YAG pumping band.

In addition, the image of the larger arc can fill the laser rod
more uniformly, probably giving a higher laser efficiency.

## 4.3    Triggering Improvements

The usual wrapped trigger wire produces an initially spiral or
stepped arc in flash lamps; the plasma follows the placement
of the trigger wire along and around the lamp. It was reasoned[1]
that if the plasma could be maintained in a straight line during
the arc growth phase, then the imaging of the radiation from the
lamp onto the laser rod would be improved. The effective bright-
ness should also increase. Both of these effects should lead to
an improved efficiency of laser output.

A straight trigger conductor was made by plating a thin strip of
nickel-layered-over-silver on the side of the flash lamp. Pre-
vious attempts to accomplish this involved painting the strip
onto the lamp but were unsatisfactory, with the strips dis-
integrating after a brief pulsing period. This time a durable
strip was deposited onto the lamp by using a recently developed
technique, called "ion plating".

In order to measure the improvements in arc control obtained by
this technique, a diagnostic tool was required that could measure
and record arc growth and position as a function of time.  Accord-
ingly, a device has been developed that is capable of photograhing
the arc growth for any $2\mu$ s interval during the flash lamp light pulse.
The block diagram of the device is shown in Figure 8. An image

16

intensifier tube is energized for $2\mu s$, and performs the function of an extremely high speed shutter. A delay line controls the time when the shutter opens, thereby making it possible to photograph the arc during any portion of its growth and decay. A camera lens focuses the arc image on the image intensifier tube target. A Polaroid oscilloscope camera photographs the arc image on the tube screen. Filters of the appropriate density are inserted in the optical path to adjust the light intensity to fall within the proper exposure range of the film. Figure 9 is a photograph of the equipment.

The pulse command triggers the lamp circuit and a delay line. Experience has shown that successive arc discharges in any lamp (over the relatively small number of pulses used in these tests) are similar in appearance, so that a growth sequence may be photographed by exposing for one successive segment per flash for a number of pulses.

An L349 lamp (4mm bore, 2.125 inch length, with Xe gas at 450 Torr was modified by adding a plated strip trigger wire. This lamp is designated the L349A. It was photographed with pulse input energies of 5 through 60 joules. The percentage of the lamp bore filled at the peak of the current pulse as a function of input energy is shown in the series of photographs presented in Figure 10 and graphically summarized in Figure 11. With energy inputs of less than 20 joules the arc does not fill the bore.

The growth of the arc of 5 and 10 joule pulses with both types of trigger wire is clearly portrayed in the time sequence of arc photographs presented in Figures 12 through 15. The helix effect observed when using the normal trigger wire is clearly seen in the photographs, in contradistinction to the smooth radial growth of the arc in the striped lamp. Further details of the smooth arc growth of the L349A in the vicinity of the cathode are presented in Figure 16. These data are presented in another form in Figures 17 through 20, again demonstrating the more regular growth of the arc in the L349A lamp, especially at the 5 joule level.

It is expected that the control of plasma arc growth achieved with the L349A lamp will result in improved laser output because of increased brightness of the arc and improved imaging of the arc on the laser rod. Laser tests are scheduled on both the L349 and L349A lamps.

17

## 5.0   IMPROVING LASER OPERATING REPRODUCIBILITY

A goal of the program is to achieve reproducibility of laser light
output within ±5%, from pulse to pulse and from lamp to lamp. The figure
must be translated into terms of lamp light output reproducibility.
Optimized lamp and power supply parameters are shown in Table IV
and Table V for the two modes of operation given in Table I. It will
be assumed initially that variations in lamp light output will have a
linear relationship with variations in laser output when using a given
laser system in which everything, including the PFN, is held constant
except the lamp itself. (The exact relationship will be determined in
this program.)

It is worth noting at this point that the reproducibility of light output
for a given energy input can be accurately determined separately from
the absolute output value. The reproducibility can be measured by
repeating the tests and calculating the deviations of the multiple tests.
The absolute output value can only be determined by comparing the light
output or energy input with calibrated standards traceable to NBS. For
the purposes of this program we are concerned primarily with reproduci-
bility.

One reasonable way to restate the requirement that the reproducibility
of laser output shall initially be within ±5% is to assume normally
distributed variations in light output and to require that a large number
of the lamps must have 99.7% ($3\sigma$ limits) of their laser test results
within a ± 5% range.

Table VI shows that for a sample size of 21 normally distributed units
all of those units must have test results within a range of ± 1.5% to
have 90% confidence that 99.7% of a large population will have test
results within a range of 5%.

### 5.1   Analysis of Lamp Variables

The primary variables in the lamp construction that can
influence the lamp light output are fill pressure, bore diameter,
and arc length. Lamp processing can also affect light output.
For example, cathode deposits on the tube walls cause a re-
duction in light output with usage. Parametric analysis of
these variables shows that light output variations are only weak
functions of fill pressure and arc length, but are a strong function
of the arc diameter. The arc diameter in turn is a complex function
of the instantaneous current, the interval since pulse initiation,

18

and bore diameter. Additional analysis is planned in order to obtain detailed insights into bore diameter effects on light output reproducibility. It may be noted already, however, that the effect of bore diameter on light output appears to operate through the effect of arc diameter on $\alpha$, the damping coefficient; non-optimal values of $\alpha$ result in slower energy delivery to the lamp and, consequently, less output per unit time.

## TABLE IV
## MODE I OPERATION

## OPTIMIZED FLASHLAMP-CIRCUIT PARAMETERS

| | | |
|---|---|---|
| Lamp Number | 102 | |
| Bore Diameter | 3 | mm |
| Arc Length | 1.00 | Inches |
| Gas | | Krypton |
| Pressure | 1500 | Torr |
| Inside Wall Area | 2.4 | $cm^2$ |
| Cross Section Area | 0.07 | $cm^2$ |
| Volume | 0.18 | cc. |
| Lamp Impedance | 12.8 | Ohm (Amp)$^{0.5}$ |
| Input Energy | 5 | Joules |
| Pulse Width | 70 | $\mu s$ |
| Pulse Rep. Rate | 1 | Pulses/Sec. |
| Capacitance | 44.3 | $\mu F$ |
| Inductance | 12.3 | $\mu H$ |
| Voltage | 475 | V |
| Circuit Impedance | 0.5 | $\Omega$ |
| Peak Current | 451.0 | A |
| Peak Current Density | 6379 | $A/cm^2$ |
| RMS Current | 1.2 | A |
| Init. Rate Current Rise | 38.7 | $A/\mu s$ |
| Peak Power | 107 | kW |
| Average Power | 5 | W |
| Peak Power Density | 497 | kW/cc |
| Ave. Power Density | 27.8 | W/cc |
| 1 Shot Explosion Energy | 91 | Joules |
| Fraction of Explosion Energy | 0.66 | |
| Expected Life | $>10^6$ | Pulses |
| Inside Wall Loading | 10.4 | $W/cm^2$ |
| Alpha | 0.80 | |

## TABLE V
## MODE II OPERATION

## OPTIMIZED FLASHLAMP-CIRCUIT PARAMETERS

| | | |
|---|---|---|
| Lamp Number | 103 | |
| Bore Diameter | 4 | mm |
| Arc Length | 2.12 | inches |
| Gas | | Xenon |
| Pressure | 1500 | Torr |
| Inside Wall Area | 6.8 | $cm^2$ |
| Cross Section Area | 0.13 | $cm^2$ |
| Volume | 0.68 | cc |
| Lamp Impedance | 22.8 | Ohm $(Amp)^{0.5}$ |
| Input Energy | 10 | Joules |
| Pulse Width | 70 | $\mu s$ |
| Pulse Rep. Rate | 20 | Pulses/Sec. |
| Capacitance | 25.7 | $\mu F$ |
| Inductance | 21.2 | $\mu H$ |
| Voltage | 882 | V |
| Circuit Impedance | 0.9 | $\Omega$ |
| Peak Current | 485.6 | A |
| Peak Current Density | 3864 | $A/cm^2$ |
| RMS Current | 13 | A |
| Init. Rate Current Rise | 41.6 | $A/\mu s$ |
| Peak Power | 214 | kW |
| Average Power | 200.0 | W |
| Peak Power Density | 316 | kW/cc |
| Ave. Power Density | 294.8 | W/cc |
| 1 Shot Explosion Energy | 257 | Joules |
| Fraction of Explosion Energy | 0.04 | |
| Expected Life | $>10^6$ | Pulses |
| Inside Wall Load | 29.5 | $W/cm^2$ |
| Alpha | 0.80 | |

## TABLE VI

## OBSERVED VARIATIONS REQUIRED TO ASSURE THAT
## 99.7% OF POPULATION LIES WITHIN ±5%
## (With 90% Confidence)

| Sample Size | Maximum Variation in Sample Values |
|:-----------:|:----------------------------------:|
| 4 | 0.5% |
| 7 | 1.0% |
| 21 | 1.5% |

### Notes:

1. Assuming Normal Distribution and Mean at 0% Variation

2. Sample Size for 90% Confidence
   That ± 3 Standard Deviations of a large sample
   Lies within ± 5% tolerance

### 5.2 Fluorescence Analysis Instrumentation

A digital readout system was devised to work with the
fluorescence analysis instrument. The readings taken
with this equipment are apparently reproducible to ±0.1%,
which is appreciably better than readings taken from oscilli-
scope photographs, ±3%. A schematic diagram of the equip-
ment is shown in Figure 21 and a photograph of the equipment
appears in Figure 22. The outputs from the two sensor diodes
shown are amplified. The smaller signal is subtracted from
the larger signal, and a peak difference signal is produced.
The peak difference signal is fed to a sample and hold circuit,
and finally the signal is displayed on a digital panel voltmeter.
The input energy to the PFN, which is discharged into the lamp,
is set by the voltage applied to the capacitor. This voltage is
controlled and is measured to an accuracy of ±0.1%.

Table VII shows a series of 10 readings taken on a single

lamp. The average deviation on this lamp, i.e. $\Sigma \dfrac{\text{(reading-mean)}}{n}$ is 0.7%.

## TABLE VII

### REPLICATE FOV DATA FOR A SINGLE LAMP

| Pulse # | Output (mv) | Deviation (mv) |
|---------|-------------|----------------|
| 1 | 1404 | 20 |
| 2 | 1420 | 4 |
| 3 | 1444 | 20 |
| 4 | 1412 | 12 |
| 5 | 1433 | 9 |
| 6 | 1413 | 11 |
| 7 | 1437 | 13 |
| 8 | 1421 | 3 |
| 9 | 1433 | 9 |
| 10 | 1423 | 1 |
| TOTAL | 14240 | 102 |
| Average | 1424.0 | |
| Average Dev. | | 10.2 |
| Average Dev. % | | 0.7% |
| Max. Dev. | | ±1.4% |

The variations in the FOV readings can be due to variations in both the lamp and the measurement equipment. Lamp and lamp-related effects include:

a) Variability of PFN energy delivery

b) Trigger wire placement and arc growth variations

22

c)      Lamp warm-up

d)      Random fluctuations due to cathode emission

e)      Other, miscellaneous, effects

Measurement equipment variations can be due to:

a)      Changes in the reflectivity of the integrating cavity.

b)      Aging of the Nd:YAG crystal and detectors.

c)      Other factors including circuit noise and differences in diode temperature effects.

Attempts will be made to separate these effects.

## 5.3    Lamp Fabrication

Three experimental approaches were taken to reducing lamp bore diameter variations from the $\pm 12\%$ characteristic of standard 4mm bore quartz tubing:

a)      4mm $\pm 1\%$ tubing was selected from standard 4mm tubing. (Size distributions were taken for several sizes and types and are shown in Figures 23 and 24.)

b)      Precision ground tubing, 4mm bore $\pm 0.05$mm, was ordered.

c)      Oversize tubing was shrunk down over precision ground tungsten rods, which were ground and polished to 4mm $\pm 0.01$mm.

Selecting tubing to the tolerances required appears to be impractical as a manufacturing step from a cost and time viewpoint. Quotations for tubing of 4mm $\pm 0.05$mm tubing tolerances were solicited from seven fabricators of standard quartz tubing, but all "no quoted".

The cost of precision ground tubing, $15 for a 12 inch
section, is high, but not prohibitive for use in production
runs of lamps.

The tubing made by shrinking down larger tubing onto the
polished tungsten rods was all within $\pm 0.02$mm of the size
desired. This method is the most suitable, precise, and
economical of the methods discussed.

While the alternatives above were being investigated,
twenty-eight lamps were constructed with selected tubing
of 4mm $\pm 0.05$mm bore diameter, and filled with xenon at
1500 Torr. They are scheduled to be life tested afer initial
measurements of useful light output are performed on them.
Lamp deterioration data will be taken as the lamps are life
tested.

## 5.4    Life Test Instrumentation

The equipment to life test 5 lamps simultaneously has been
completed and evaluated as satisfactory.

The flashlamp life test unit consists of three separate single
mesh pulse forming networks to correspond to the three
originally specified modes of operation. The capacitance
and inductance of the networks can be varied in integral in-
crements. The PFN charge voltage can be varied from 0 to 1500
volts. Each PFN has its associated lamp triggering and failure
sensing mechanism. Lamp triggering is accomplished with a
series trigger transformer with $18\mu$H saturated inductance driven
by a pulse generator. Lamp failure is sensed indirectly by counting
lamp fires. The lamp fire signals are integrated and applied to an
AND gate, which causes the entire system to shut off in case there
is the absence of a fire signal from any of the lamps for 10 con-
secutive shots.

## 6.0  REFERENCES

1.  L. Noble, J. Moffat, L. Reed and J. Richter, "Optical Pumps for Lasers", Final Report, May 1971 ECOM-0035-F.

2.  N. L. Yeamans and J. E. Creedon, "Long-Life High-Repetition-Rate Flash Tubes", R&D Technical Rpt., ECOM-3043, Nov. 1968.

3.  J. P. Markiewicz and J. L. Emmett, "Design of Flashlamp Driving Circuits", IEEE J. of Quant. Electr., Vol. QE-2, No. 11, Nov. 1966.

4.  J. H. Goncz, "Resistivity of Xenon Plasma", J. Applied Phys., 36, 742 (1965).

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6.  L. Noble, "Optical Pumps for Erbium Lasers", Final Rpt., Contr. DAAB07-70-C-0296, October 1971.

7.  G. W. LeCompte and H. E. Edgerton, J. Applied Phys., 27, 1427 (1956).
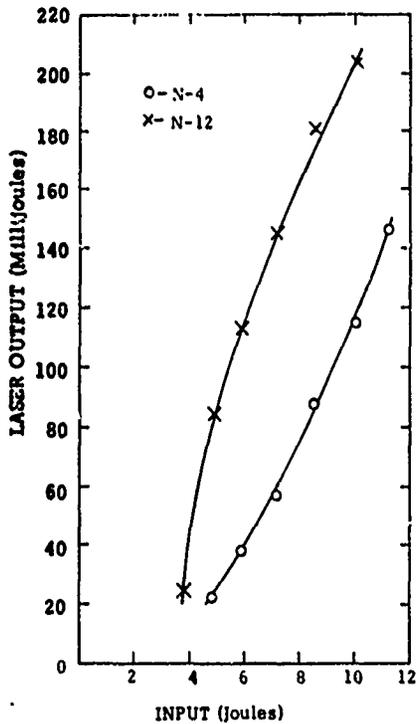
LASER OUTPUT (Millijoules) vs INPUT (Joules) graph

O - N-4
X - N-12

**LASER DATA**

| | |
|---|---|
| Rod: | Nd:YAG, 1/4" x 2-1/2" |
| A/R Coating: | None |
| Output Mirror: | 55 % Reflective |
| Cavity: | Elliptical, Close Wrapped |
| Coolant: | Water |
| Inductance: | 9 Microhenries |
| Capacitance: | 47.3 Microfarads (not critically damped, not optimized) |
| Operating Mode: | Normal |
| Pulse Repetition Rate: | 10 pps. |

**LAMP DATA**

| | Lamp N-4 | Lamp N-12 |
|---|---|---|
| Lamp Bore Diameter (mm): | 4 | 3 |
| Lamp Arc Length (inches): | 2.125 | 2.125 |
| Lamp Fill Gas: | Xenon | Krypton |
| Lamp Fill Pressure (Torr): | 450 | 3000 |
| Initiation Method: | External | Simmer Pulse |

FIGURE 1    LASER OUTPUT DATA FOR 3000 TORR KRYPTON LAMP AND 450 TORR XENON LAMP

1034
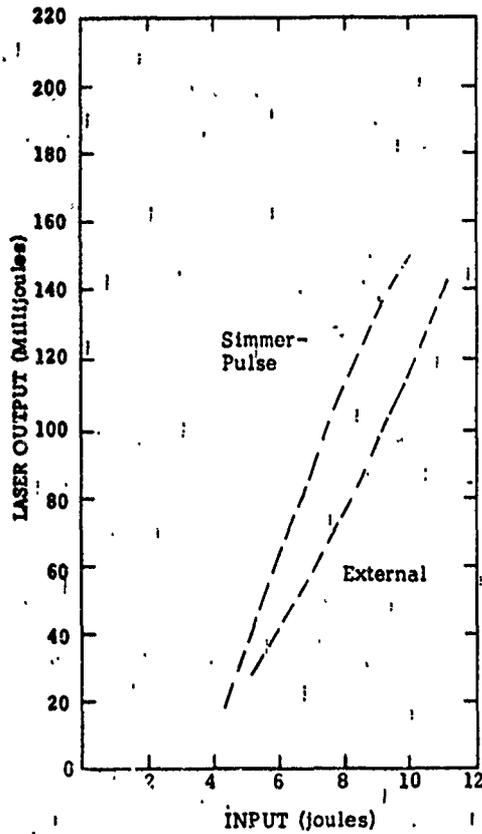
26

**LASER DATA**

| | |
|---|---|
| Rod: | Nd:YAG, 1/4" x 2-1/2" |
| A/R Coating: | None |
| Output Mirror: | 55% Reflective |
| Cavity: | Elliptical, Close Wrapped Water |
| Inductance: | 9 Microhenries |
| Capacitance: | 47.3 Microfarads (not critically damped, not optimized) |

**LAMP DATA**

| | |
|---|---|
| Lamp Bore Diameter: | 4 mm |
| Lamp Arc Length: | 2.125 inches |
| Lamp Fill: | Xenon Gas |
| Lamp Fill Pressure: | 450 Torr |
| Initiation Method: | Simmer Pulse and External |

FIGURE 2    LASER OUTPUT DATA FOR XENON LAMP FOR SIMMER PULSE AND EXTERNAL TRIGGER OPERATION

1025
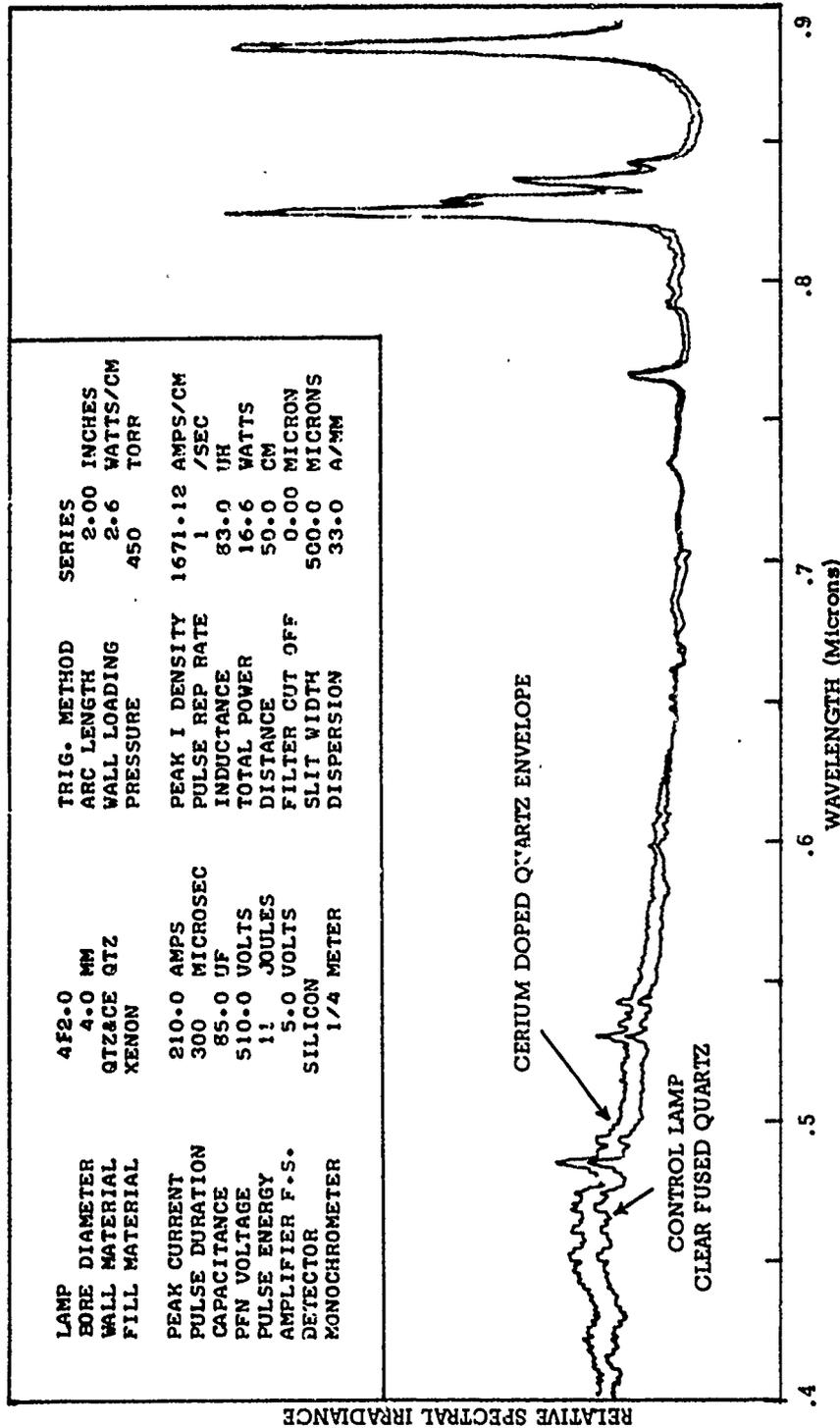
FIGURE 3 COMPARATIVE SPECTRAL DATA FOR A CERIUM DOPED QUARTZ ENVELOPE LAMP AND A STANDARD QUARTZ ENVELOPE LAMP

28
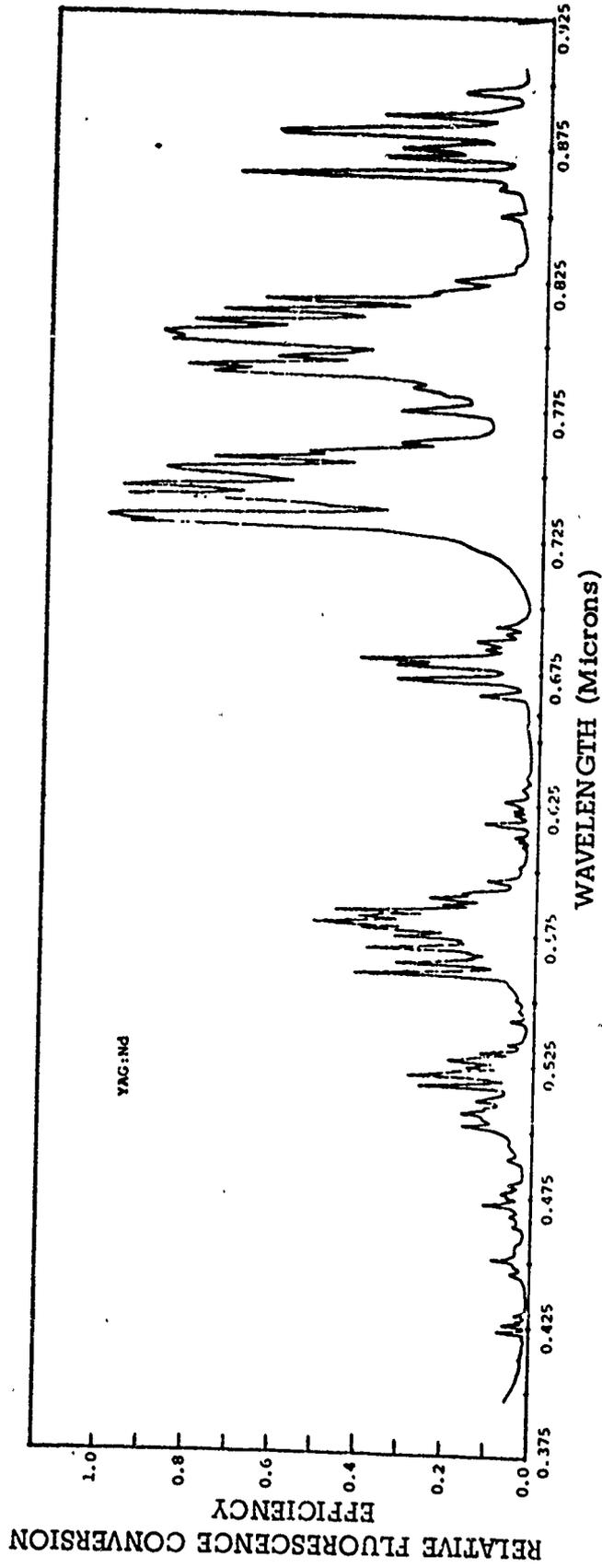
FIGURE 4    EXCITATION SPECTRA FOR Nd:YAG

1001

Lamp Bore Diameter: 3, 4 & 5mm
Lamp Arc Length: 2.125 inches
PFN Stored Energy: 10 Joules
Lamp Input Energy 8.3 Joules
Lamp Fill Gas: 450 Torr Xenon
Initiation Method: ——External Trigger
----Simmer-Pulse
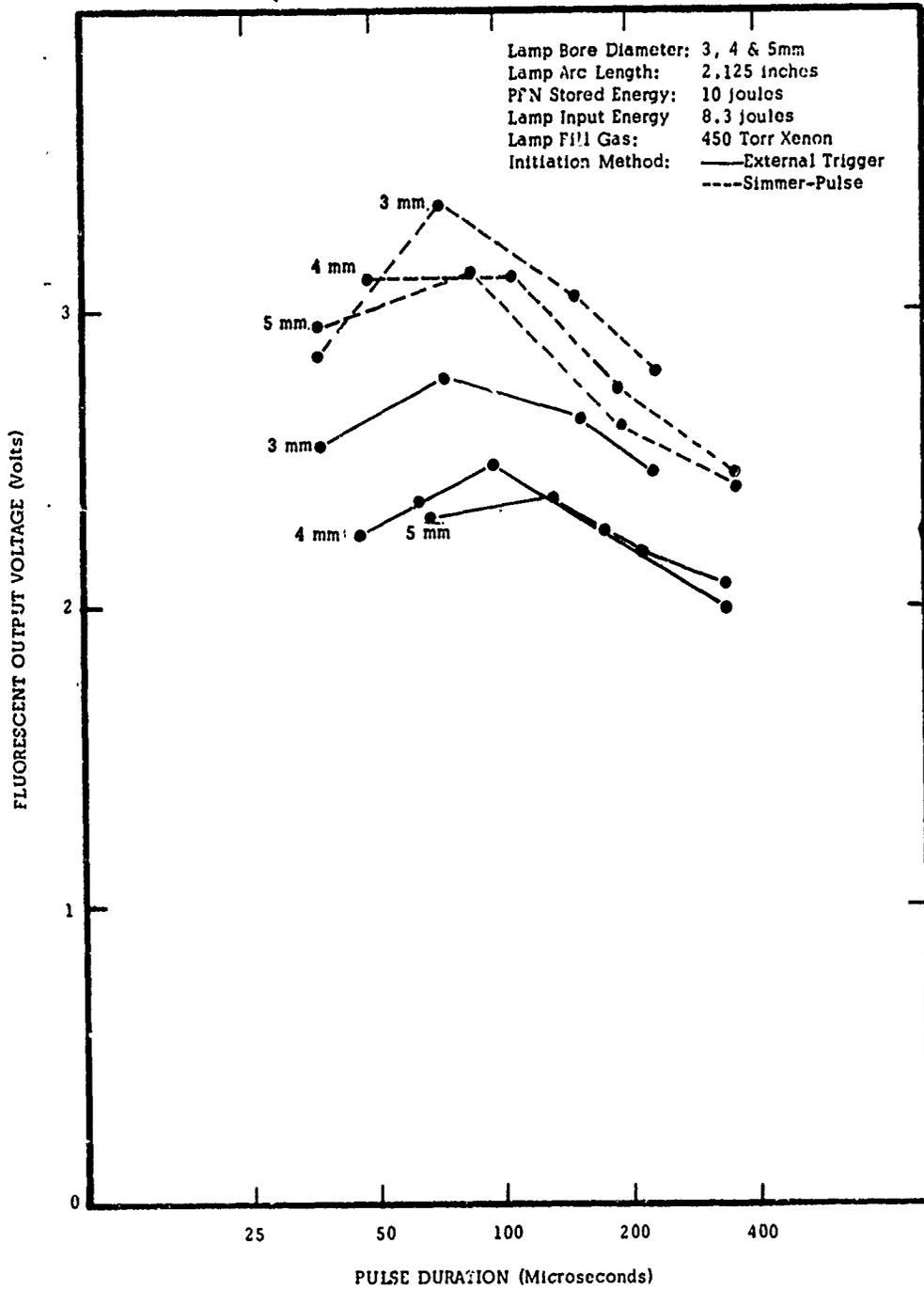
1018

FIGURE 5    FOV DATA FOR 450 TORR XENON LAMPS, EXTERNAL TRIGGER AND
SIMMER PULSE (10 JOULES)
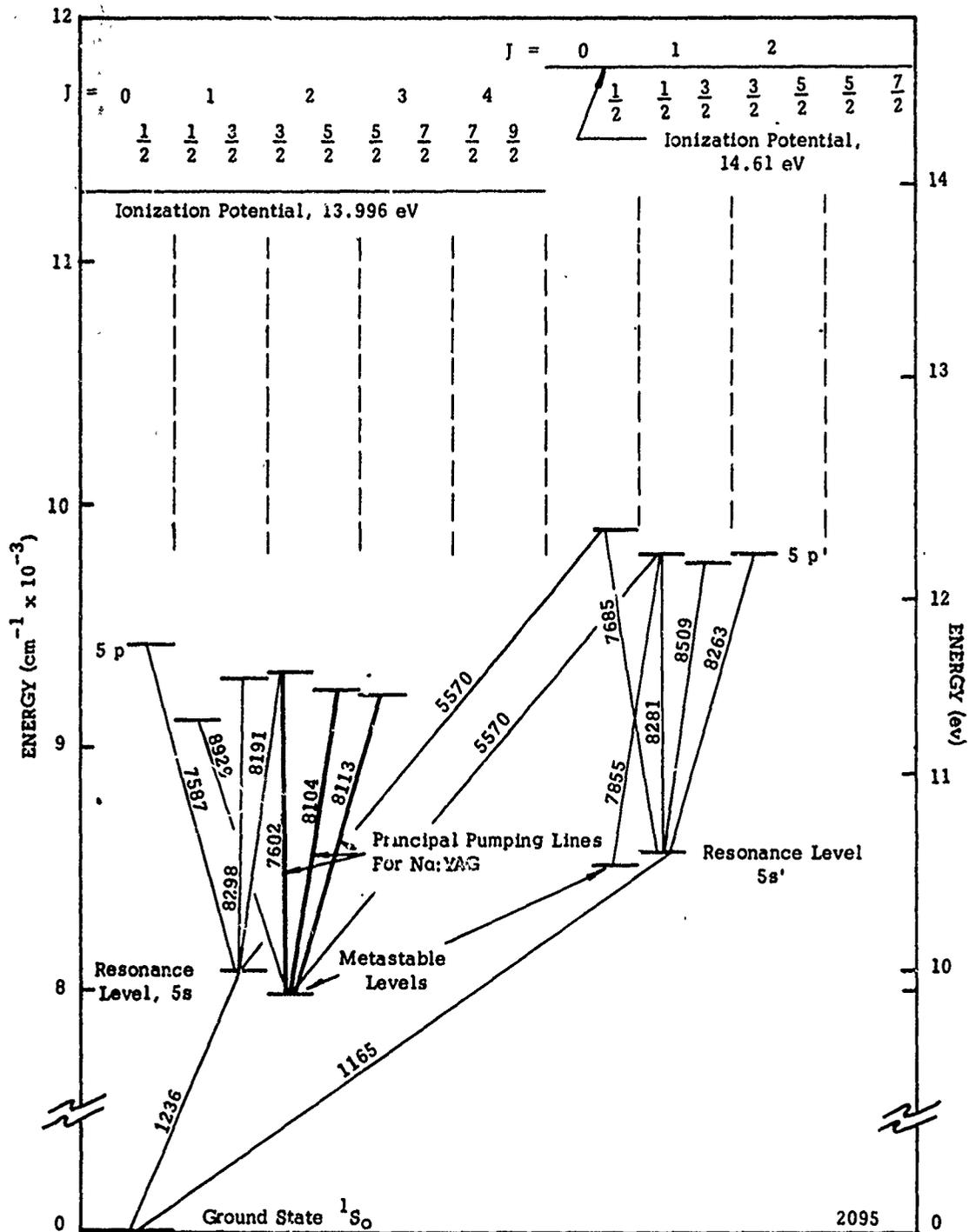
FIGURE 6 GROTRIAN ENERGY LEVEL DIAGRAM FOR KRYPTON
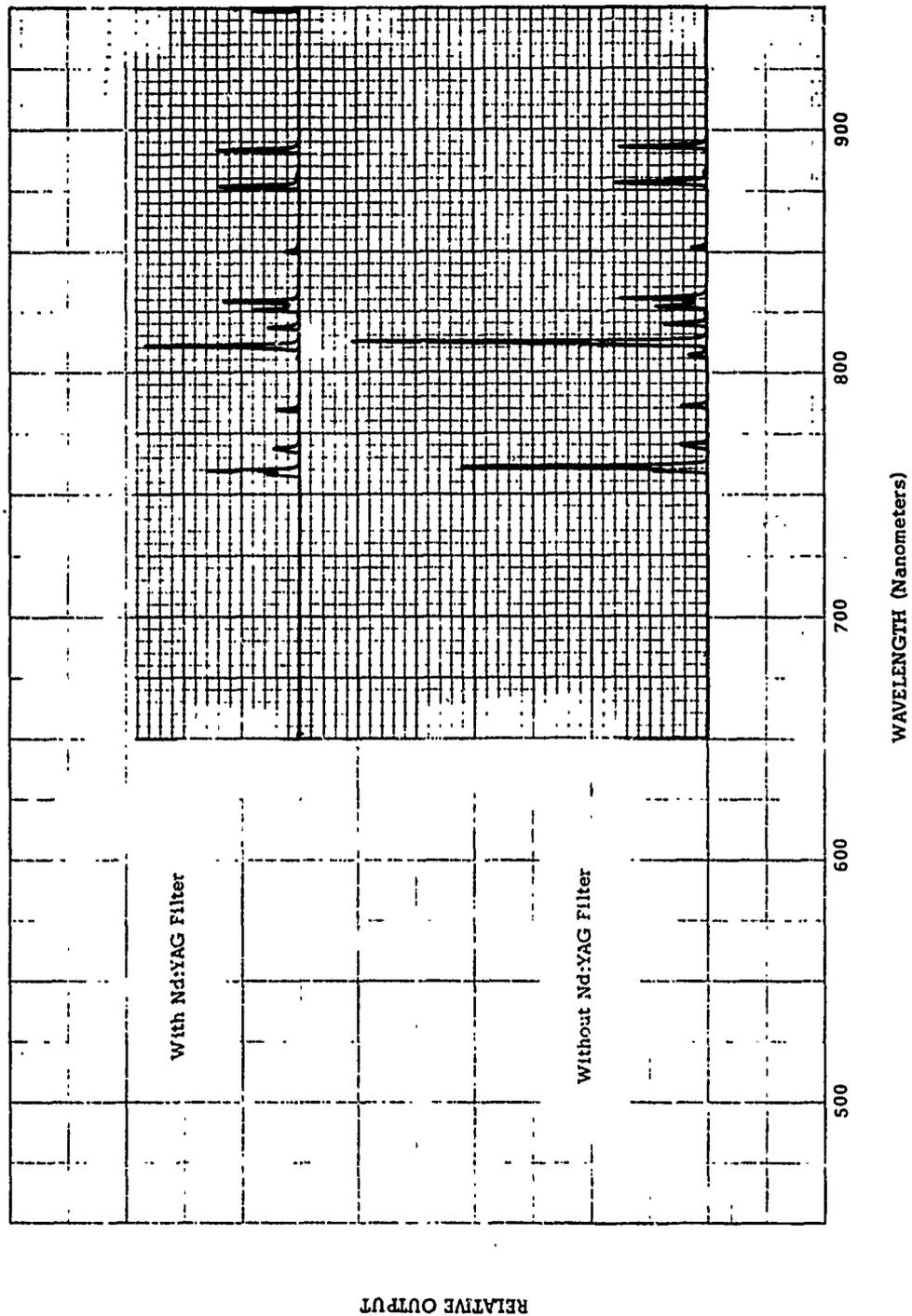
FIGURE 7   EMISSION SPECTRUM AND NON ABSORBED RADIATION OF 4 ATMOSPHERE KRYPTON LAMP

1056
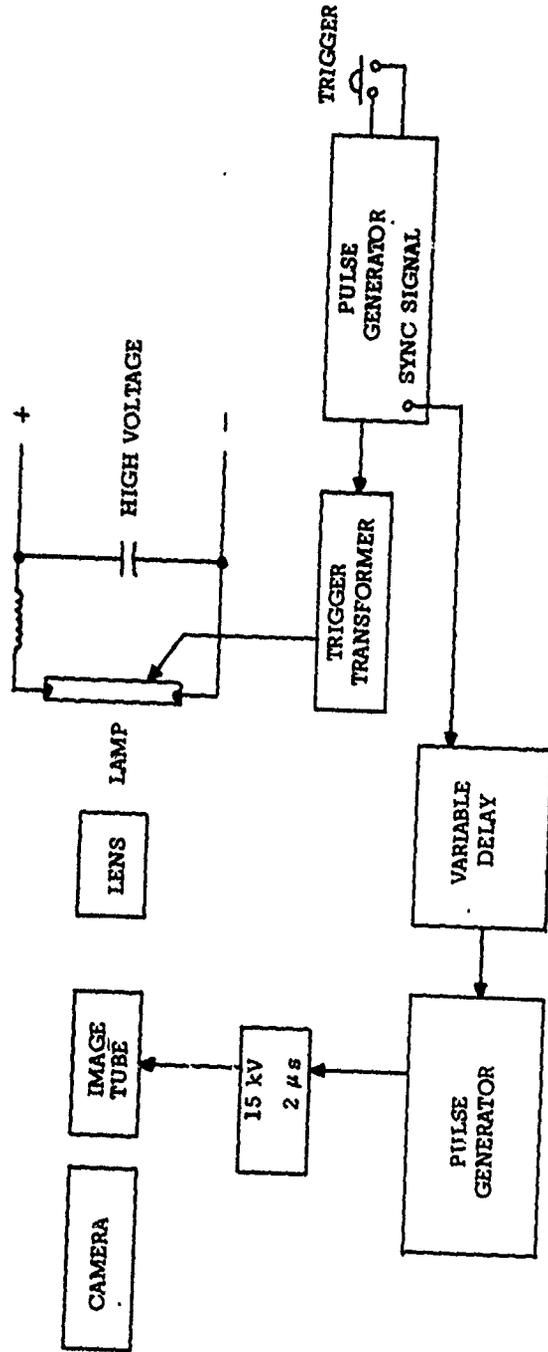
FIGURE 8    BLOCK DIAGRAM OF PULSE ARC GROWTH IMAGE RECORDER

33
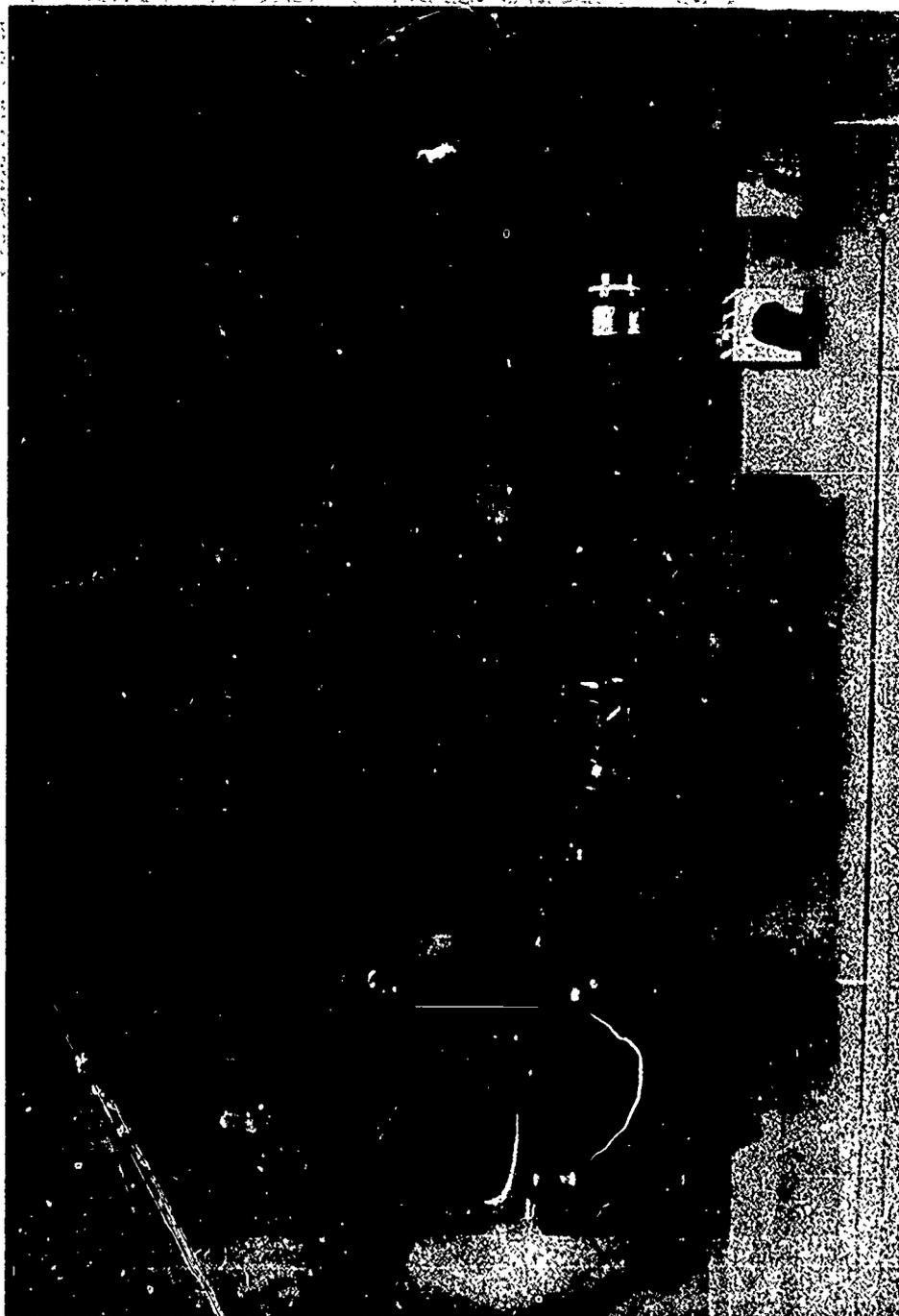
FIGURE 9 PULSE ARC GROWTH IMAGE RECORDER

3001

LAMP L349

5 Joules
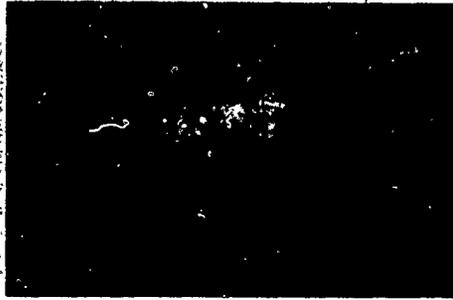


Y = 100 Amperes/cm
X = 20 μs/cm

PHOTOGRAPH OF ARC



POSITION OF TUBE WALL



TRIGGER

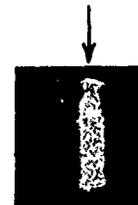(SAME SCALE AS PHOTOGRAPH)

10 Joules



Y = 100 Amperes/cm
X = 20 μs/cm



20 Joules



Y = 100 Amperes/cm
X = 20 μs/cm



4003

FIGURE 10A    CURRENT-TIME CURVES AND PHOTOGRAPHS OF PLASMA FOR PULSE
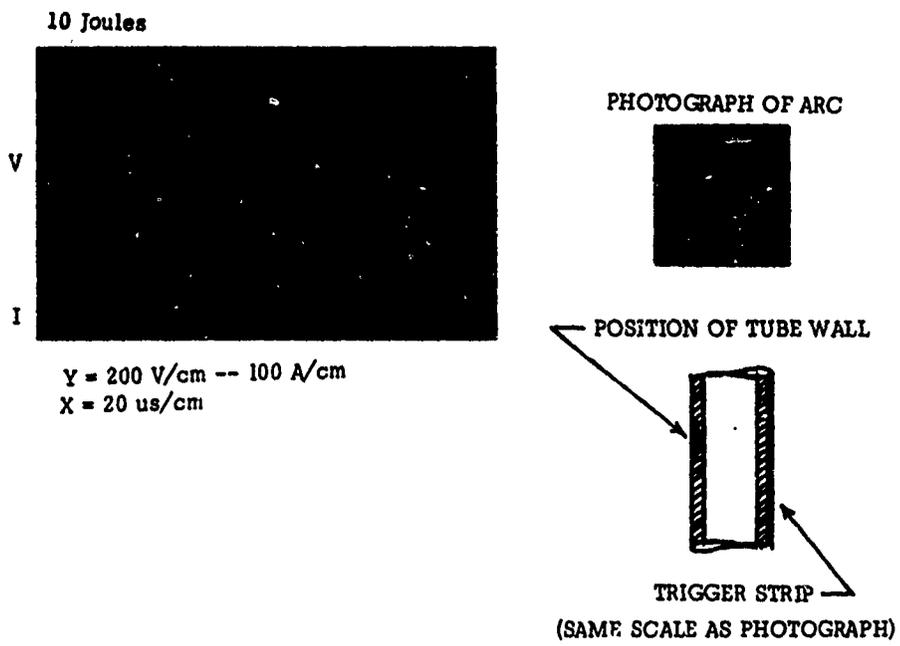ENERGIES OF 5, 10, 20, 40 and 60 JOULES

35

40 Joules

Y = 200 Amperes/cm
X = 20 μs/cm

60 Joules

Y = 200 Amperes/cm
X = 20 μs/cm

Lamp L349A
5 Joules

V

I

Y = 200 V/cm -- 100 A/cm
X = 20us/cm

PHOTOGRAPH OF ARC

←POSITION OF TUBE WALL

TRIGGER

(SAME SCALE AS PHOTOGRAPH)

TRIGGER STRIP —

4003

FIGURE 10B    CURRENT-TIME CURVES AND PHOTOGRAPHS OF PLASMA FOR PULSE
ENERGIES OF 5, 10, 20, 40 and 60 JOULES

**10 Joules**



V

I

Y = 200 V/cm -- 100 A/cm
X = 20 us/cm

**PHOTOGRAPH OF ARC**



POSITION OF TUBE WALL



TRIGGER STRIP

(SAME SCALE AS PHOTOGRAPH)

FIGURE 10C   CURRENT-TIME CURVES AND PHOTOGRAPHS OF PLASMA FOR PULSE
ENERGIES OF 5, 10, 20, 40 and 60 JOULES

FIGURE 11 PLASMA DIAMETER AS A FUNCTION OF INPUT ENERGY

MEASURED VALUES
INTERPOLATED VALUES
L349    SPIRAL WRAP TRIGGER
        TURBULENT DISCHARGE
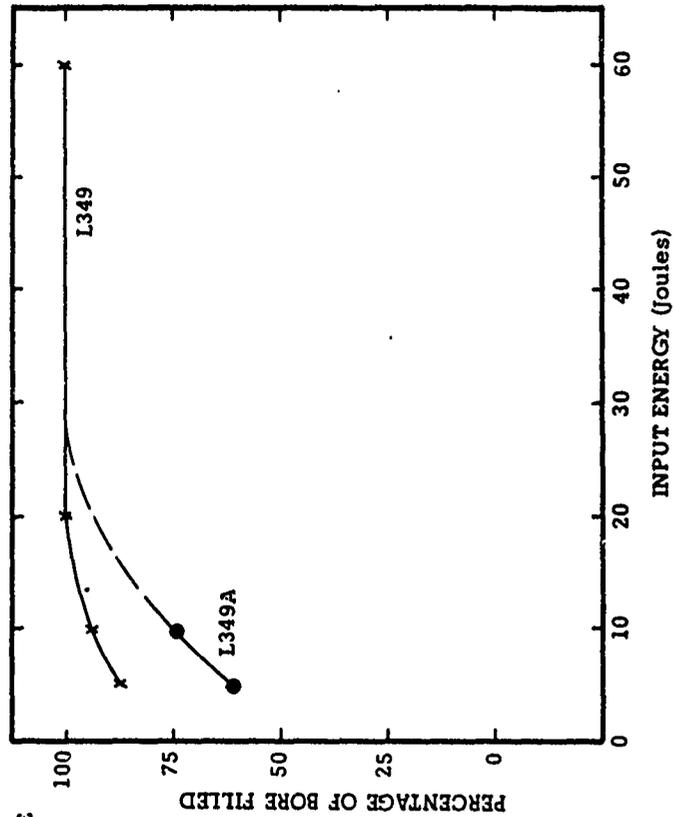L349A   PLATED STRIPE
        LAMINAR DISCHARGE

4000

38

POSITION OF TUBE WALL

TIME ($\mu$ sec)

| | |
|---|---|
| 10 | 90 |
| 20 | 100 |
| 30 | 110 |
| 40 | 120 |
| 50 | 130 |
| 60 | 140 |
| 70 $I_{pk}$ | 150 |
| 80 | 160 |

TRIGGER

(SAME SCALE AS PHOTOGRAPH)

Lamp L349 5 Joules
Arc Growth Sequence

4001
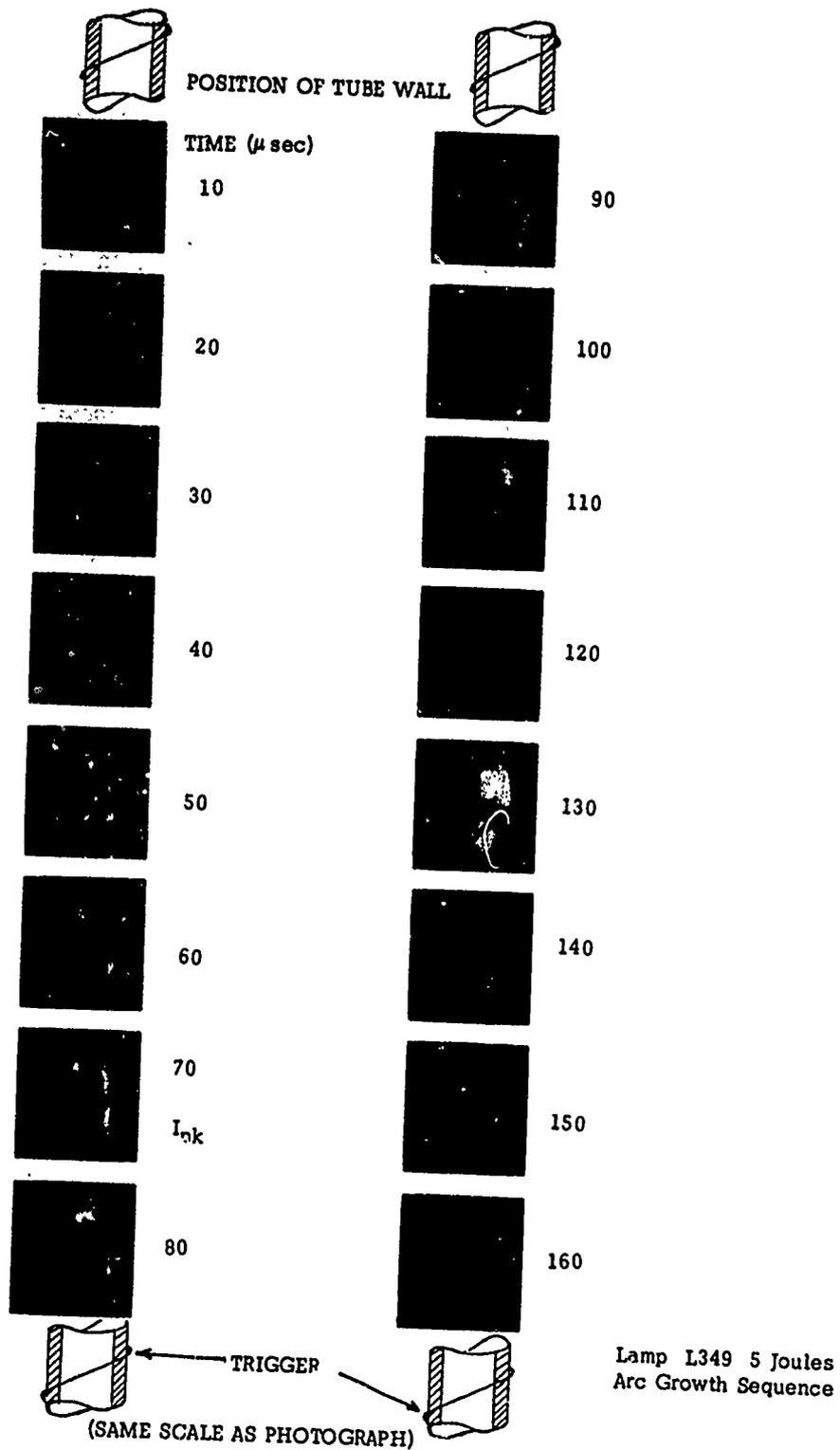
FIGURE 12    PLASMA GROWTH IN L349 AT 5 JOULES

39

FIGURE 13     PLASMA GROWTH IN L349 AT 10 JOULES

TIME ($\mu$ sec)

POSITION OF TUBE WALL

(SAME SCALE AS PHOTOGRAPH)

TRIGGER STRIP

Lamp L349A 5 Joules
Arc Growth Sequence

FIGURE 14    PLASMA GROWTH IN L349A AT 5 JOULES

41

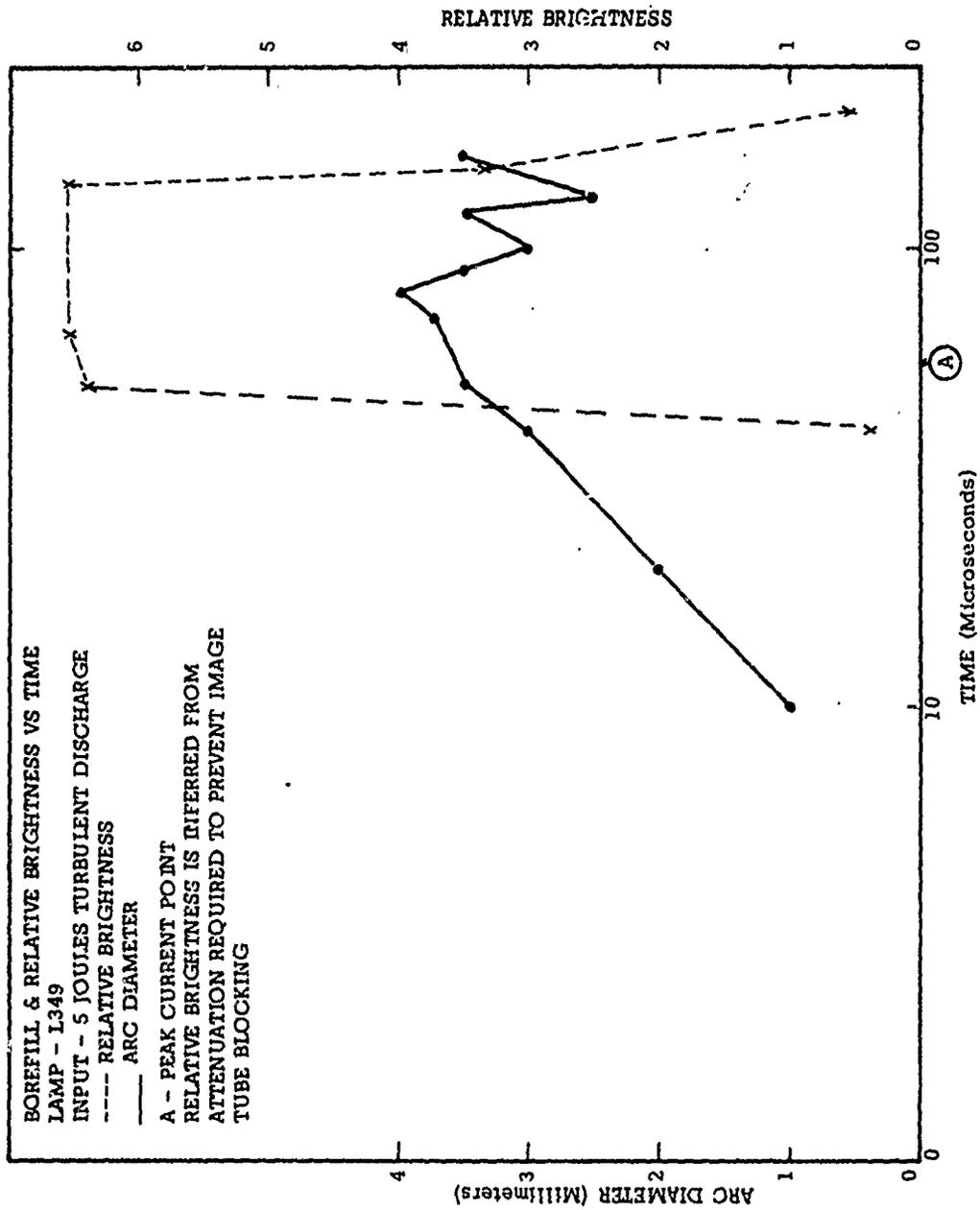FIGURE 15    PLASMA GROWTH IN L349A AT 10 JOULES

42
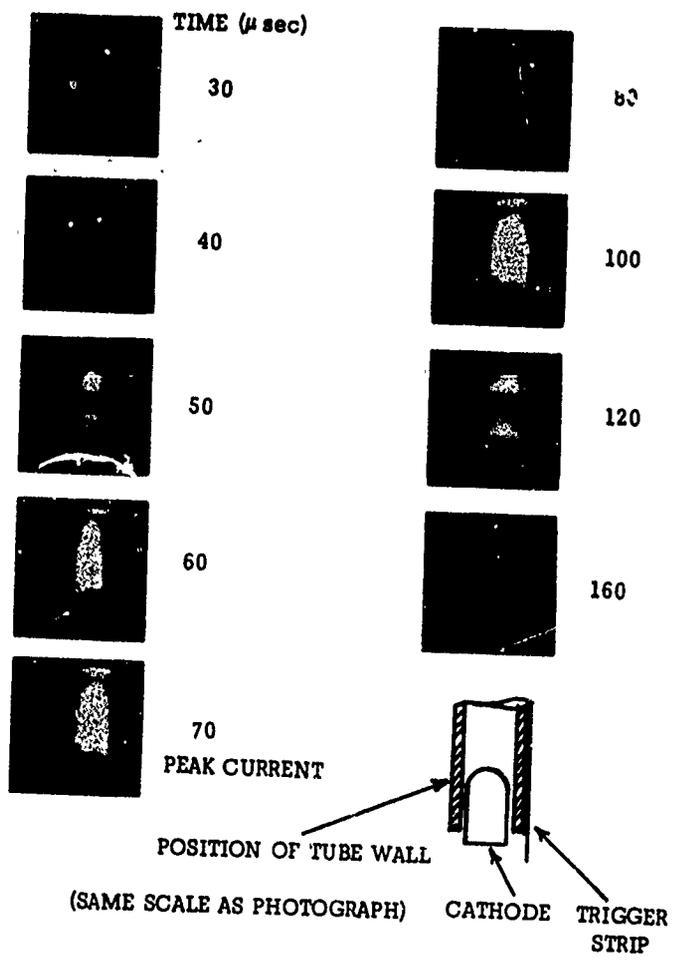
FIGURE 16    PLASMA GROWTH IN L349A AT 10 JOULES NEAR CATHODE

43

4005

BOREFILL & RELATIVE BRIGHTNESS VS TIME
LAMP – L349
INPUT – 5 JOULES TURBULENT DISCHARGE
---- RELATIVE BRIGHTNESS
—— ARC DIAMETER

A – PEAK CURRENT POINT
RELATIVE BRIGHTNESS IS INFERRED FROM
ATTENUATION REQUIRED TO PREVENT IMAGE
TUBE BLOCKING

FIGURE 17  PLASMA DIAMETER IN L349 AT 5 JOULES

44

3003

RELATIVE BRIGHTNESS

BOREFILL & RELATIVE BRIGHTNESS VS TIME
LAMP - L349A
INPUT - 5 JOULES LAMINAR DISCHARGE
--- RELATIVE BRIGHTNESS
— ARC DIAMETER
A - PEAK CURRENT POINT
RELATIVE BRIGHTNESS IS INFERRED FROM
ATTENUATION REQUIRED TO PREVENT
IMAGE TUBE BLOCKING

TIME (Microseconds)

ARC DIAMETER (Millimeters)
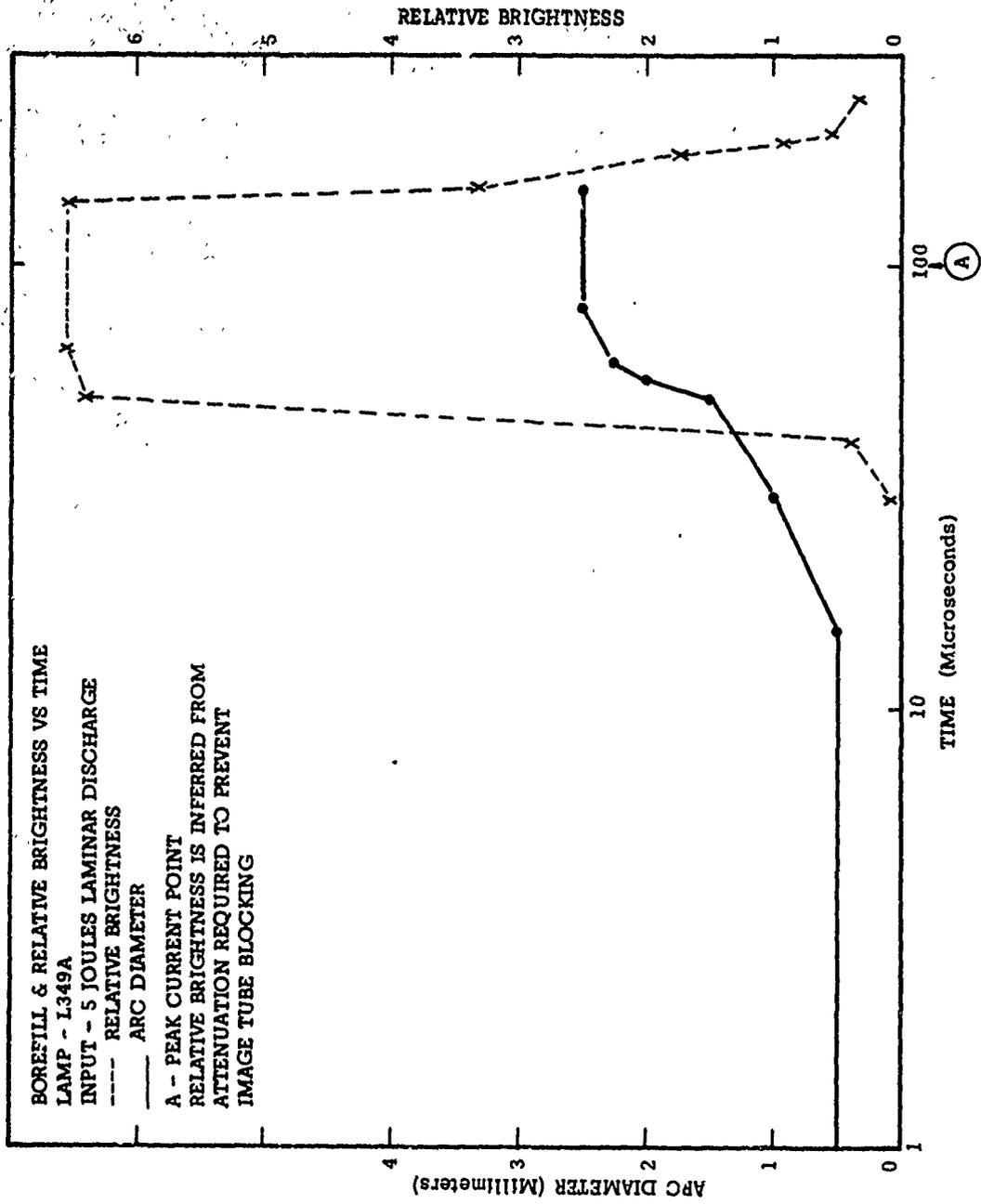
FIGURE 18 PLASMA DIAMETER IN L349A AT 5 JOULES

4006

45
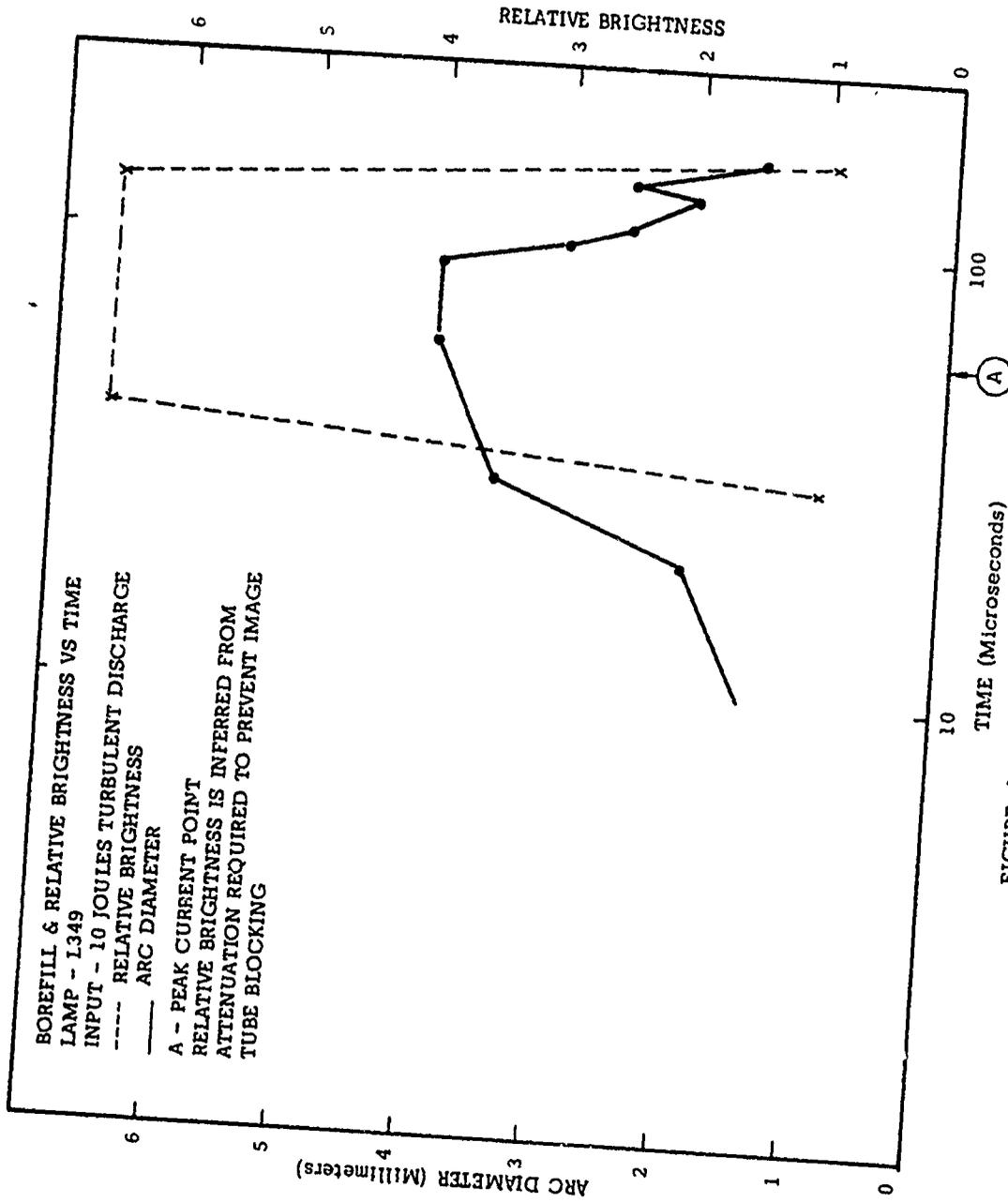
FIGURE 19  PLASMA DIAMETER IN L349 AT 10 JOULES

BOREFILL & RELATIVE BRIGHTNESS VS TIME
LAMP - L349
INPUT - 10 JOULES TURBULENT DISCHARGE
--- RELATIVE BRIGHTNESS
—— ARC DIAMETER

A - PEAK CURRENT POINT
RELATIVE BRIGHTNESS IS INFERRED FROM
ATTENUATION REQUIRED TO PREVENT IMAGE
TUBE BLOCKING

4007

46
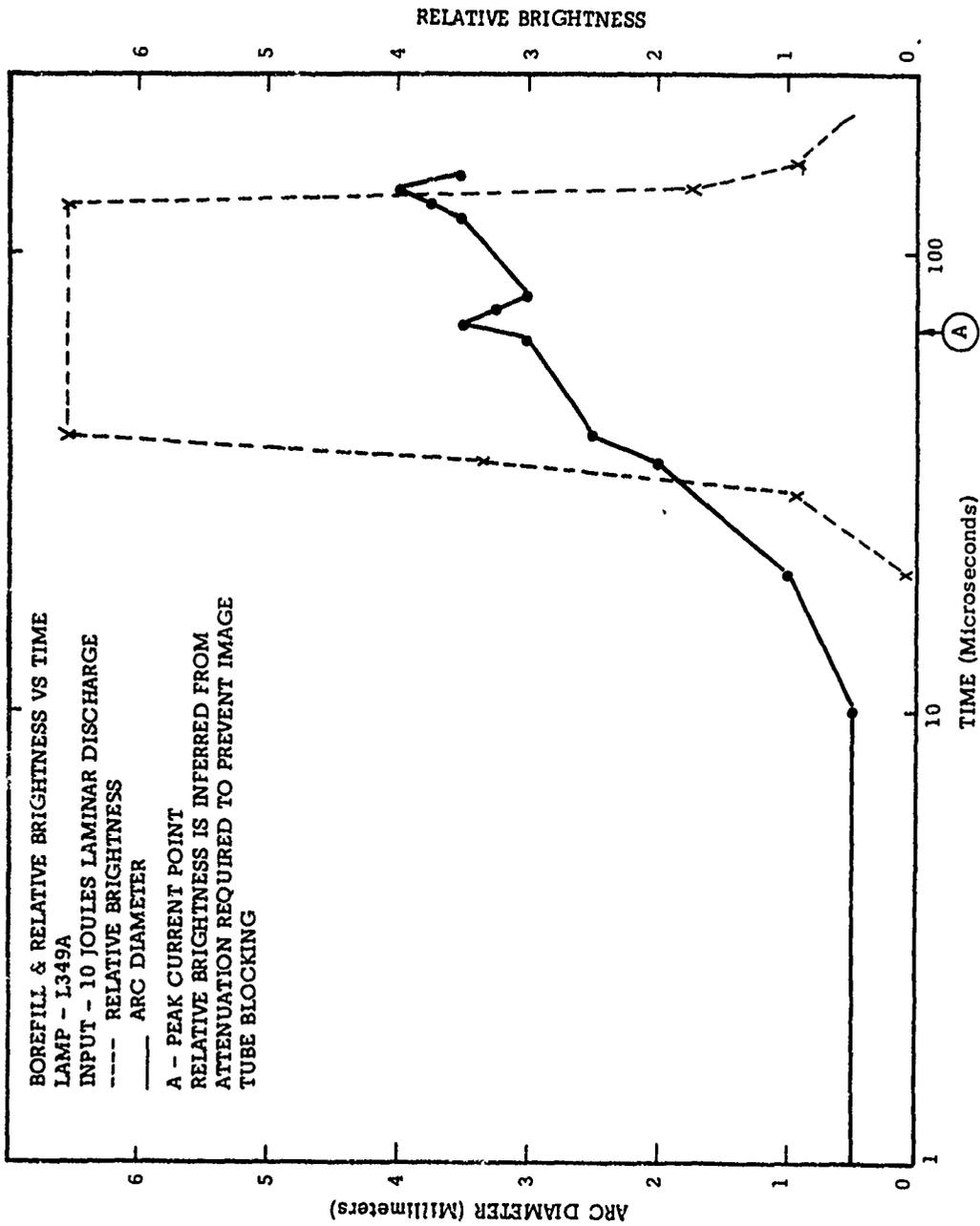
FIGURE 20 PLASMA DIAMETER IN L349A AT 10 JOULES

BOREFILL & RELATIVE BRIGHTNESS VS TIME
LAMP - L349A
INPUT - 10 JOULES LAMINAR DISCHARGE
-·-·- RELATIVE BRIGHTNESS
——— ARC DIAMETER

A - PEAK CURRENT POINT
RELATIVE BRIGHTNESS IS INFERRED FROM
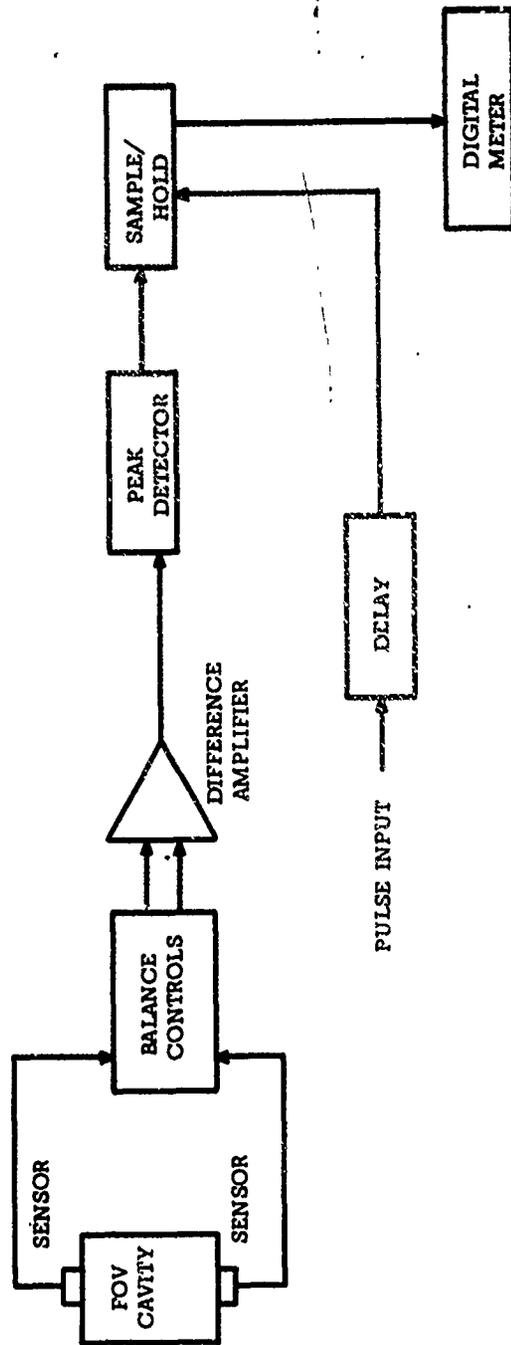ATTENUATION REQUIRED TO PREVENT IMAGE
TUBE BLOCKING

4008

FIGURE 21  SCHEMATIC DIAGRAM OF PULSED FLUORESCENT ANALYSIS TESTER WITH
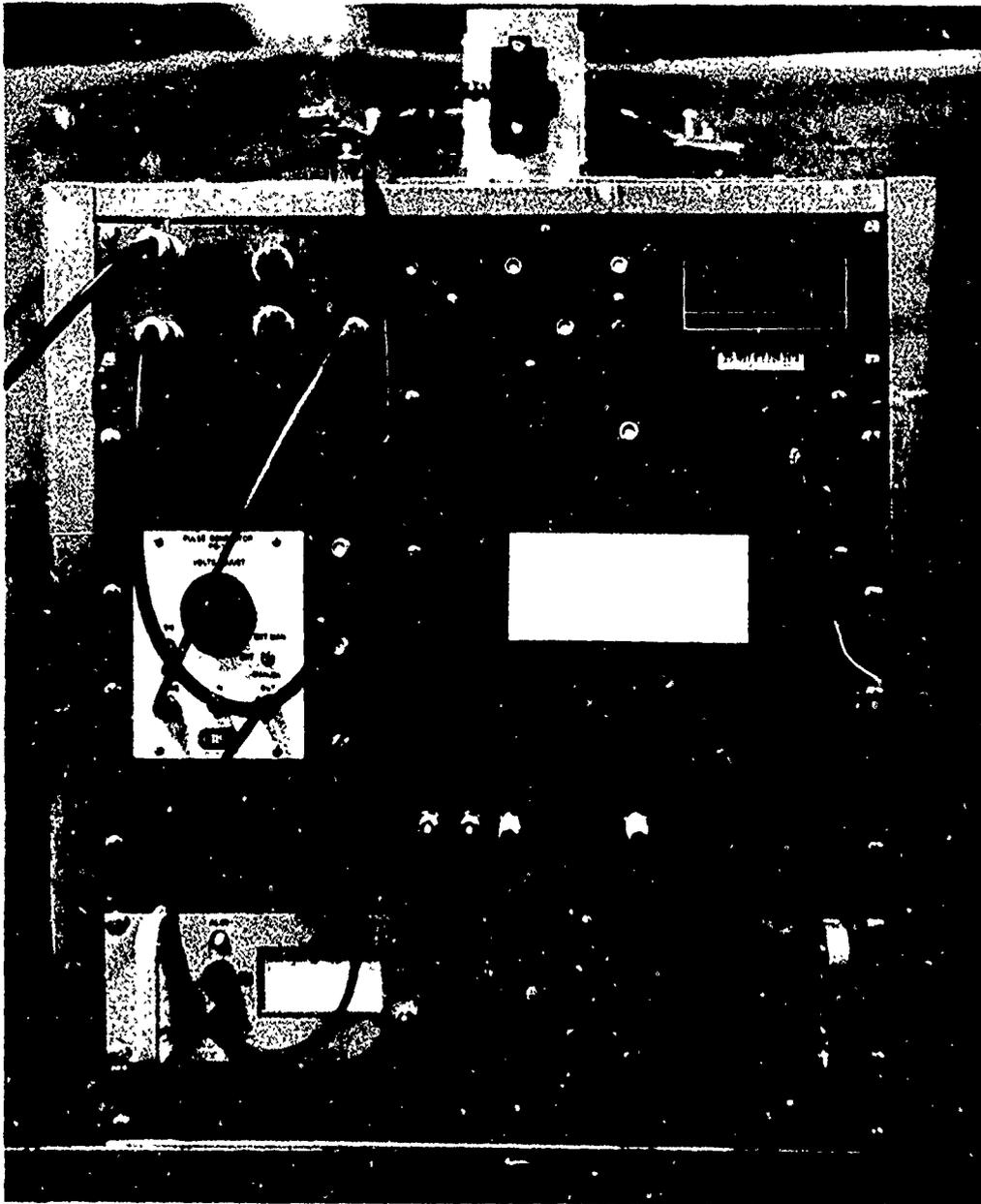DIGITAL READOUT ATTACHMENT

4009

48

FIGURE 22   PHOTOGRAPH OF PULSED FLUORESCENT ANALYSIS TESTER WITH
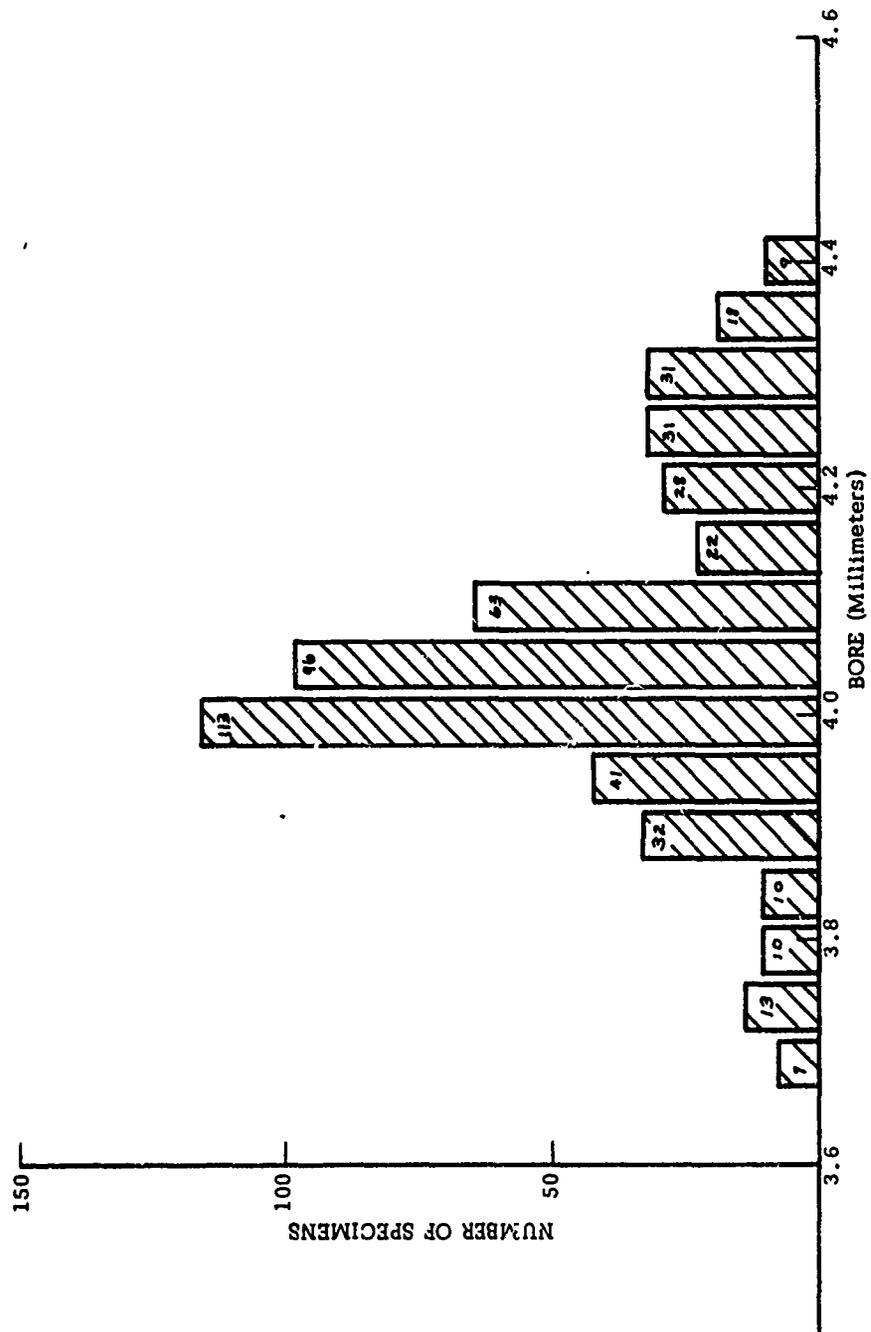DIGITAL READOUT ATTACHMENT

4010

FIGURE 23  BORE SIZE DISTRIBUTION ON 4 X 6 MM AMERSIL QUARTZ TUBING FREQUENCY
BAR CHART

BORE (Millimeters)
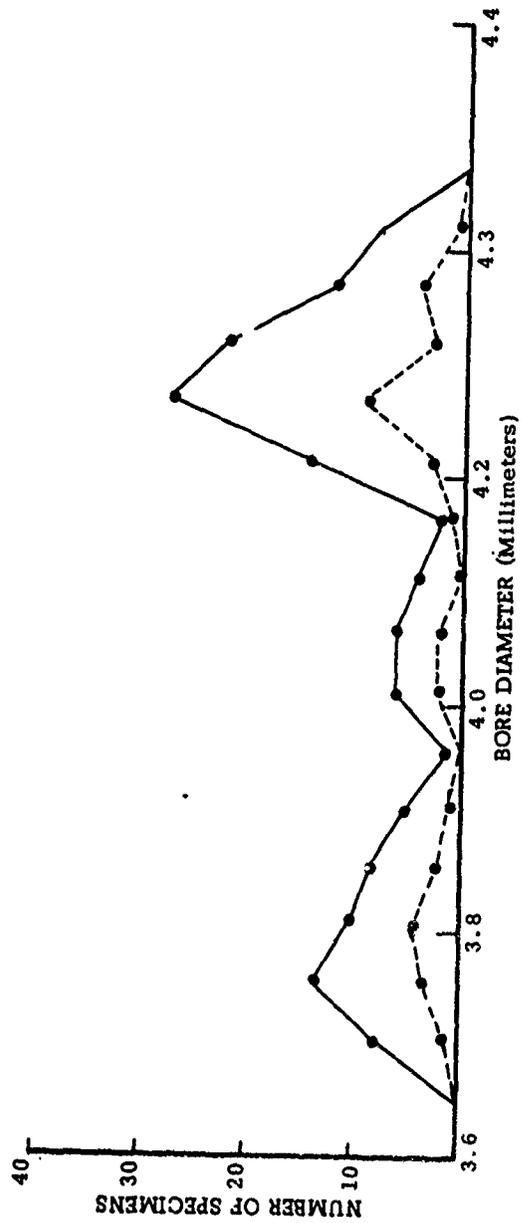
NUMBER OF SPECIMENS

FIGURE 24  BORE SIZE DISTRIBUTION ON GERMISIL QUARTZ TUBING, FREQUENCY POLYGON

4012

51