PRODUCTION AND EXAMINATION OF LOW PRESSURE SULFUR MICROWAVE EXCITED ELECTRODELESS DISCHARGE LAMPS

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by

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B. S., Iowa State University, Ames, 1970

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Chemistry

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1973

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TABLE OF CONTENTS

	PAGE
INTRODUCTION	
Considerations	1
Purpose	2
Review of Sulfur Spectra Literature	2
Review of Electrodeless Discharge Lamp Literature	5
PRODUCTION OF LAMPS	
Lamp Blank Construction	12
Vacuum System	15
Fill Procedure	18
INSTRUMENTATION AND METHODS	
Microwave Source and Optical System	21
Heater	21
Evaluation of Lamps	26
EXPERIMENTAL RESULTS AND DISCUSSION	
Intensity of Lamps	30
Temperature Effects	72
Stability	78
Lamp Reproducibility	78
Atomic Absorption Study	78
CONCLUSIONS	82
APPENDIX	83
ACKNOWLEDGMENTS	103
LITERATURE CITED	104
VITA	116

Introduction

In recent years more and more has been done to lower the detection limits of the elements and to develop faster methods of analysis because of the interest in trace elements in soil and biological material and the concern over pollutants in the environment.

Since its development in 1955 (106), atomic absorption has proved useful in providing fast analysis and low detection limits. To date, atomic absorption has been applied to almost all of the metals in the periodic table but to only a few of the non-metals.

Atomic absorption has not been applied to non-metals for two reasons. First, the resonance lines are usually located in the vacuum UV region. Second, they have low boiling points and thus fabrication of hollow cathode lamps becomes a problem. This problem was partially overcome by mixing elements or putting high boiling point compounds in the cathode. However, this was done at a loss of spectral intensity.

More recently, microwave excited electrodeless discharge lamps have come into use for atomic absorption line sources. These lamps are applicable to both metals and non-metals.

They have several advantages over hollow cathodes. First, there is no cathode which can be easily eroded away, and second, the lamps are cheap and easily constructed, they can be made quite stable, and they provide a sharp line emission spectrum of the element.

Purpose

The purpose of this investigation is to produce and examine low pressure, microwave excited electrodeless discharge lamps containing various sulfur compounds and fill gases for their possible application as sulfur line sources for atomic absorption.

Review of Sulfur Literature

Sulfur is an element that was known to the ancients. Whether they realized it or not, they probably burned some sulfur and thus were the first observers of the blue S_2 spectrum. The first recorded observation of sulfur spectra was in 1823 by Herschel (47) who observed the blue and violet spectra being emitted by burning sulfur. Mulder (78, 79) in 1864 was the first to map the spectrum of sulfur. Using a Geissler tube, Plucker and Hittorf (84) published the first photograph of the sulfur (S_2) spectrum in 1865. In 1869 Salet (87,88,89,90,91,92,93) started his work in studying the spectrum of sulfur and published many of the early papers on sulfur spectra.

Work on sulfur spectra continued and the early history was summarized in detail by Kayser (57) in 1912. In 1957 Gaydon (37) summarized the work on the spectroscopy of flames containing sulfur. Earlier, Rosen (85) summarized the work on sulfur spectra, especially the early work on S_2 from 1927-1950. Gilbert has brought the study of sulfur

spectroscopy up to 1970 in Mavrodineanu's Analytical Flame Spectroscopy (66).

Wavelengths, intensities, and vibrational levels for the molecular sulfur species in flames have been tabulated by Pearse and Gaydon (83).

Much of the work on the atomic lines and ion lines of sulfur was done in the 1920's. Wavelengths, intensities, and energy levels have now been tabulated by the National Bureau of Standards (80).

In 1923 Curie (22) studied the spark spectrum of vapor over molten non-metals. He was followed by Cameron (56), McLennan (70), Ingram (50), Lacroute (61), and Gilles (42) in the later 20's who all studied S I and S II spectra. Frericks (35), Meissner (75), and Hunter (49) continued the study of S I and S II in the 1930's. More recently atomic and ion lines of sulfur have been studied by Kelly (60), Berezin (5), and Bridges (15).

The early work on sulfur spectra was done in a variety of ways. The flame was the first method of excitation used, but S_2 was about the only species observed. The Geissler tube was next used to produce atom and ion lines of sulfur. The Geissler tube, being a sealed tube with two electrodes in it, served its purpose well and variations of it are still used today. Some other methods used were the D.C. arc and various electrodeless methods. The first electrodeless lamps contained sulfur vapor with or without a fill gas. These lamps were excited using a mercury arc. Sometimes

an outside spark was used or the lamp was wrapped with a transformer coil. And in some cases a flame was used to create a discharge.

Early spectroscopic determinations were done using emission spectroscopy in the vacuum UV as the sulfur resonance lines are at 1807 A^{o}, 1819 A^{o}, and 1820 A^{o}. As flame emission became a useful analytical tool, methods were developed for determining sulfur using the S_2 bands.

The first S_2 method was by Cowan and Sugihara (19) in 1959. Since then twenty-nine papers (6, 7, 8, 9, 10, 11, 12, 13, 14, 16, 20, 21, 27, 30, 31, 38, 39, 40, 41, 55, 63, 77, 94, 98, 99, 100, 102, 104, 105) have been published on S_2 flame emission methods. Using the S_2 methods, detection limits varying from 500 ppm to 0.02 ppb depending on the method and sometimes the form of sulfur put into the flame are obtained.

In 1969 Fuwa and Vallee (36) used a hydrogen lamp as a source and determined sulfur by S_2 molecular absorption using an air-hydrogen flame in a 2.73 meter heated vycor tube for the absorption cell. Taylor, et. al. (103) in 1970 determined sulfur by atomic absorption at 2169 A^{o} using a helium plasma as the absorption cell with an electrodeless discharge lamp source. Kirkbright, et. al. (58, 59) determined sulfur using a nitrogen separated nitrous oxide-acetylene flame. However they used the sulfur resonance line at 1807 A^{o} and a vacuum spectrograph. An electrodeless discharge lamp

was used as the source.

Review of Electrodeless Discharge Lamps (EDL)

An electrodeless discharge lamp is a sealed quartz tube which contains a metal or metal salt vapor and some inert gas at low pressure. By coupling the lamp to microwave energy, the inert gas carries the discharge and excites the other atoms in the lamp. The discharge has been described as being a cold plasma which is confined to the surface of the plasma.

Electrodeless discharge lamps have been used for a number of years. Graham (44) used one to study sulfur spectra in 1911. He placed sulfur in a quartz tube at 10 torr and used both a flame and spark to study sulfur spectra. Hagenback and Frig (46), in 1917, used electrodeless ring discharge tubes. These were tubes about 2 cm in diameter and 20 cm long with a transformer coil wound around the outside for excitation. Jackson (53) in 1928 was probably the first to use microwaves to excite electrodeless discharge lamps. He used a 10 MHz oscillator to produce cesium spectra.

Electrodeless discharge lamps then became more and more a part of spectroscopy. In the late 40's, Meggers (73, 74) did much to further the use of electrodeless discharge lamps. It wasn't until the 1960's that electrodeless discharge lamps were used analytically as line sources for atomic fluorescence (110). Walsh (86) in 1957 investigated electrodeless discharge lamps for use as atomic absorption line

sources but said that they were not useful because they were too unstable.

Only in recent years has the use of electrodeless discharge lamps for atomic absorption spectroscopy come about (25, 26, 29, 51, 52, 95). Dagnall, et. al. (26) were the first to apply such lamps to atomic absorption spectroscopy.

The main problem thus far in using electrodeless discharge lamps in atomic absorption spectroscopy is stability (76). To be acceptable as asource, the stability should be 0.25 percent or better for a single path instrument. Overall the lamp must meet the following criteria (95) to be acceptable as a source: (1) high stability, (2) high intensity, (3) narrow spectral lines, (4) minimal line reversal, and (5) low background and the absence of band spectra. The above criteria are dependent on the manufacturing and operating parameters. In manufacturing an electrodeless discharge lamp, the following parameters are important: lamp size, pretreatment of the lamp, vacuum system, nature of the fill gas, pressure of the fill gas, material containing the desired element, amount of material placed in lamp, and lamp fill procedure (24, 25, 26, 43, 48, 65, 81, 82, 95, 97, 107). At present there is no set value to place on each of these parameters and produce the perfect electrodeless discharge lamp.

The size of the lamp is usually 30 mm $\pm$ 5 mm long and 8 mm $\pm$ 1 mm in diameter.It was reported that the longer the tube the more intense the discharge (97). However if the

tube is too long, a temperature gradient will result which causes the contents of the lamp to distill and thus produce an unstable discharge (29).

For pretreatment, everyone has their own method. A common treatment is to heat the unfilled lamp under vacuum. Keeping the quartz clean is a necessity.

For production of the lamps, one needs a vacuum system capable of obtaining 10^{-6} torr. One should also refrain from the use of mercury in the vacuum system.

The nature of the fill gas must be determined for each element since sputtering is a function of the fill gas and the volatility of the element (97). Also to be taken into consideration is that high pressures produce longer lamp life (97) and lower pressures give less coupling to the lamp walls (97).

The form of the element to be placed in the lamp depends on the element. Sometimes the element will suffice. If a compound is used, it is usually a halogen, generally the iodide. Some researchers prefer to make the compound in the lamp. This in itself is a problem as it can result in added impurities because of the uncertainty of how much of each reactant to add. An excess of one component may cause a pressure problem (24). Typical amounts of material placed in a lamp vary from 0.1 to 50 mg., the usual being 1 to 10 mg. In determining the amount to put in the lamp, usually the higher the volatility of the element the smaller the amount of material needed (97). Ideally all of the material

should be vapor because excess solid material affects the coupling efficency as the solids move around as a result of distillation (23). This movement of solids is a result of a temperature gradient and gives the lamp an unstable discharge.

Fill procedure isn't as critical as the other parameters. It has been reported that drying and partially decomposing the compound so as to vaporize it onto the walls of the lamp gives greater spectral radiant output (82).

Obtaining a good seal on the lamp and not decomposing the fill material in the process is important.

Once the lamp has been constructed, the following operational parameters must be considered: microwave power, type of antenna, position of lamp in the field, operating temperature of the lamp, and tuning (17, 23, 32, 33, 34, 54, 65, 70, 97, 107, 111, 112, 113).

Electrodeless discharge lamps have been excited by both microwaves and radio waves, but for analytical work microwave frequencies are more desirable (31, 54, 65). Microwaves (100 MHz) can be more efficiently coupled to the lamp resulting in increased intensity and lifetime of the lamp. Most analytical work done today uses a 2450 MHz frequency capable of delivering up to 125 watts of power.

For coupling the microwaves to the lamp, various director antennas and resonant cavities have been used. A cavity which produces a uniform field is desirable because it will increase the stability of the lamp (48). Fehsenfeld, Evenson,

and Broida (32,33) have reviewed six cavities in their work. Mansfield (65) has evaluated the "A" and "C" antennas and three cavities for use in atomic fluorescence. His findings were that the "A" antenna was superior for his work. The "C" antenna, Broida cavity, and Evenson cavity all develop "hot spots" and were unusable for analytical purposes. A tapered rectangular cavity evaluated by Mansfield had a lower coupling efficiency than the "A" antenna.

Position of the lamp in the microwave field is important because of the need for a high coupling efficiency of the microwave energy to the lamp. Since positioning the lamp alone does not always provide the highest coupling efficiency, Schrenk, Valente, and Smith (96) have devised tuning stubs for use in obtaining a better coupling efficiency.

Temperature of the lamp is probably the most important operating parameter because it affects the microwave power requirement, the tuning, the spectral output, self-reversal of spectral lines, the coupling efficiency, and the life of the lamp (70, 65, 82, 107, 97, 111, 112, 113, 17, 23, 24).

The intensity of a lamp depends on how much microwave power is being applied to it. By increasing or decreasing the applied power, various observations have been made. Sputtering is proportional to the applied power. As the sputtering increases so does the temperature and volatility of the compound in the lamp (97). If a compound of low volatility is in the lamp, an increase in applied power should

increase the intensity. A drawback to this seemingly good feature is that it may cause lamp softening and failure (97). By applying more power to a highly volatile compound, the intensity will become unstable because of a pressure increase (24) and the lamp may go out. Volatile compound lamps operating at high microwave power may be hampered by temperature gradients (97).

Temperature, if used to one's advantage, can help increase the lifetime and intensity of the lamp. Increasing the power but cooling the lamp can increase the stability of the lamp (48). Increasing the temperature of certain lamps results in increased stability. This was first done by vacuum jacketing the lamp (113). An air jacket (65) also may be used to increase the lamp stability. Worden (112) in 1963 was the first to use a heater to control the temperature of his lamps. Winefordner (113, 17) did more studies on temperature effects and their control. His studies led to the development of multi-element lamps (107, 82) which operate for certain elements depending on the optimum temperature for the element in the lamp.

McCormack, et. al. (69) in 1965 was the first to use an electrodeless discharge method for sulfur. In his method he measured the CS emission from organic compounds in argon at 2575 A°. This was followed by Bache and Liske (4) who used helium in their system and the sulfur ion line at 5453.8A°. Dagnall, West, and Whitehead (28) also used an electrodeless

discharge as a gas chromatograph detector and monitored sulfur at the 1820A° resonance line. Aldous, Dagnall, Pratt, and West (2) put organic sulfur compounds in an electrodeless discharge lamp with 3 torr of He but had many lamp failures because of decomposition. Taylor, et. al. (103) in their atomic absorption method for sulfur used a sulfur-argon electrodeless discharge lamp. B.V. L'Vov (62) reported a sulfur electrodeless discharge lamp in 1970 but no analytical data. Finally there are the applications of sulfur electrodeless discharge lamps to atomic absorption by Kirkbright, et. al. (58, 59). In this work they used a 60 mm long by 8 mm i.d. quartz tube with 1 mg of sulfur and 3 torr of argon.

Production of Lamps

Lamp Blank Construction

In this study, over five hundred electrodeless discharge lamps were constructed and evaluated.

The electrodeless discharge lamps were constructed from 9 mm i.d. by 11 mm o.d. quartz tubing and 0.5-1.0 mm i.d. by 5-7 mm o.d. quartz capillary tubing (Amersil, Inc., Hillside, N.J.). The 3 cm long lamp blanks were fabricated entirely by hand using an oxygen-gas hand torch and a few other glass blowing tools. The quartz was cleaned with hot concentrated nitric acid, rinsed in distilled water, and dried in an oven at 150°C before use.

Stepwise construction of the lamp is shown in Figure 1. The first step is to seal the end of a piece of quartz capillary tubing. Then (step 2) is to blow out a bubble on the sealed capillary tubing. Next (step 3) a piece of 9 mm i.d. quartz tubing is sealed to the blown out capillary. About 3 cm from where the capillary ends the flame is applied (step 4) and the tubing is cut by the flame. The closed end is then heated and blown out to a smooth test tube end (step 5). The lamp is then heated to the softening point (step 6) so as to remove any small cracks and cristobalite that may have formed during construction of the lamp. The lamp should resemble the one shown in step 6 when finished. The finished lamps

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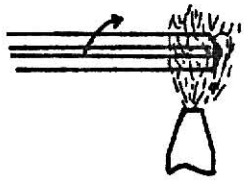
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EXPLANATION: FIG. 1

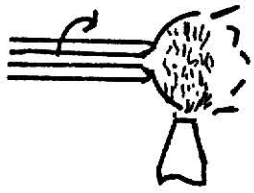
Stepwise construction of lamp blank

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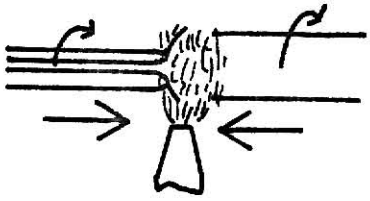
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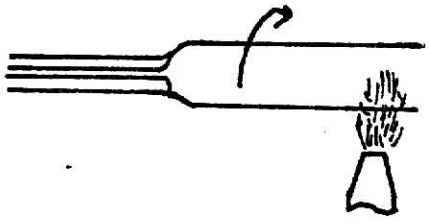
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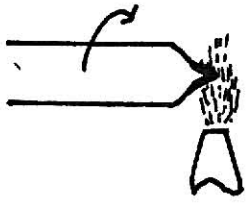
(2)



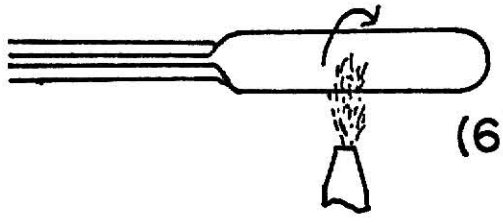
(3)



(4)



(5)



(6)

were then stored in a desiccator over calcium chloride until used.

Vacuum System

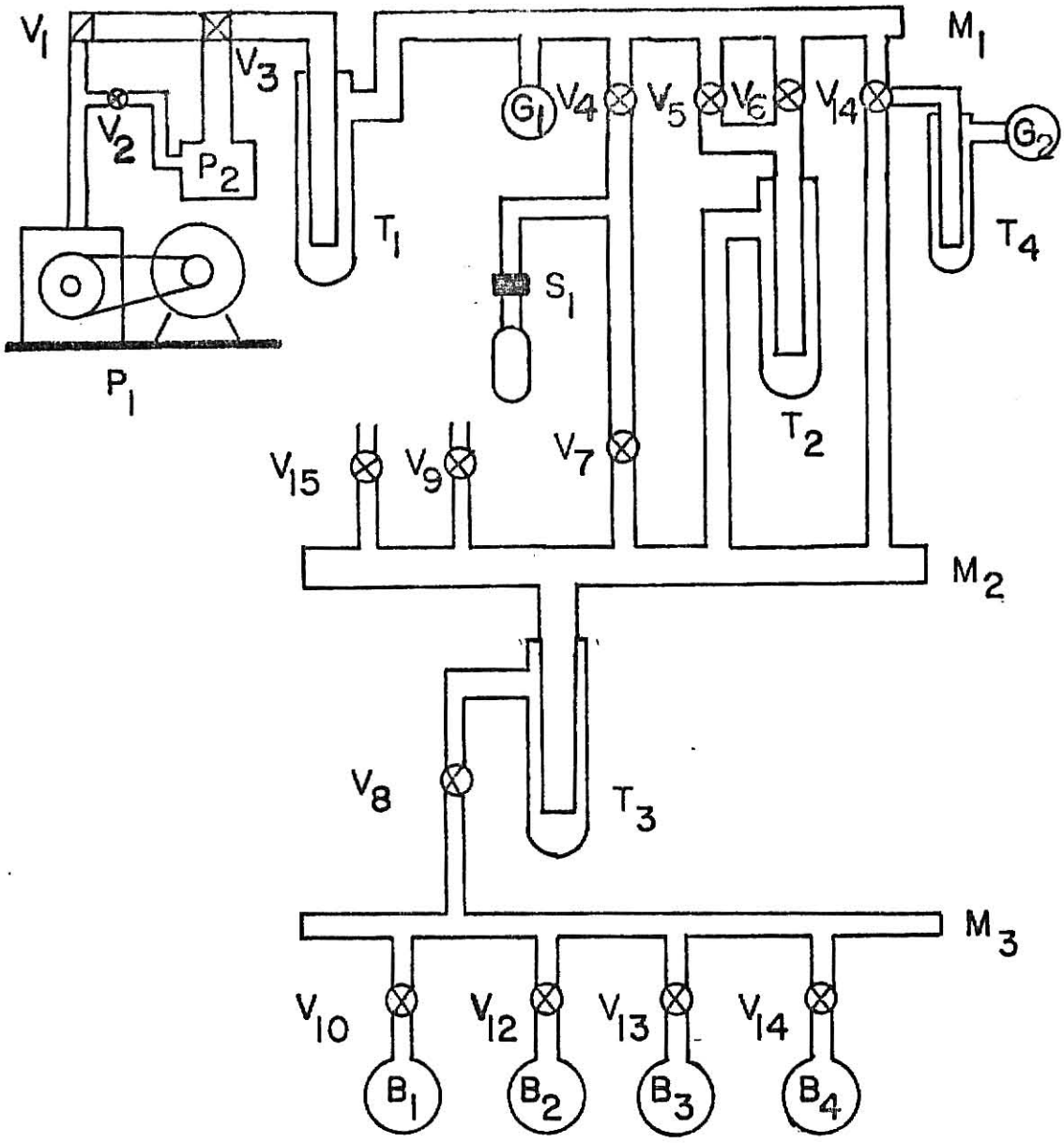
The vacuum system, Figure 2, used in this study is a modification of the one used by Mansfield (65). Pressures in the range of 10^{-6} to 10^{-7} torr were obtained with it.

Some of the important components of the system are as follows: P_1, vacuum pump (Welch-Duo-Seal, The Welch Scientific Co., Skokie, Ill.); P_2, diffusion pump (Model 400, Optical Film Engineering Co., Philadelphia, Pa.) utilizing silicone diffusion pump oil (704, Dow Corning Corp., Midland, Mich.); V_1 (8 mm stopcock, Scientific Glass Apparatus (SGA), Elk Grove Village, Ill.); V_2 and V_3 (18 mm, SGA); T_1,T_2, T_3, T_4 traps; G_1, cold cathode gauge (Kontes/ Martin, Evanston, Ill.); V_4 and V_7 (Pyrex, 2 mm Hyvac, Fischer Scientific, St. Louis, Mo.); V_5, V_8, V_9, teflon needle valves, 4 mm (Fischer and Porter Co., Warminster, Pa.); V_6 (8 mm, SGA); S_1, 6 mm O-ring connector, Ultra-Torr (Cajon, Cleveland, Ohio); V_{10}, V_{11}, V_{12}, V_{13}, 4 mm oblique (Pyrex); V_{14} and V_{15} 3 mm, 3-way (SGA); and G_2, McLeod Gauge (Hg) made by the local glassblower. Manifolds M_1 and M_2 are 3.5 cm in diameter and M_3 is 2 cm in diameter. B_1, B_2, B_3, and B_4 are 1-liter Pyrex flasks.

With this system, V_1, V_2, and V_3 were used to shut the diffusion pump off from the system and use only the Welch-Duo-Seal pump. T_1 always contained liquid nitrogen. T_4

EXPLANATION: FIG. 2

Vacuum system used to fill electrodeless discharge lamps.



VACUUM SYSTEM

contained ice water as liquid nitrogen or acetone-Dry Ice would pull H_2S or SO_2 into the trap. T_4 was used to prevent mercury from getting into the main system from the McLeod gauge. The other traps, T_2 and T_3, were not used. V_6 was the main stopcock to the secondary manifold. V_5 was used to make small pressure adjustments of the fill gas. V_4 and V_7 were used to evacuate, flush, and fill the lamp. V_{14} could be turned to read pressures either in the secondary or primary manifold, or it could be used to connect M_1 and M_2. V_{15} was used for filling B_1, B_2, B_3, and B_4. V_9 was used to connect extra gas vessels which was helpful in mixing gases. V_8 was used to connect M_2 and M_3. G_2 was used to measure fill gas pressures from 0.010 to 1.700 torr. G_1 was used to monitor the evacuation of the lamp.

Fill Procedure

To fill a lamp, M_1, M_2, and M_3 were evacuated to 10^{-6} torr. The desired fill gas was then put in M_3 from one of the gas vessels and then a small amount was bled into M_2 through V_8. If gases were to be mixed or if they were not in one of the permanent vessels, the gas vessel was attached at V_9 and put into M_2 at this point.

If a solid compound was to be placed in the lamp, about 1 mg was added to the lamp blank before it was put on the vacuum rack at S_1. If only gases were to be used, the lamp blank was attached directly to S_1. If only gases were to

be added to the lamp blank, it was "flamed out" under vacuum before filling. Lamp blanks containing sulfur were lightly flamed out. Na_2S and ZnS were a little more vigorously flamed out as Na_2S is a very hygroscopic compound. CS_2 was put in the lamp blank using a drawn out eyedropper and putting two small drops (ca. 1 mg) in the main body of the lamp, trying not to touch the capillary wall with CS_2. The lamp blanks containing CS_2 had a liquid nitrogen trap placed on them during evacuation.

All lamps but CS_2 were evacuated to 10^{-6} torr. CS_2, because of its high volatility, had its lamps evacuated to 10^{-5} torr. The lamp blank was then flushed three times with the fill gas or the mixture of fill gas and sulfur gas of the filling pressure(s). The pressure was adjusted as needed using V_5.

Having evacuated and flushed the lamp blank, V_7 was opened to the fill gas or fill gas mixture and the lamp cooled to liquid nitrogen temperatures. V_7 was then closed and the lamp was sealed at the capillary portion just above the main body of the lamp, being careful not to collapse the main body of the lamp. The capillary was heated from all directions as best as possible to make a uniform seal. The main body of the lamp was then removed from the capillary by bending the lamp at the point of heating away from the flame so as to stretch and draw out the quartz. Two or three times at this removes the lamp which is then sealed onto a six inch by 2 mm diameter quartz rod at the point of detactment.

To fill a lamp, the procedure was repeated and the gas pressure(s) in M_2 readjusted as needed using V_5, V_8, or V_9.

If gases were to be mixed in M_2, they were mixed by adding a known pressure of each gas to M_2.

The sulfur containing compounds used in this study were as follows: elemental sulfur flowers (Baker and Adamson, Morristown, N.J.); ZnS, reagent (Fischer, St. Louis, Mo.); $Na_2S \cdot 9H_2O$, 99.8% (Baker Chemical Co., Phillipsburg, N.J.); CS_2, reagent (B&A); H_2S, high purity grade (Fischer); SO_2, high purity grade (Fischer).

The fill gases used in this study were as follows: He, high purity grade (Fischer); Ne, Kr, and Xe (Airco, Welders Products and Services, Kansas City, Mo.); Ar (Matheson Co., Joliet, Ill.).

Evaluation Equipment

Microwave Source and Optical System

A 2450 Mhz microwave generator rated at 125 watts was used as a microwave source to maintain the discharge in the electrodeless discharge lamp(Scintillonics, Inc., Fort Collins, Colo.). The lamp was suspended above an "A" antenna by a large wooden clamp (Figure 3). The lamp was tuned using tuning stubs described by Schrenk, et. al. (96). A tesla coil was used to initiate the discharge.

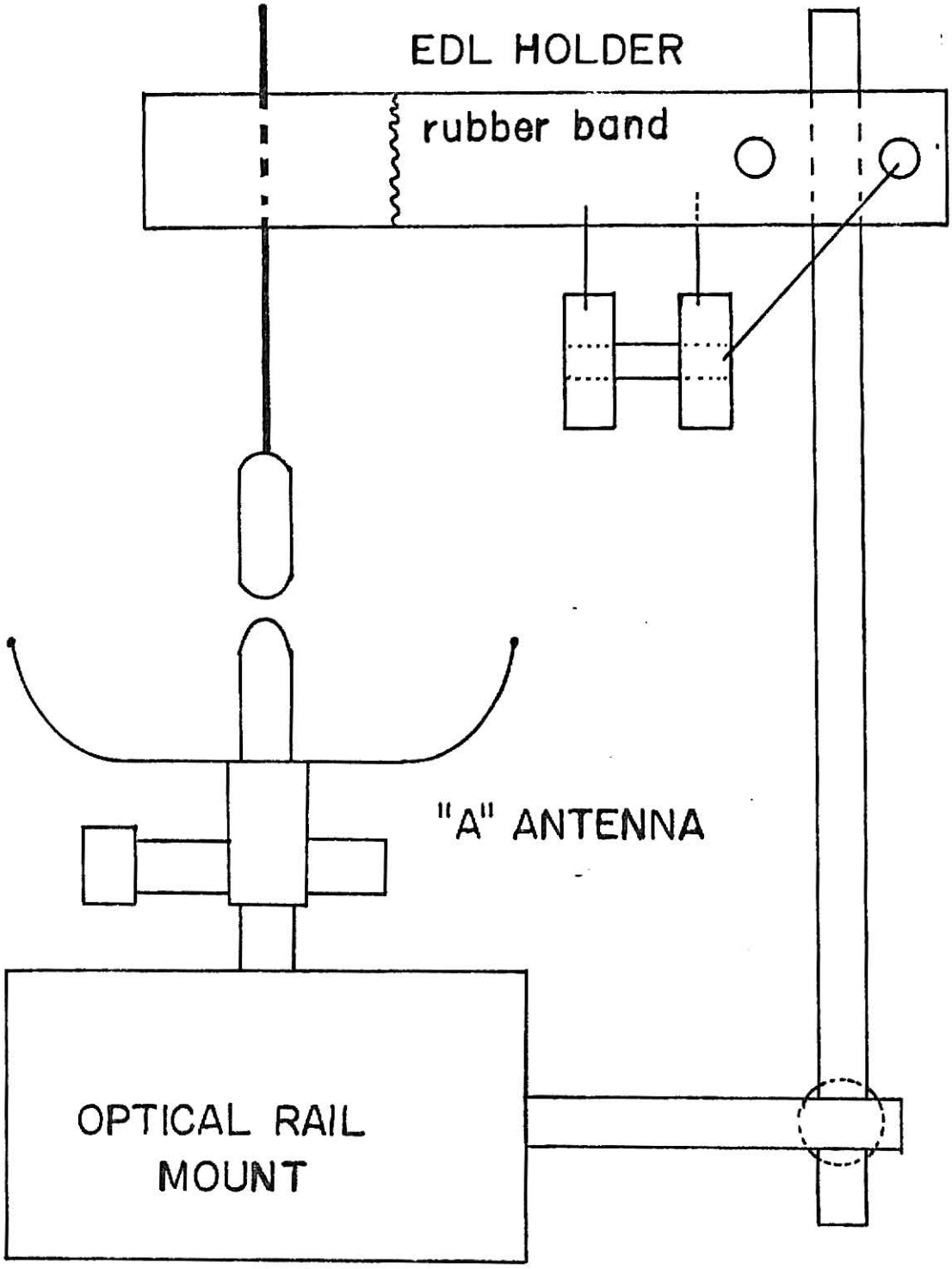
A 3.4 meter Ebert mount spectrograph (Jarrell-Ash Co., Waltham, Mass.) with a 30,000 lines/in. grating was used for the monochrometer in the evaluation. The spectrograph was set up for electronic read out using a R106 photomultiplier tube (Hamamatsu TV Co., Ltd., Japan), Jarrell-Ash amplifier and power supply, a digital voltmeter (Fairchild Instrumentation, Sunnyvale, Cal.), and a strip-chart recorder (Honeywell, Brown Electronik, Minneapolis, Minn.).

Heater

The heater was described by Winefordner (17), but was modified slightly for this project (Figure 4). The main body of the heater, A, was constructed out of stainless steel so as to withstand temperatures up to 1000°C. The body was wrapped with asbestos cord. B is the heating coil which consists of two ceramic cores from diffusion pump heaters (SGA) connected with 3/16 inch threaded rod. The coil is

EXPLANATION: FIG. 3

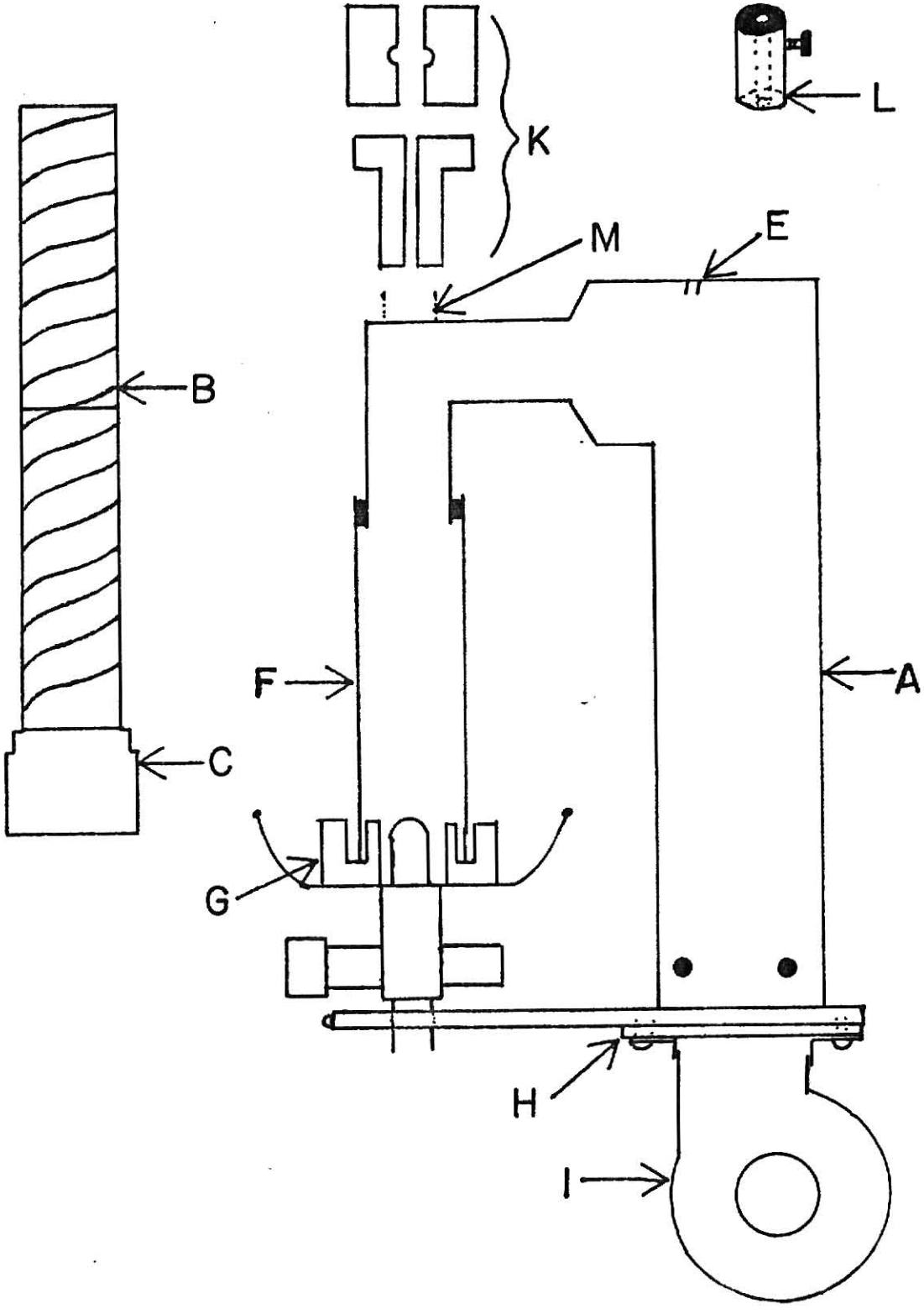
Lamp suspended above an "A" antenna.


EDL HOLDER
rubber band
"A" ANTENNA
OPTICAL RAIL
MOUNT

EXPLANATION: FIG. 4

Heater and "A" antenna setup used in evaluating the temperature effects on the lamp.

HEATER, "A" ANTENNA, and FAN



20 ohms, constructed of 15 gauge spring wound nichrome wire. The conducting base was removed from the upper core. A ceramic light socket, C, is used to contain both electric connections for the heating coil. E is the position of the controlling thermocouple. F is a 3.5 cm diameter quartz tube and G are asbestos supports. H is made of asbestos pads to insulate the fan, I, (Rotron Nugget, Rotron Mfg. Co., Woodstock, N.Y.). K is a bolt with a 2 mm hole drilled in it, then cut in half to steady and position the lamp in the heater. L is a sleave with a set screw to hold the lamp rod, to premit more freedom in adjustment. M is the hole that the lamp enters through.

The temperature controller was designrd by Dr. M. VanSwaay of this department. The thermocouple amplifier used in calibration of the controller and heater was built by Mr. Bill Ryan of this department.

Evaluation of the Lamps

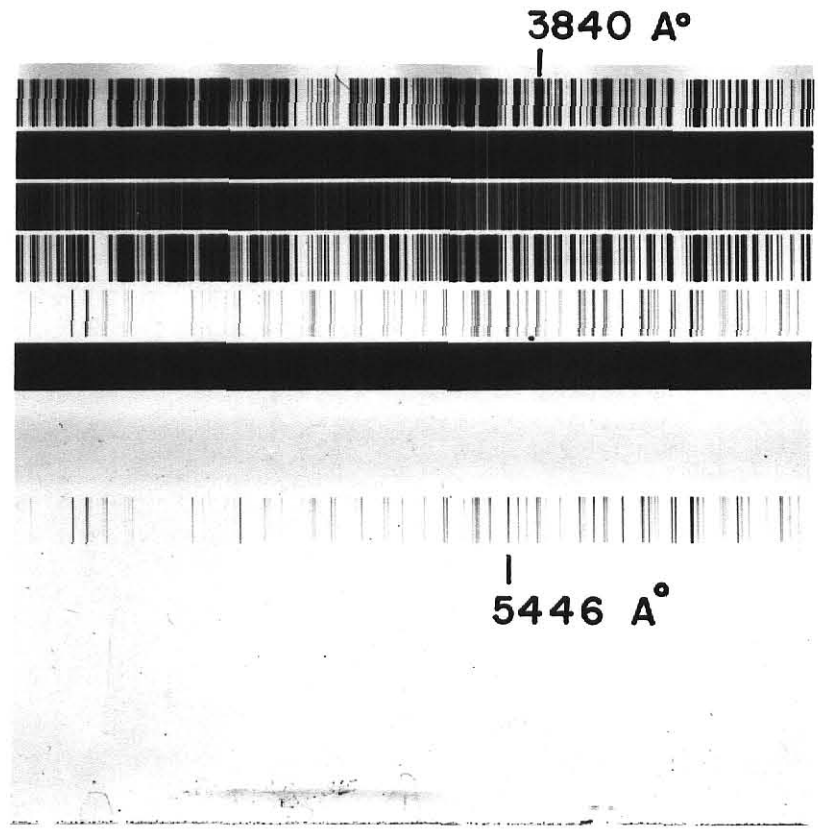
To obtain comparable data one must maintain constant settings in the operation of his power supply, amplifier, and photomultiplier tube. Also one would hope that the lamps would operate in about the same position above the "A" antenna so that refocusing would be a minimim. Due to the fact that all lamps were not evaluated consecutively, it is possible that some of the settings varied. There is always the possibility of drift during operation.

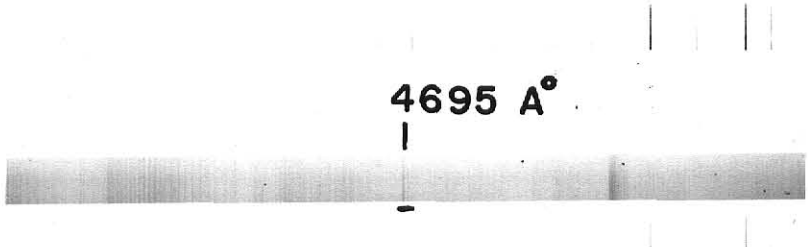
EXPLANATION: FIG. 5

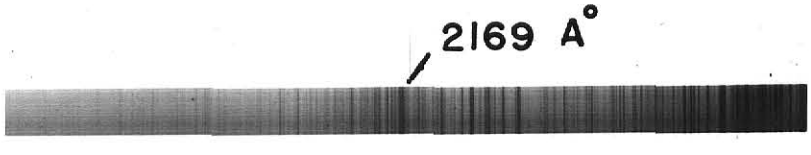
Wavelengths of sulfur investigated.

THIS BOOK CONTAINS SEVERAL DOCUMENTS THAT ARE OF POOR QUALITY DUE TO BEING A PHOTOCOPY OF A PHOTO.

THIS IS AS RECEIVED FROM CUSTOMER.


3840 A°
5446 A°


4695 A°


2169 A°

THIS BOOK CONTAINS NUMEROUS PAGES WITH ILLEGIBLE PAGE NUMBERS THAT ARE CUT OFF, MISSING OR OF POOR QUALITY TEXT.

THIS IS AS RECEIVED FROM THE CUSTOMER.

For evaluation, the photomultiplier tube was set and run at 865 volts. The lamps were always examined at a standing wave ratio (SWR) of 1 with 100 watts output power if possible. A few lamps could not be tuned to this setting.

In this study, four different wavelengths were investigated, 2169 A° (S I) (103), 3840 A° (S_2 band head) (83), 4695 A° (S I) (80), and 5454 A° (S II) (4), Figure 5. All of these sulfur lines or band head have been used to determine sulfur spectroscopically and do not require a vacuum spectrograph. In addition to 4695 A°, there is a sulfur line at 4694 A° which is more intense and a sulfur line at 4696 A° which is slightly weaker.

The entrance slit to the spectrograph was set at 100 microns. The slit to the photomultiplier tube was set at 50 microns.

The first evaluations were made of the electrodeless discharge lamps in air or flowing air without any jacket or heater.

EXPERIMENTAL RESULTS AND DISCUSSION

Intensity of Lamps

The purpose of this investigation was the production and evaluation of lamps containing various sulfur containing compounds and varying in fill gas pressure.

The first lamps studied were those containing elemental sulfur. Figures 6-17 present intensity versus fill gas pressure curves for sulfur and five different inert gases. These figures are representative results obtained using elemental sulfur. Data for the sulfur lamps not represented here are listed in Table A-1 of the appendix.

The optimum fill gas pressure occurs around 0.1 to 0.2 torr, the exception being neon which shows an optimum fill gas pressure around 0.8 to 1.0 torr. The reason for this difference is not known at present. There is an initial spike between 0 and 0.1 torr of the fill gas. The reason for this phenomona is unknown at this time, but it occurs for all fill gases in elemental sulfur lamps.

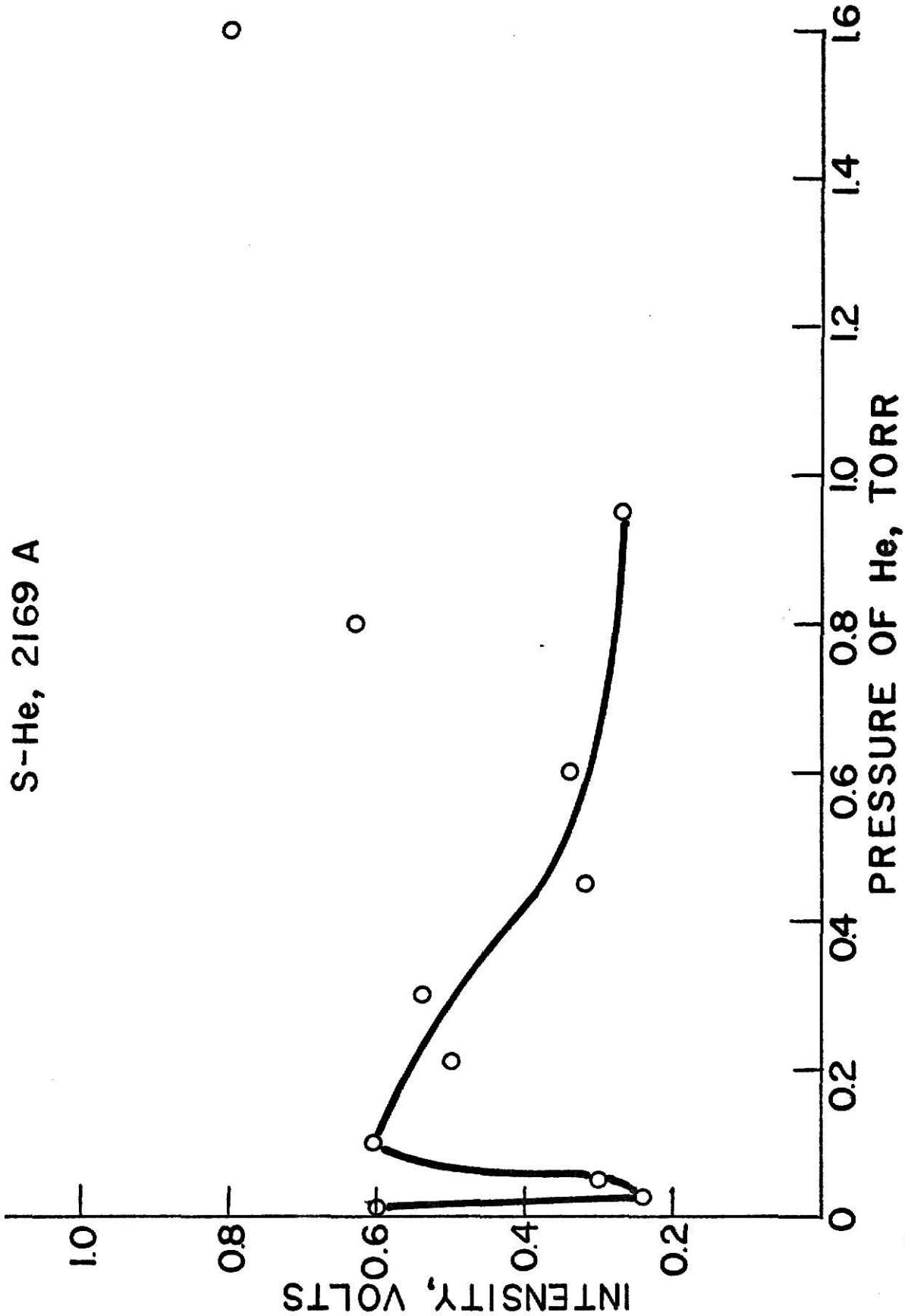
The 3840 A° intensity versus fill gas pressure curves are not shown for most of the elemental sulfur lamps. These curves indicate the same optimum fill gas pressure ranges. Also this wavelength region is usually quite intense because of the high background from the S_2 band spectra.

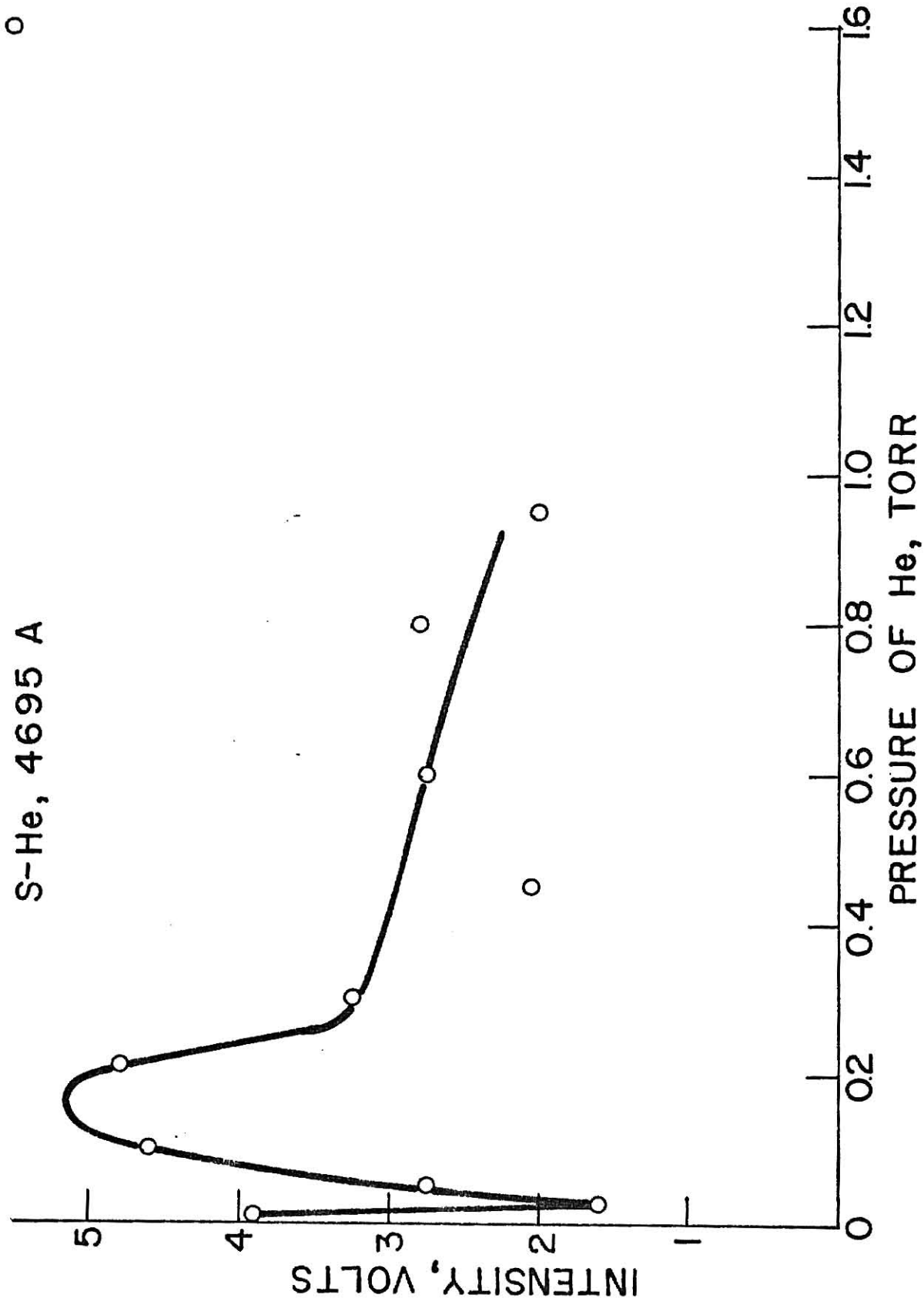
In scanning over 3840 A°, one usually observes 60 to 80 percent background. Emissions at 4695 A° and 5454 A°

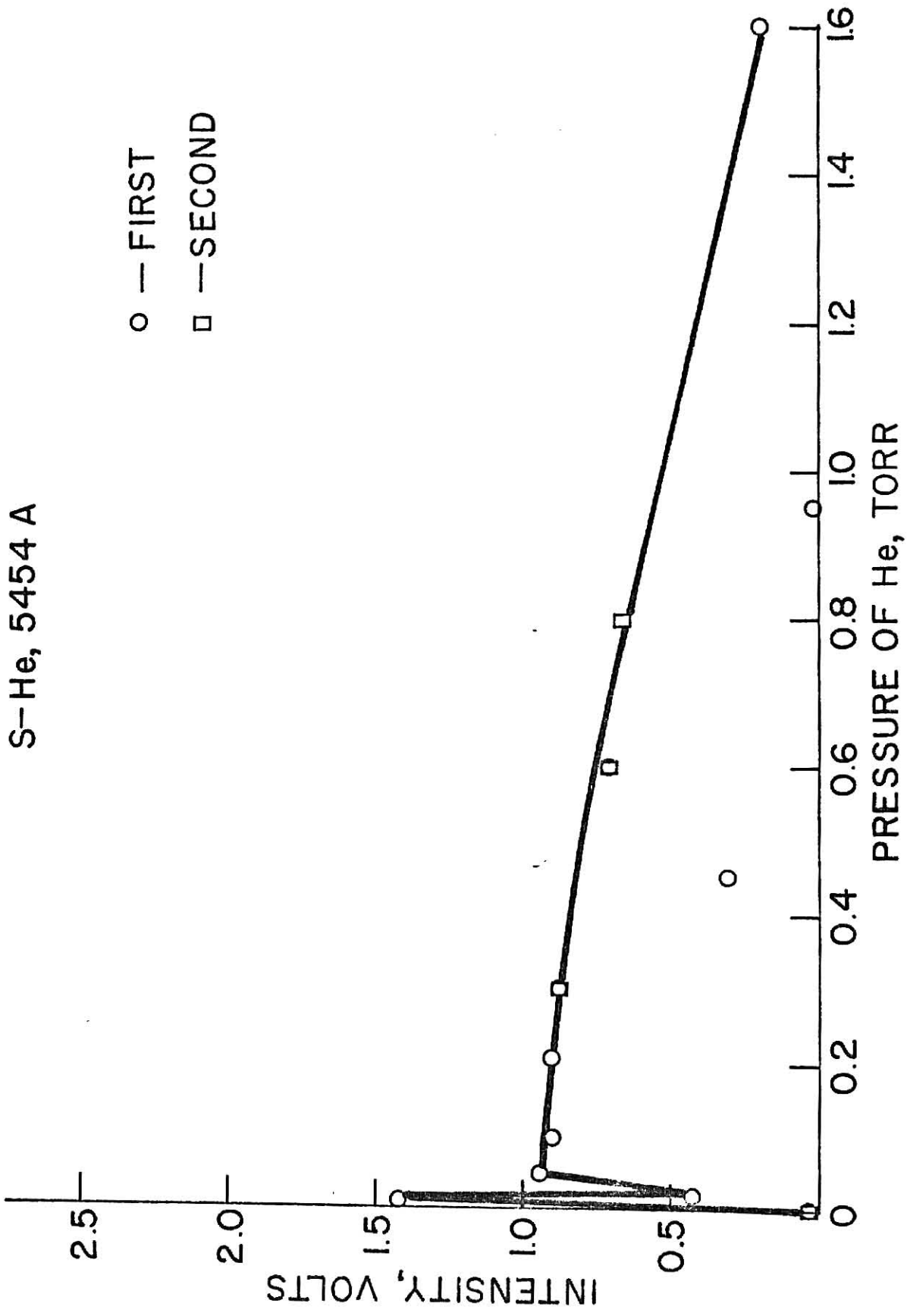
EXPLANATION: FIG. 6-17

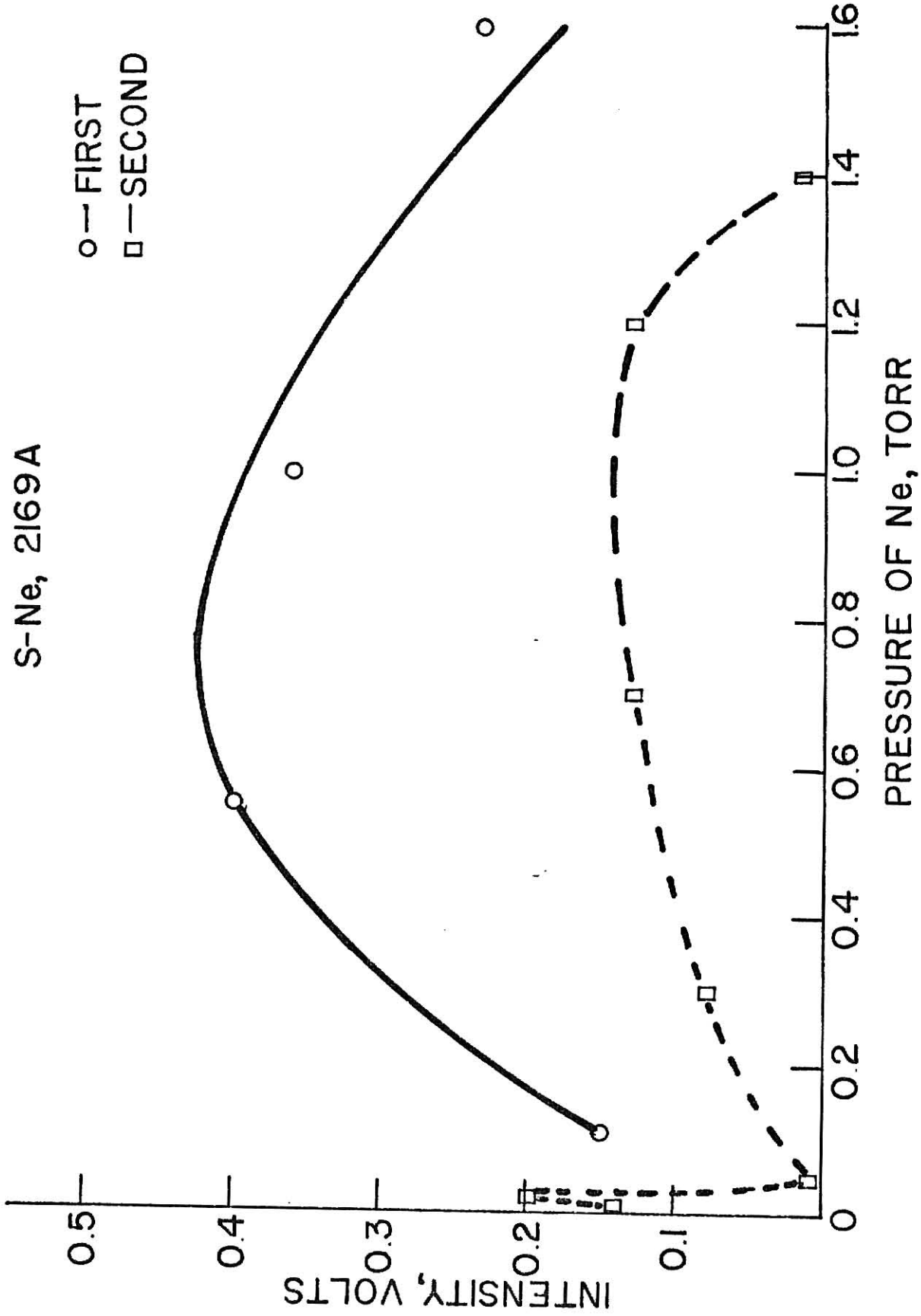
6: Helium, 2169 A°
7: Helium, 4695 A°
8: Helium, 5454 A°
9: Neon, 2169 A°
10: Neon, 4695 A°
11: Neon, 5454 A°
12: Argon, 2169 A°
13: Argon, 3840 A°
14: Argon, 4695 A°
15: Krypton, 2169 A° and 5454 A°
16: Krypton, 3840 A° and 4695 A°
17: Xenon, 2169 A°, 4695 A°, and 5454 A°

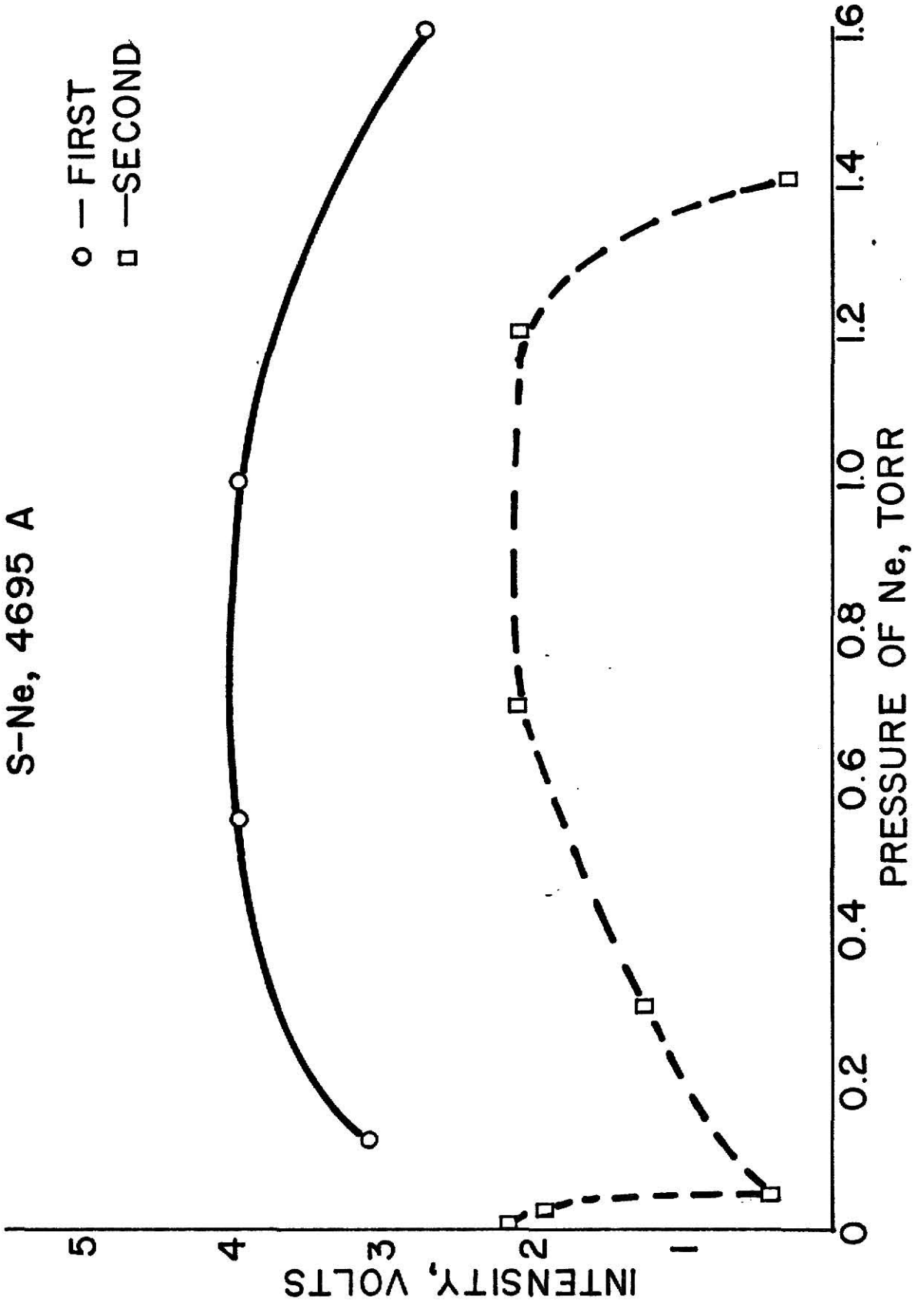
The intensities of these elemental sulfur containing lamps were plotted versus fill gas pressure.

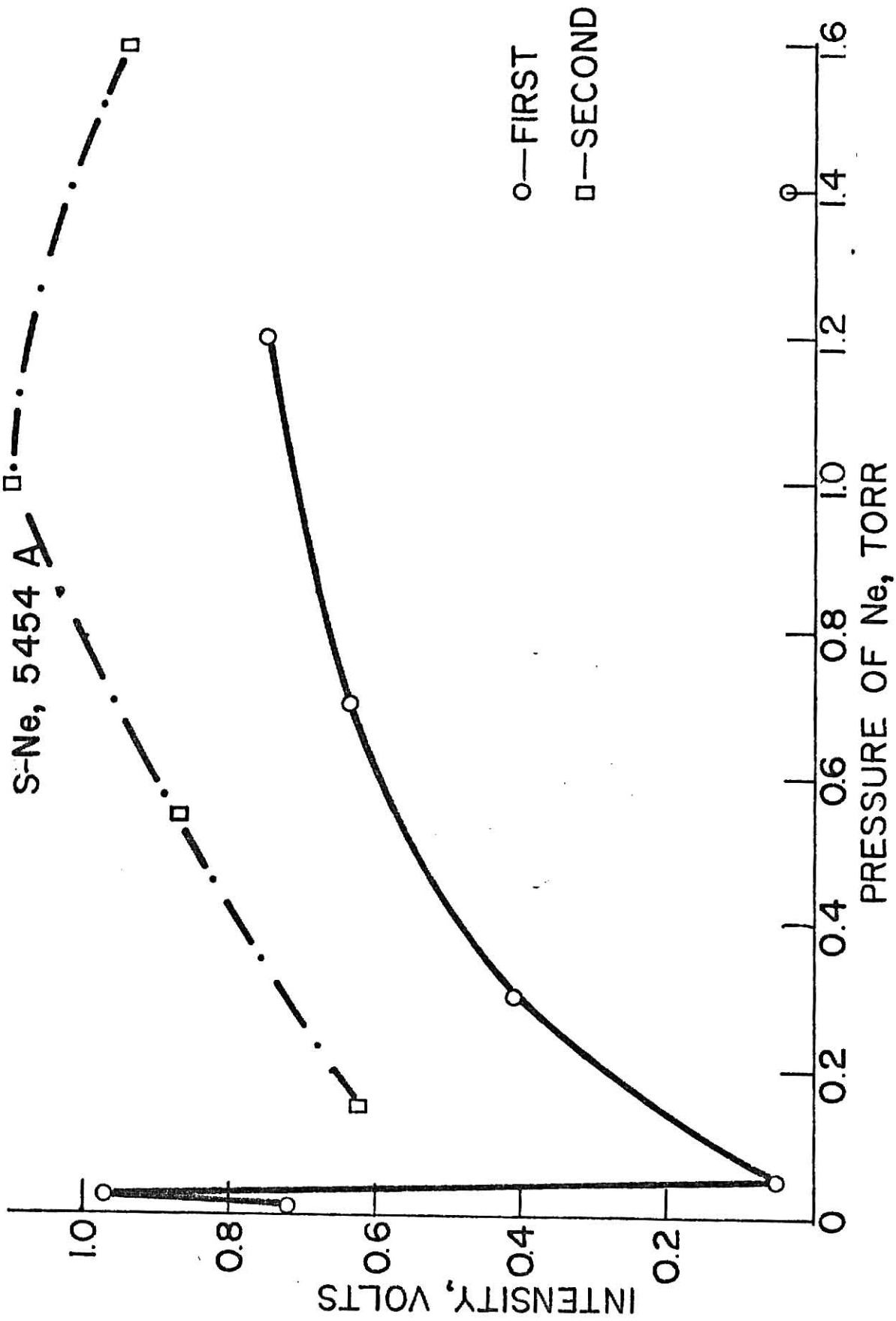

S-He, 2169 A
INTENSITY, VOLTS
0.2
0.4
0.6
0.8
1.0
PRESSURE OF He, TORR
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6

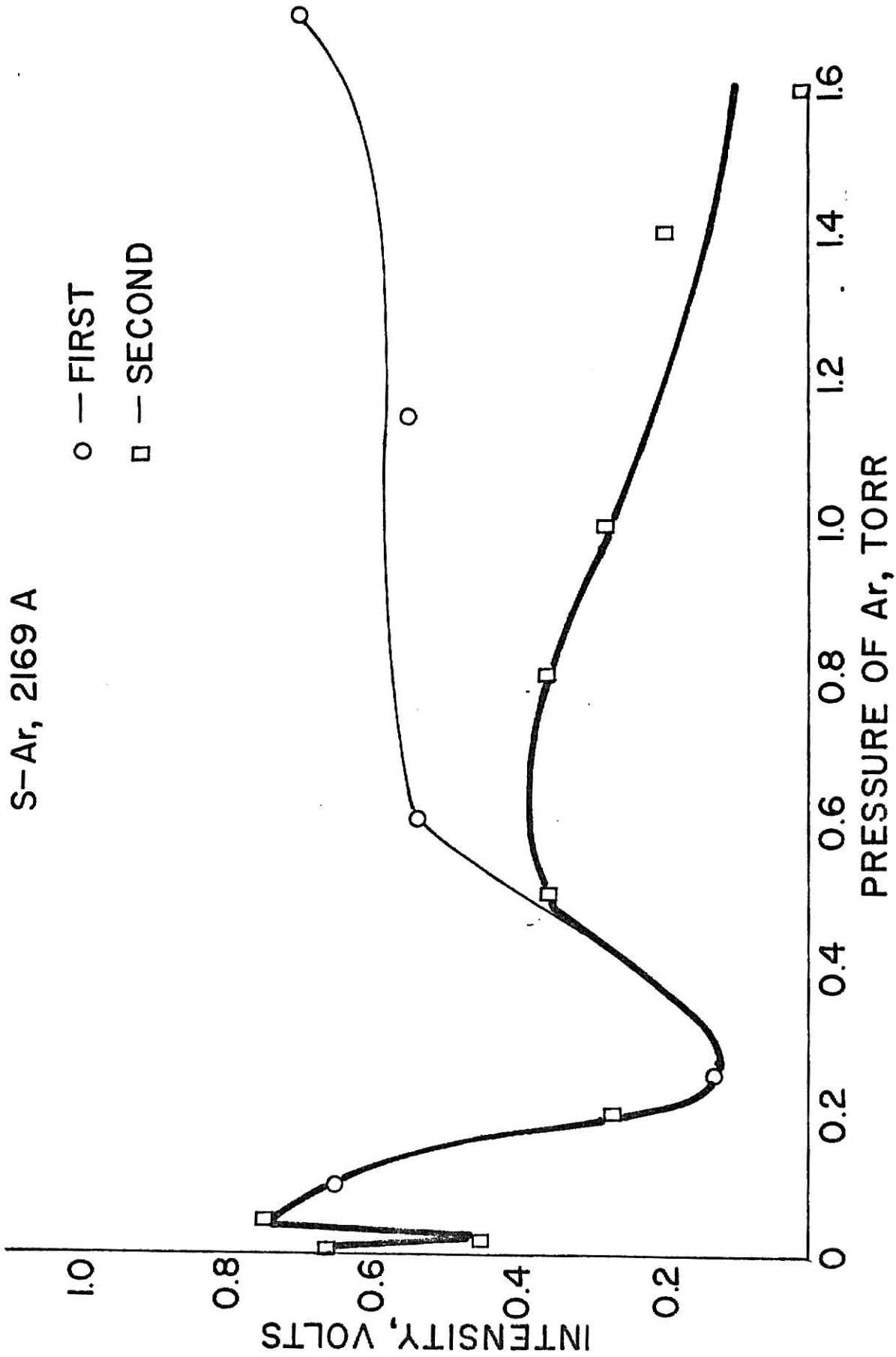

S-He, 4695 A
INTENSITY, VOLTS
PRESSURE OF He, TORR
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1
2
3
4
5

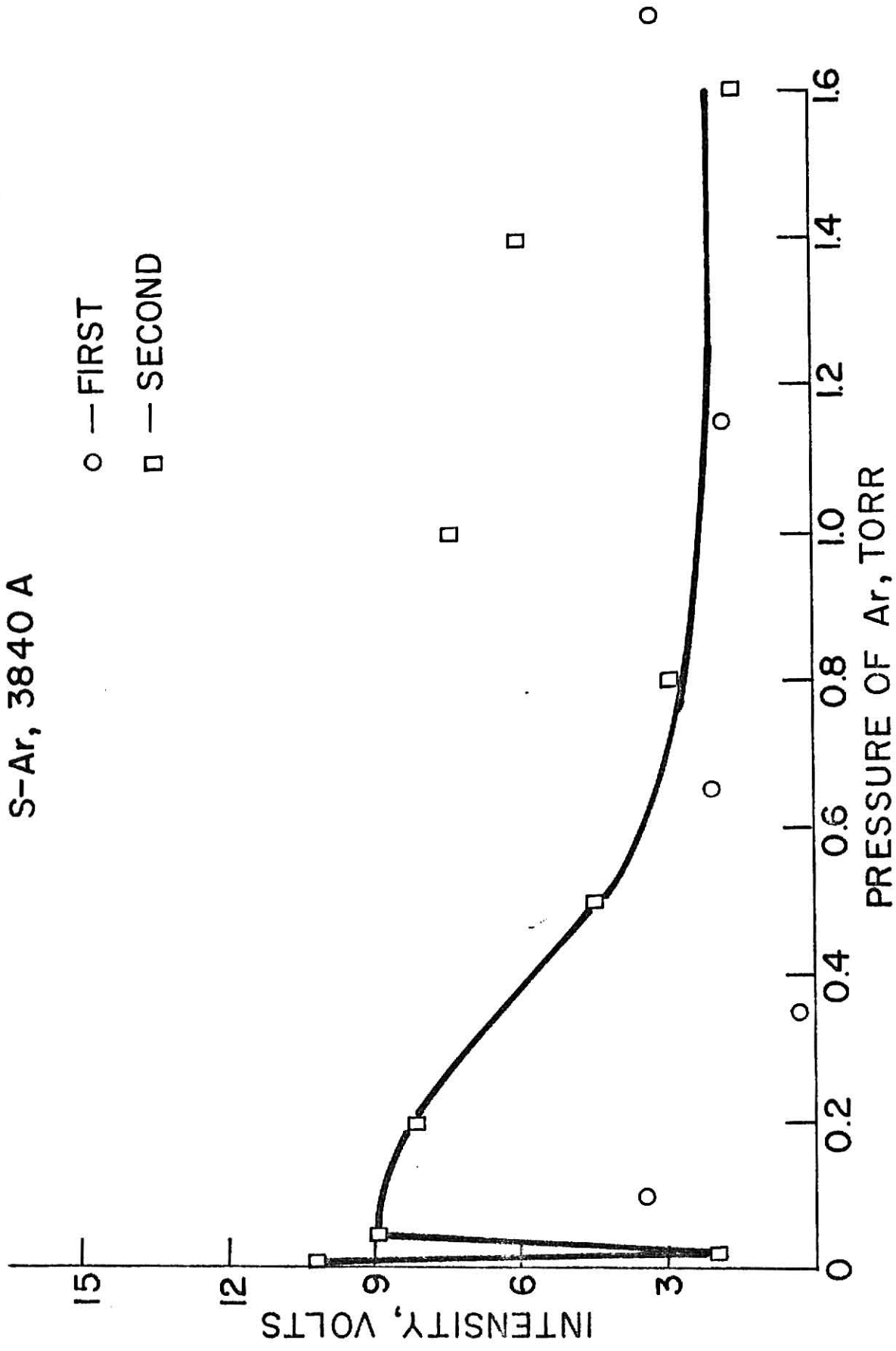

S–He, 5454 A
o — FIRST
□ —SECOND
INTENSITY, VOLTS
2.5
2.0
1.5
1.0
0.5
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
PRESSURE OF He, TORR

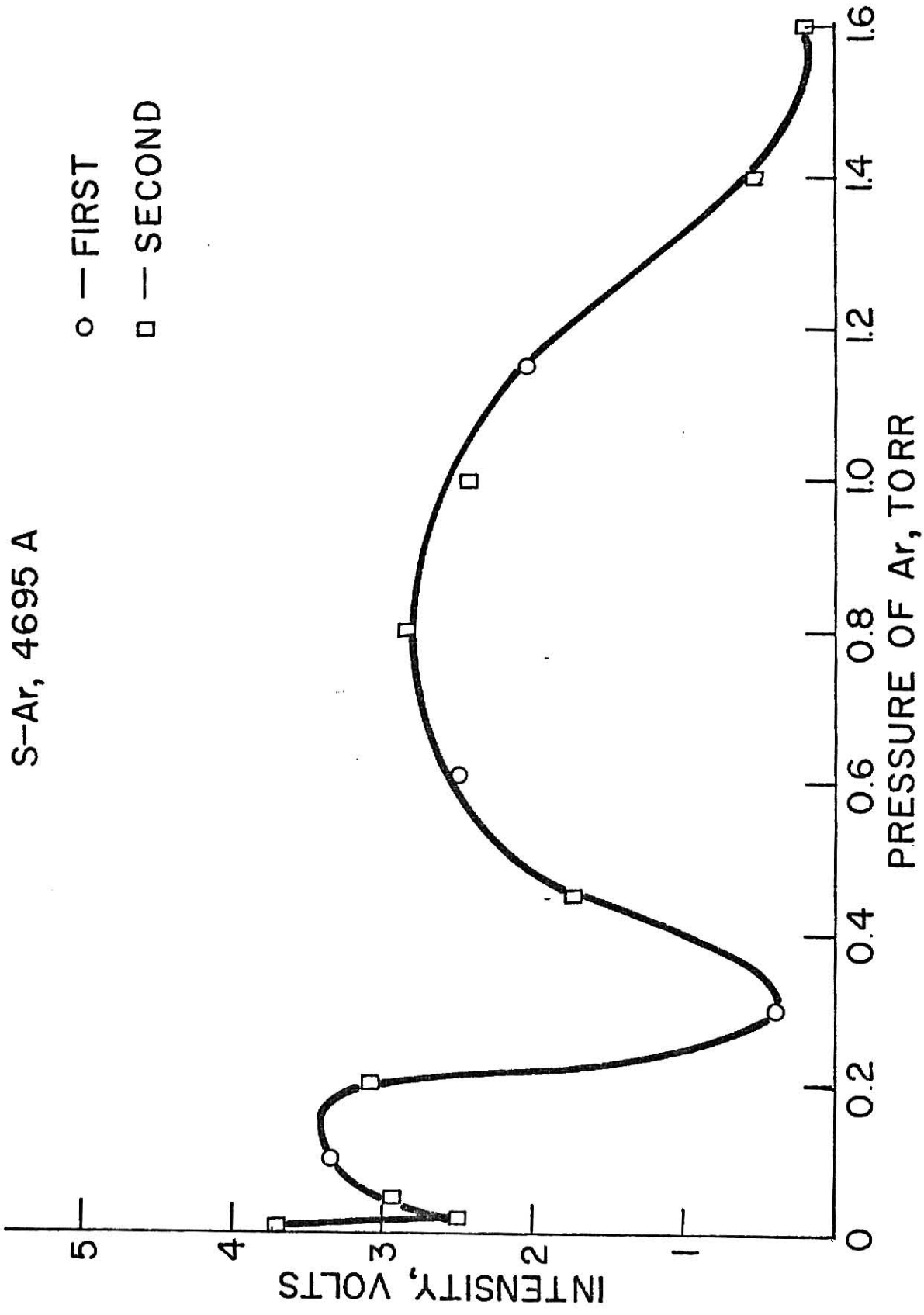

S-Ne, 2169A
o—FIRST
□—SECOND
INTENSITY, VOLTS
0.1
0.2
0.3
0.4
0.5
PRESSURE OF Ne, TORR
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6

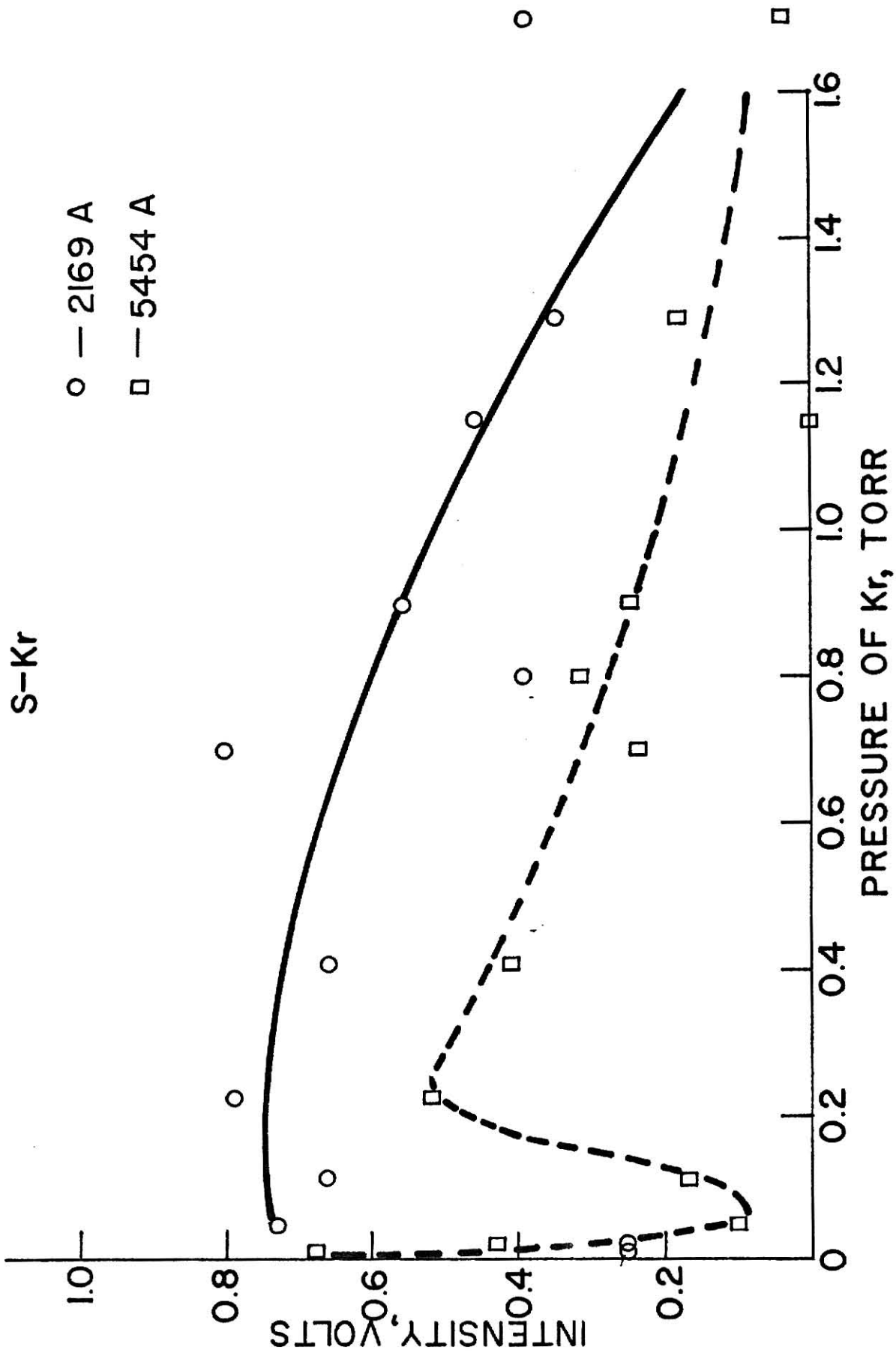

S-Ne, 4695 A
o — FIRST
□ —SECOND
INTENSITY, VOLTS
PRESSURE OF Ne, TORR
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1
2
3
4
5

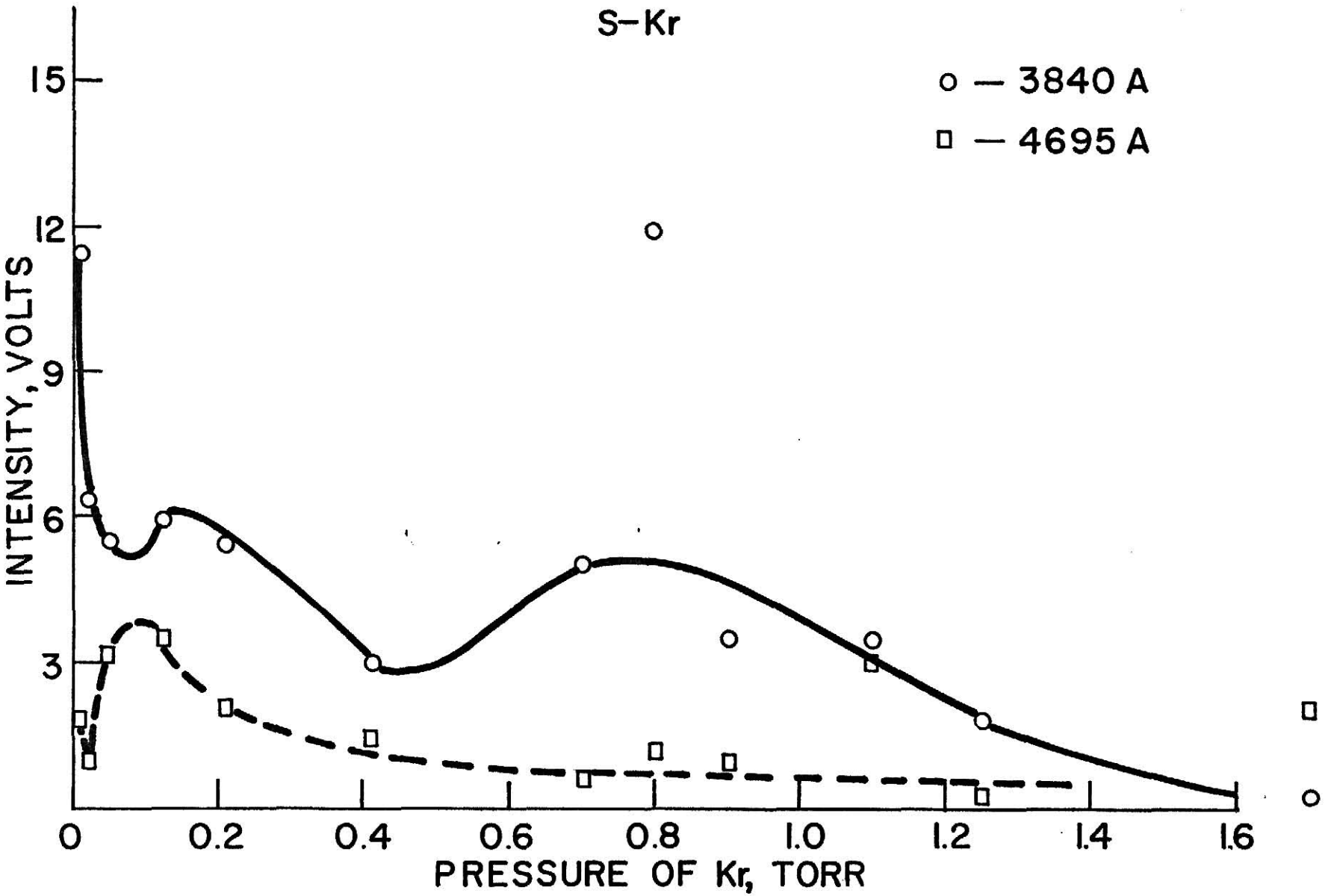

S-Ne, 5454 Å
o—FIRST
□—SECOND
INTENSITY, VOLTS
1.0
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
PRESSURE OF Ne, TORR

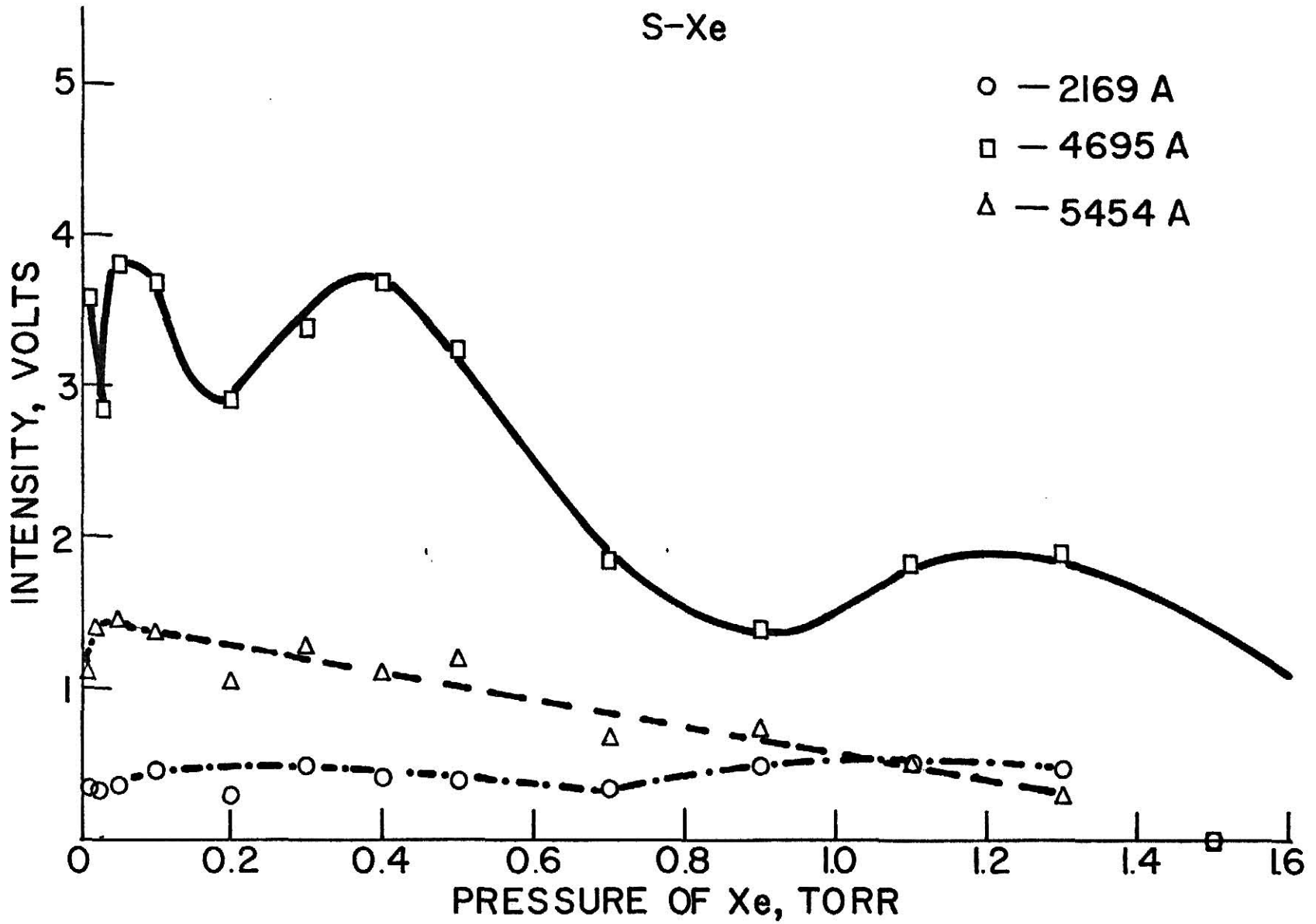

S-Ar, 2169 A
o — FIRST
□ — SECOND
INTENSITY, VOLTS
1.0
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
PRESSURE OF Ar, TORR


S-Ar, 3840 A
o — FIRST
□ — SECOND
INTENSITY, VOLTS
15
12
9
6
3
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
PRESSURE OF Ar, TORR


S–Ar, 4695 A
o — FIRST
□ — SECOND
INTENSITY, VOLTS
PRESSURE OF Ar, TORR
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1
2
3
4
5


S-Kr
○ — 2169 A
□ — 5454 A
INTENSITY, VOLTS
PRESSURE OF Kr, TORR
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6


S–Kr
o — 3840 A
□ — 4695 A
INTENSITY, VOLTS
15
12
9
6
3
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
PRESSURE OF Kr, TORR


S-Xe
o — 2169 A
□ — 4695 A
Δ — 5454 A
INTENSITY, VOLTS
1
2
3
4
5
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
PRESSURE OF Xe, TORR

showed around 10 to 20 percent background.

No one fill gas is best for all wavelengths. A lamp which is intense at one wavelength may be weak at another. This is due to the ionization potential of the fill gas, the energy level of the sulfur emission line, and its wavelength with its respective transition probability.

Figures 18-23 show the intensity versus fill gas pressure curves for some of the better H_2S lamps. The data which is not plotted is listed in Table A-2 of the appendix. As with elemental sulfur, most optimum pressures are in the range of 0.1 to 0.3 torr. There is a little more variation of the optimum fill gas pressure with wavelength. The initial spike that was present in the elemental sulfur intensity versus pressure curves was not present in most of the H_2S lamp curves. In most of the curves where the spike appearred, it was not very prominent.

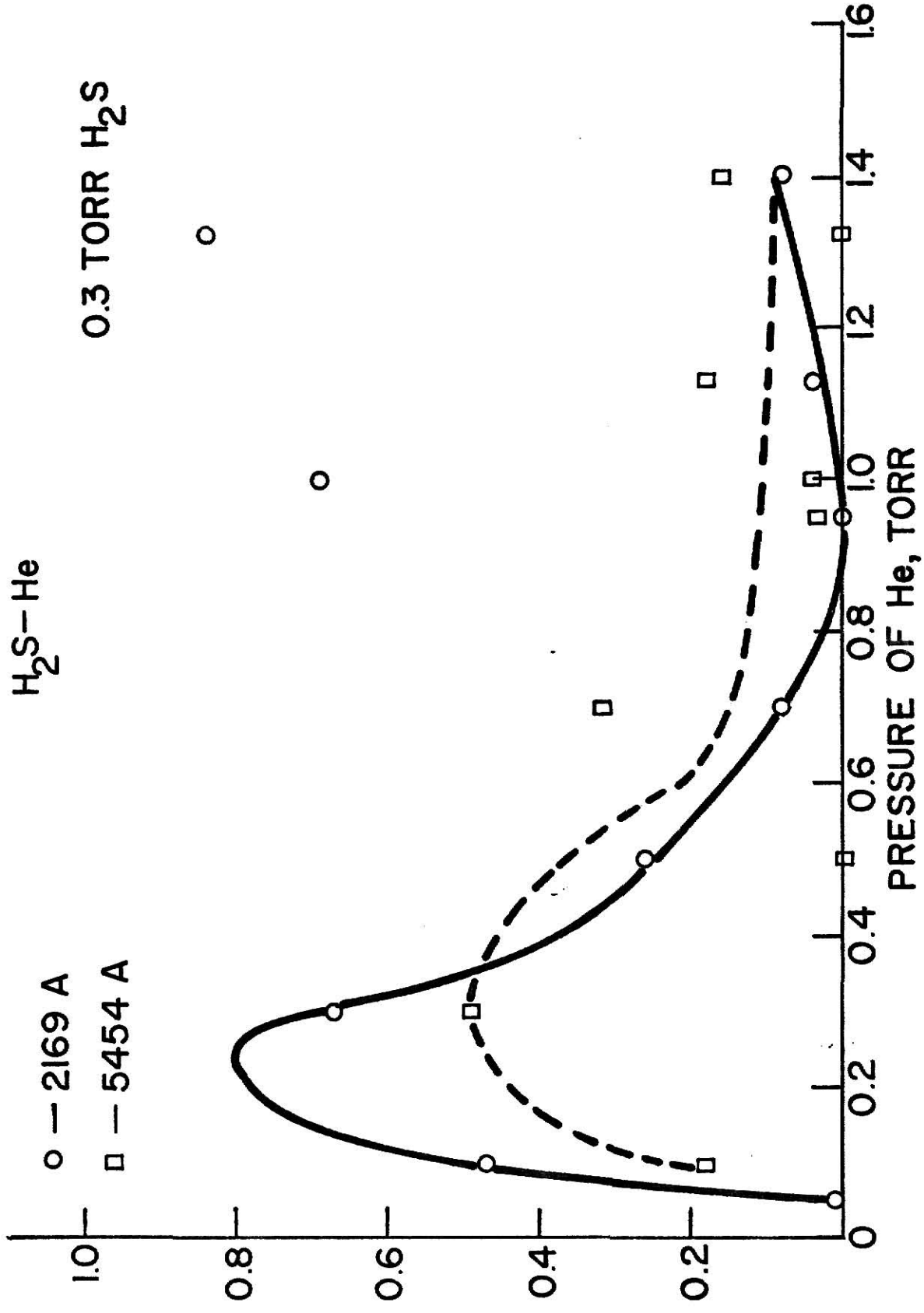
The intensities of the H_2S lamps are of the same order of magnitude as those obtained for the elemental sulfur lamps.

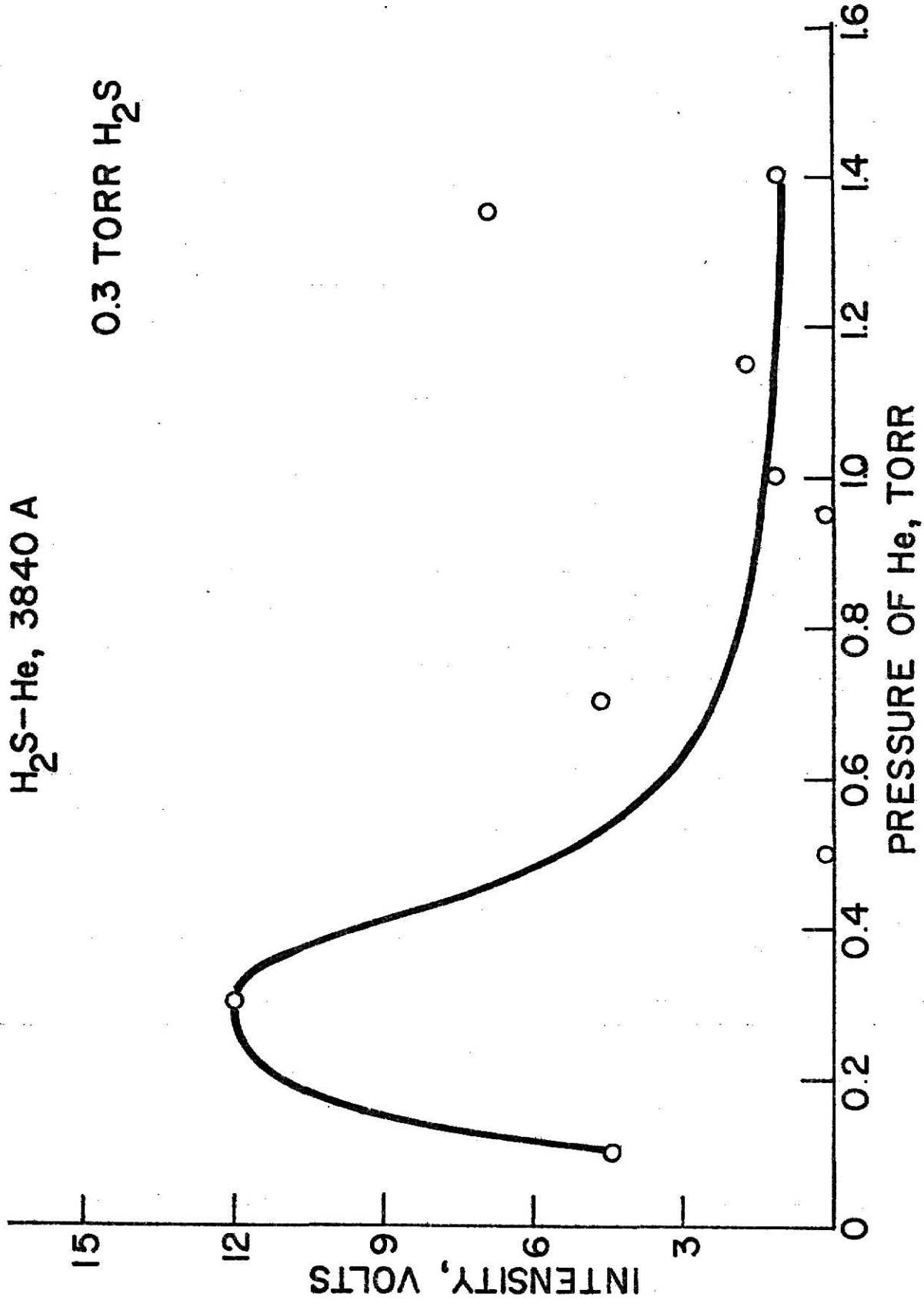
Sulfur emission lines from SO_2 lamps did not exhibit intensities comparable to those from elemental sulfur or H_2S. This can be seen in Figures 24-26 and Table A-3 of the appendix. The pressure ranges were about the same as those observed for the previously discussed lamps. SO_2 lamps show more wandering in their pressure-intensity curves. However some individual lamps did show good intensities. Helium,

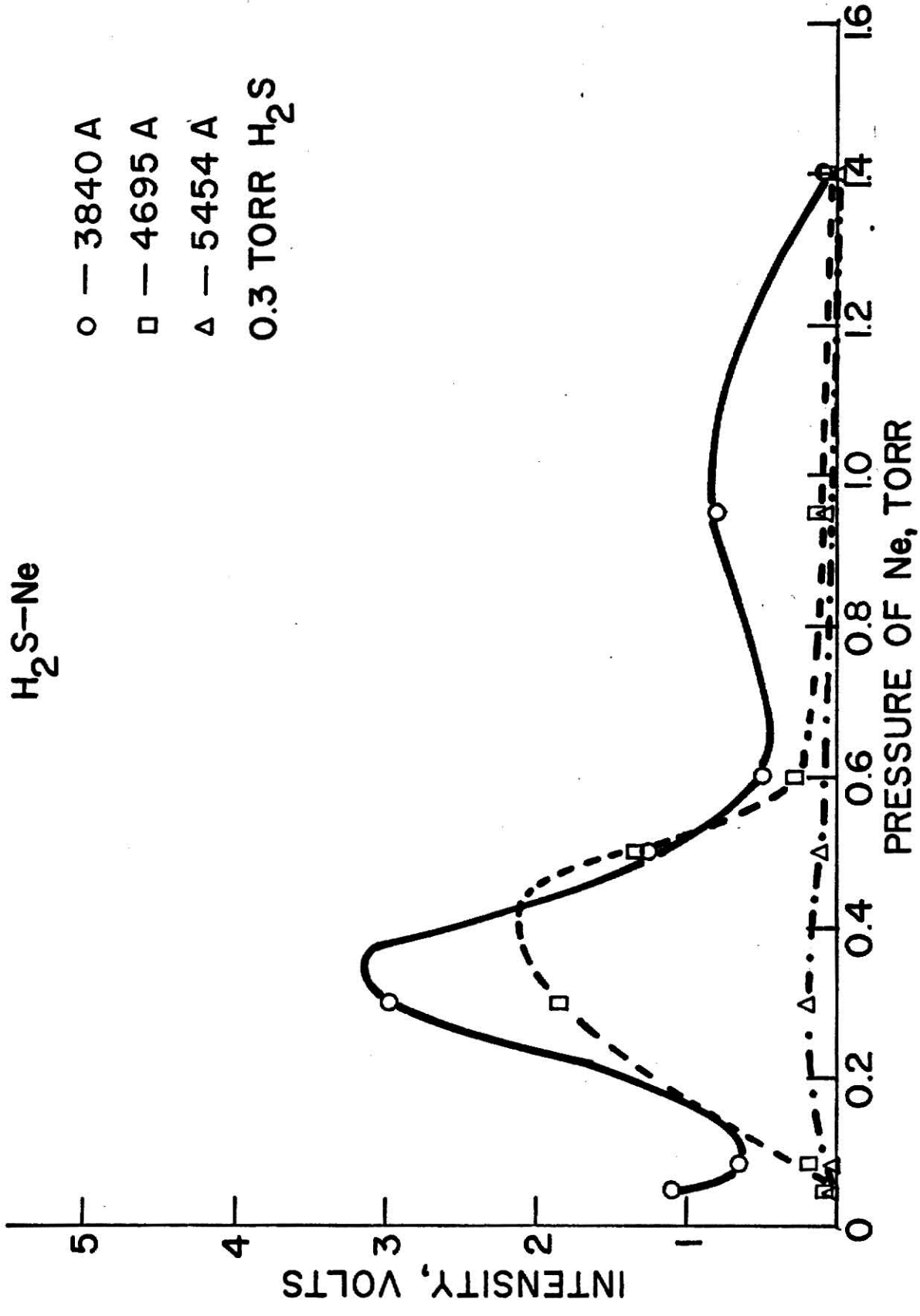
EXPLANATION: FIG. 18-23

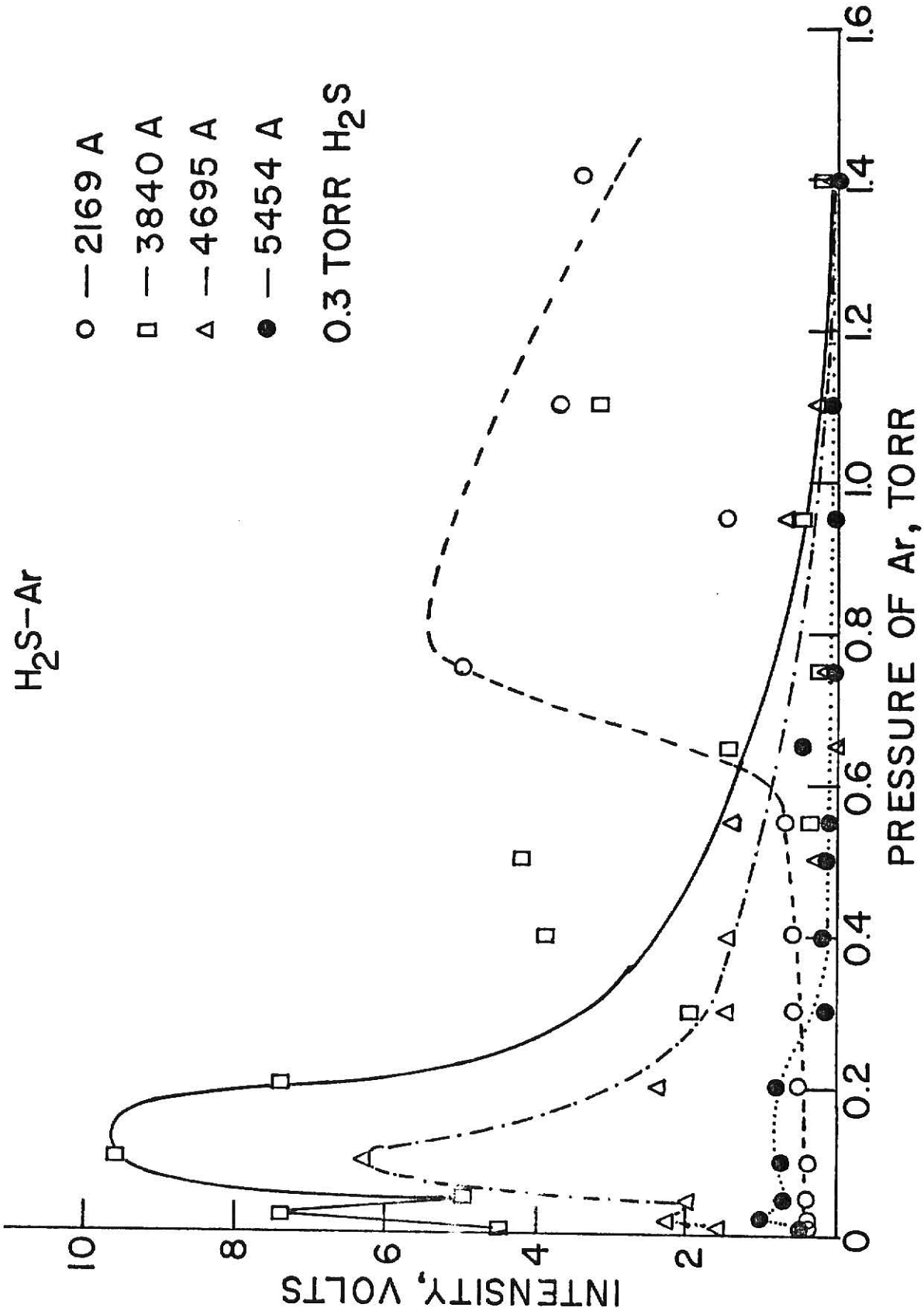
18: Helium, 2169 A° and 5454 A°
19: Helium, 3840 A°
20: Neon, 3840 A°, 4695 A°, and 5454 A°
21: Argon, 2169 A°, 3840 A°, 4695 A°, and 5454 A°
22: Xenon, 2169 A° and 5454 A°
23: Xenon, 4695 A°

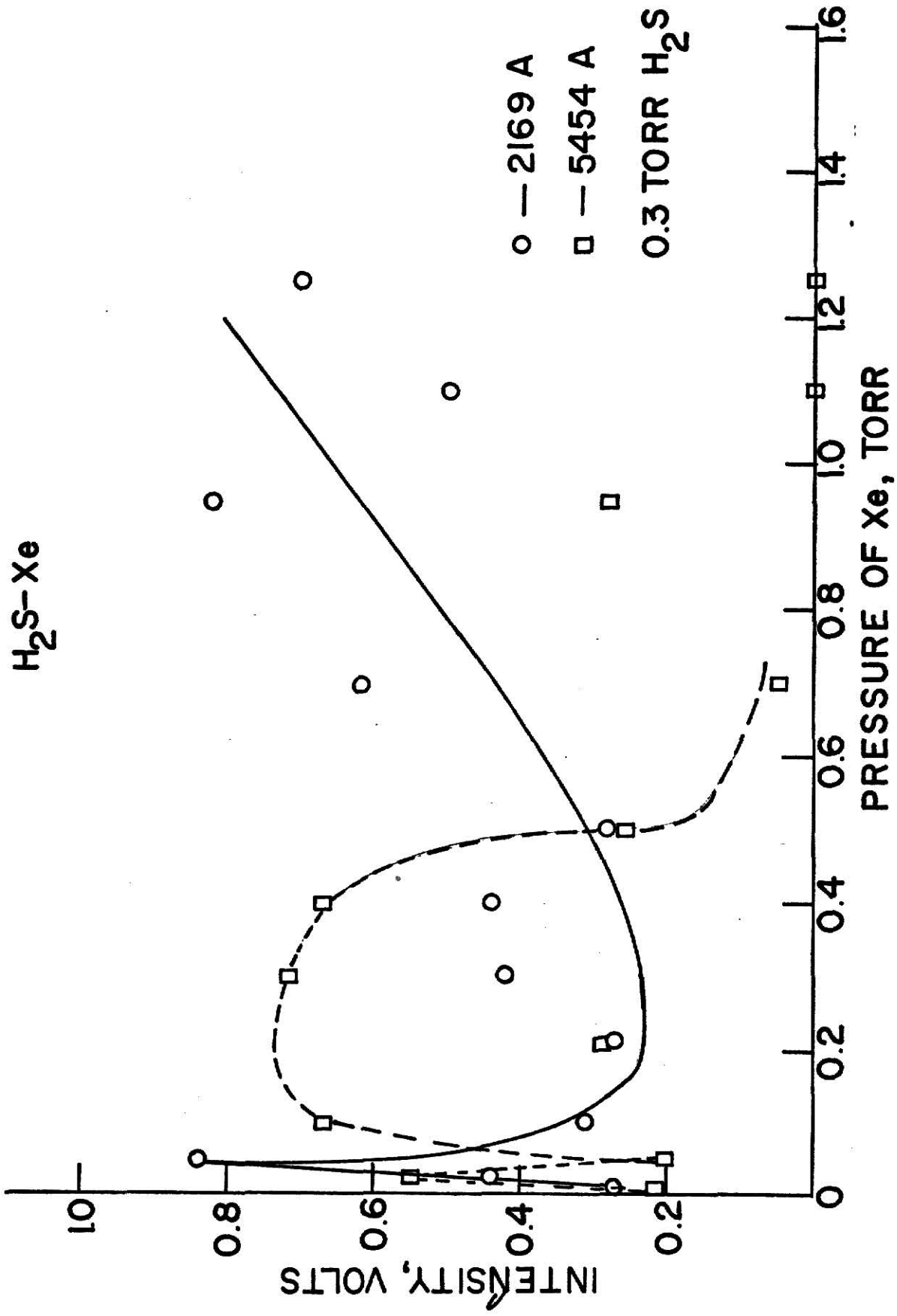
The intensities of these H_2S containing lamps were plotted versus fill gas pressure.

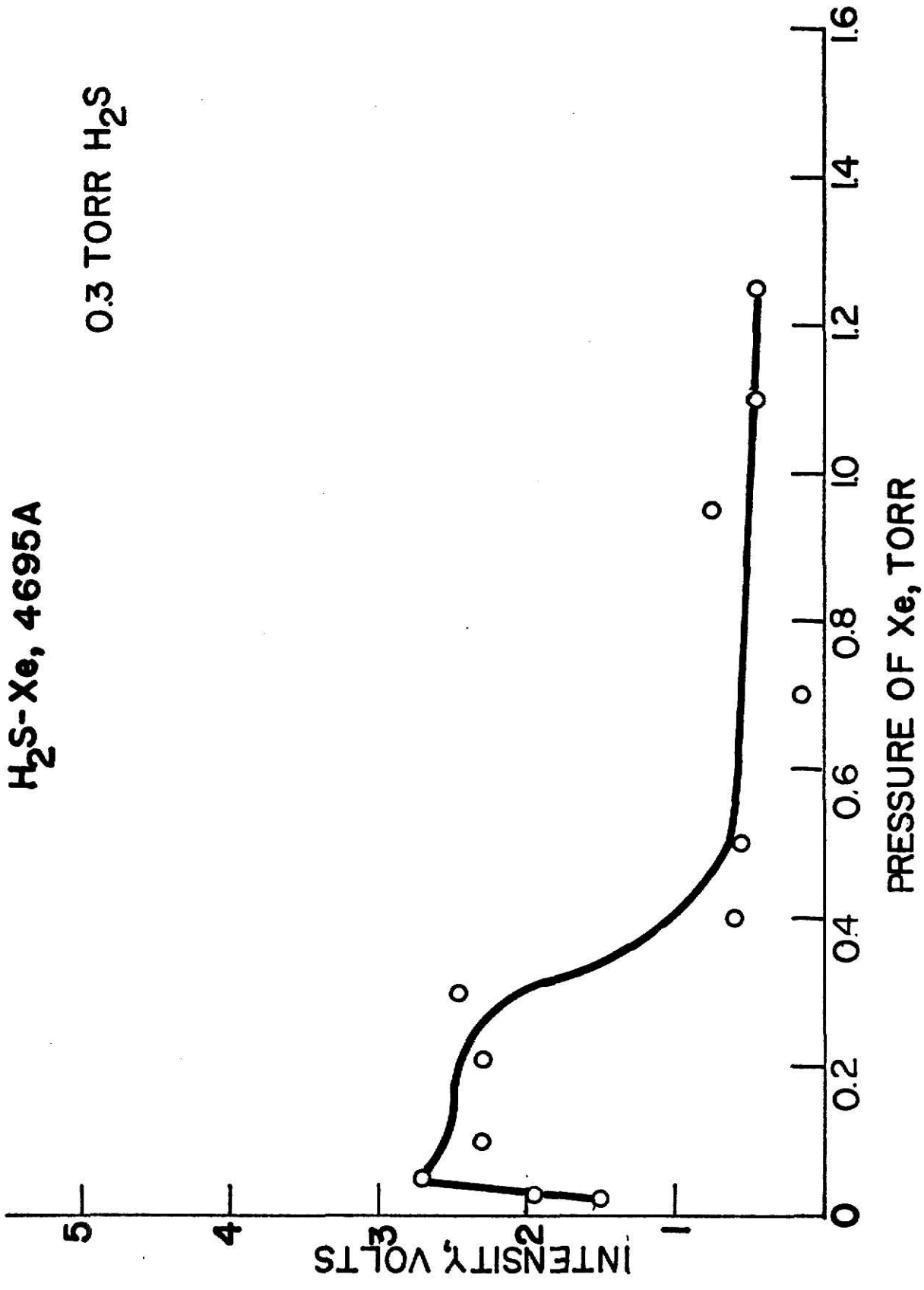

H2S–He
0.3 TORR H2S
o — 2169 A
□ — 5454 A
1.0
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
PRESSURE OF He, TORR


H_2S–He, 3840 A
0.3 TORR H_2S
INTENSITY, VOLTS
15
12
9
6
3
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
PRESSURE OF He, TORR


H2S–Ne
o — 3840 A
□ — 4695 A
Δ — 5454 A
0.3 TORR H2S
INTENSITY, VOLTS
PRESSURE OF Ne, TORR
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1
2
3
4
5


H2S–Ar
0.3 TORR H2S
○ — 2169 A
□ — 3840 A
△ — 4695 A
● — 5454 A
INTENSITY, VOLTS
PRESSURE OF Ar, TORR
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
2
4
6
8
10

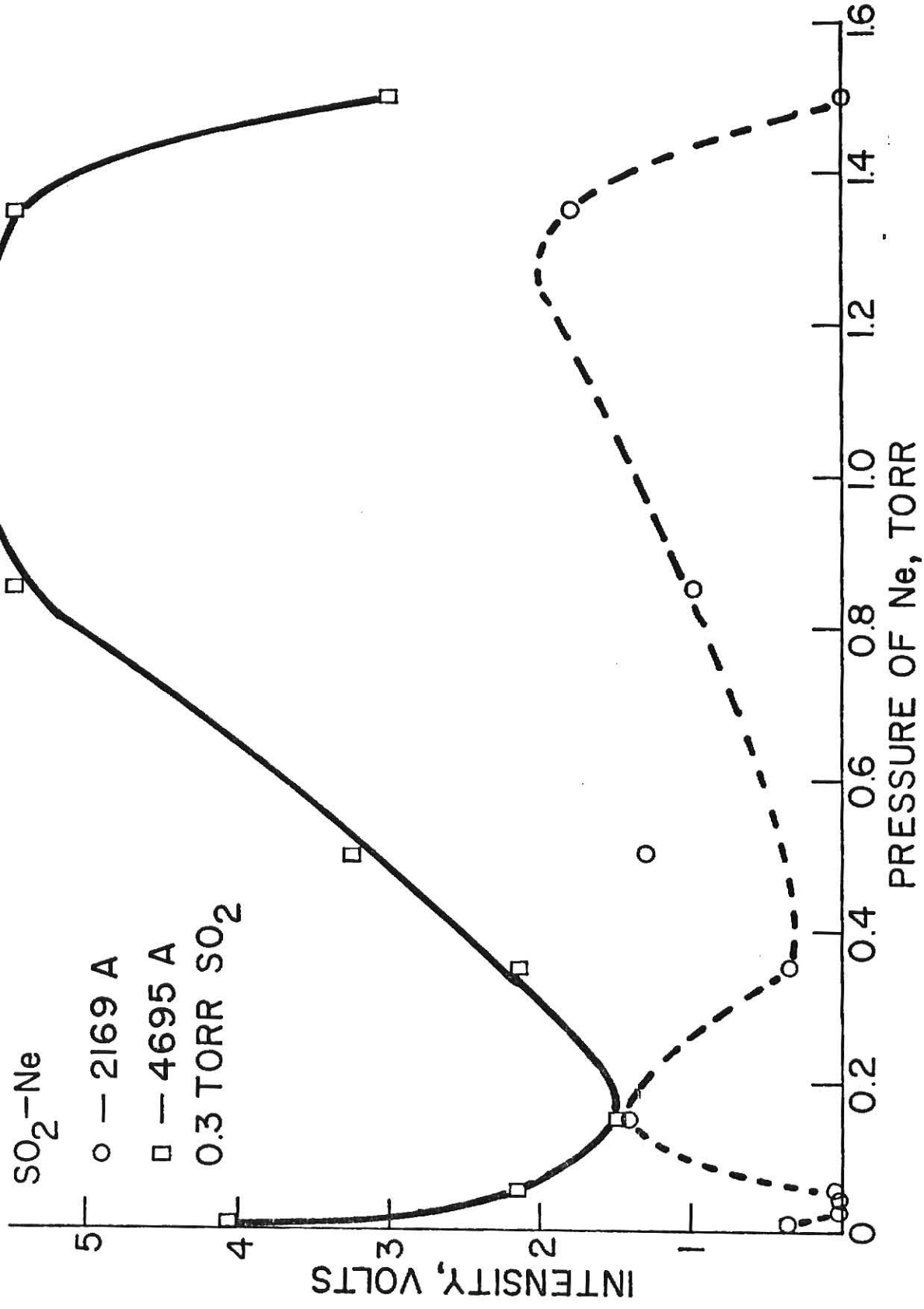

H2S–Xe
o — 2169 A
□ — 5454 A
0.3 TORR H2S
INTENSITY, VOLTS
PRESSURE OF Xe, TORR
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
0.2
0.4
0.6
0.8
1.0

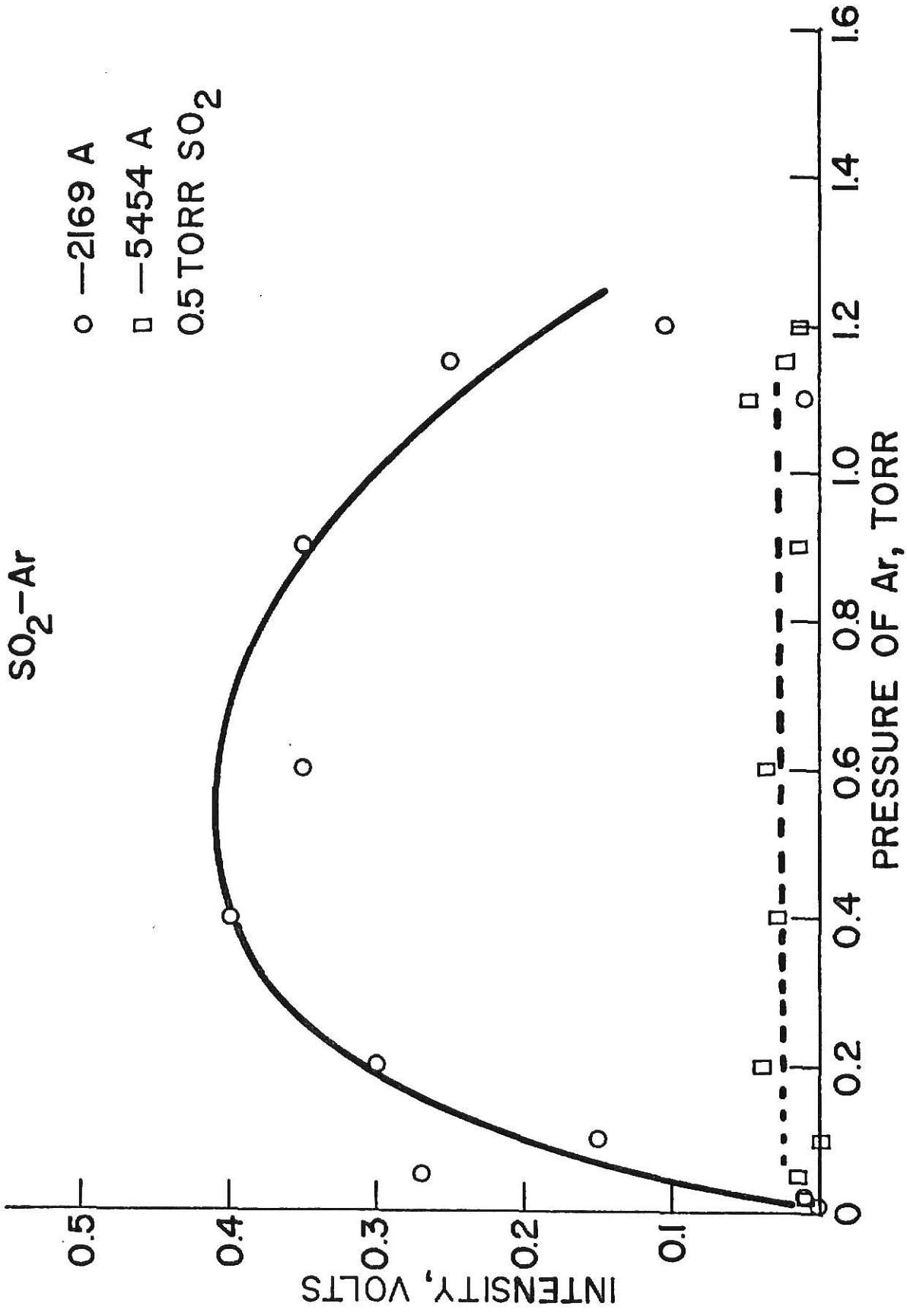

H_2S-Xe, 4695A
0.3 TORR H_2S
INTENSITY, VOLTS
PRESSURE OF Xe, TORR
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1
2
3
4
5

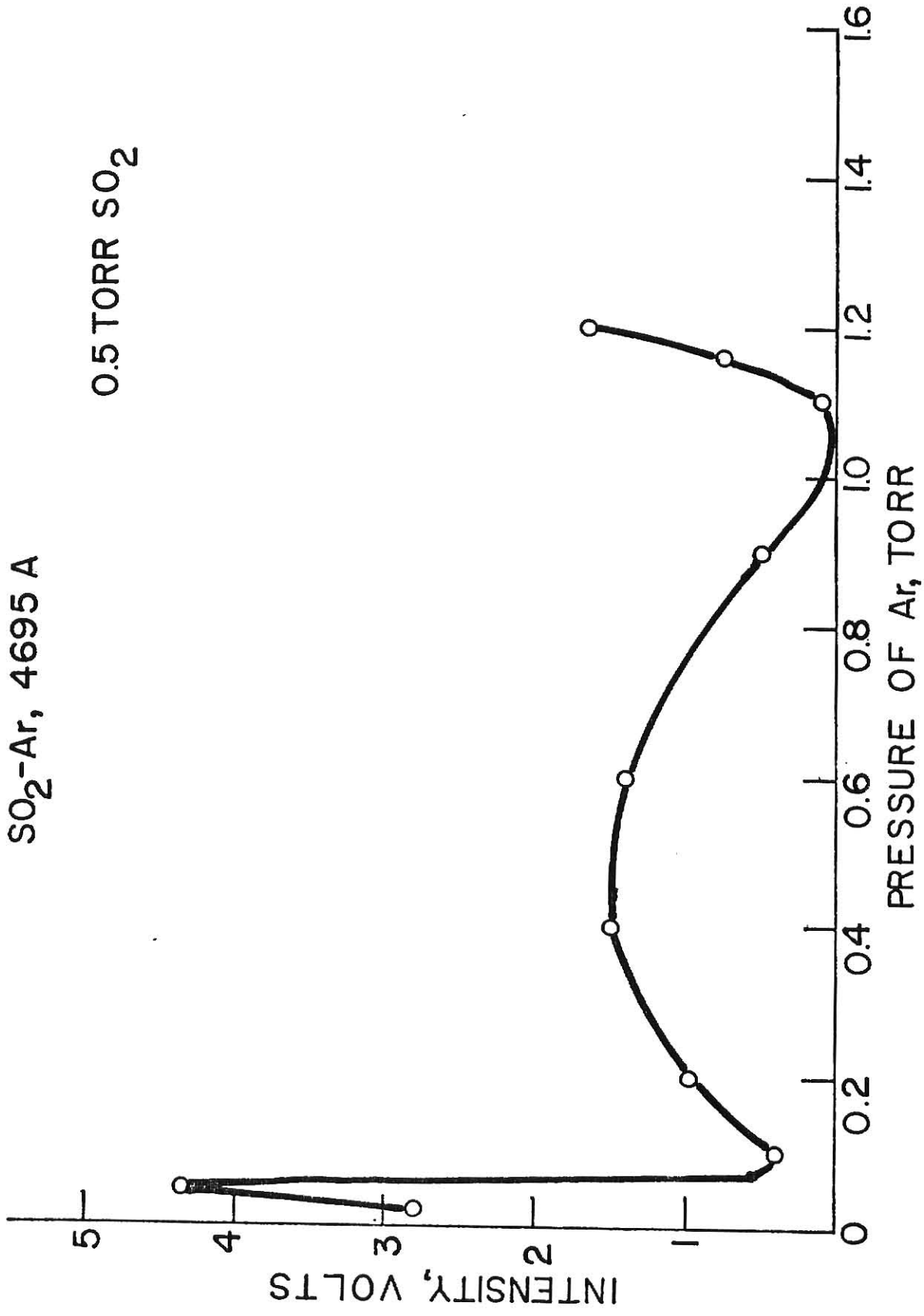
EXPLANATION: FIG. 24-26

24: Neon, 2169 A° and 4695 A°
25: Argon, 2169 A° and 5454 A°
26: Argon, 4695 A°

The intensities of these SO_2 containing lamps were plotted versus fill gas pressure.


SO_2–Ne
o — 2169 A
□ — 4695 A
0.3 TORR SO_2
INTENSITY, VOLTS
PRESSURE OF Ne, TORR
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1
2
3
4
5


SO_2–Ar
o —2169 A
□ —5454 A
0.5 TORR SO_2
INTENSITY, VOLTS
0.5
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
PRESSURE OF Ar, TORR


SO_2-Ar, 4695 A
0.5 TORR SO_2
INTENSITY, VOLTS
PRESSURE OF Ar, TORR
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1
2
3
4
5

krypton, and xenon produced many lamp failures with SO_2.

Na_2S and ZnS exhibited very weak sulfur emission. These lamps also exhibited a fairly high mortality rate. The intensities which were observed were located at approximately the same optimum fill gas pressures as previously observed. Figures 27-32 show this with the remaining data in Tables A-4 and A-5 of the appendix. The tail, which occurs at higher pressures, is probably due to increased sputtering which follows the increase in fill gas pressure.

CS_2 lamps were difficult to make because of the high volatility of this compound. The number of these lamps that ignited (Table A-6 of the appendix) was small, and those that did produced much lower intensities than the H_2S or elemental sulfur lamps; however they were more intense than ZnS or Na_2S lamps. One would expect CS_2 to dissociate to sulfur quite readily and give sulfur emission. Due to the volatility of CS_2, the pressure in the lamps was too unpredictible and prevented igniting of the lamp or gave non-uniform intensities in those that did ignite.

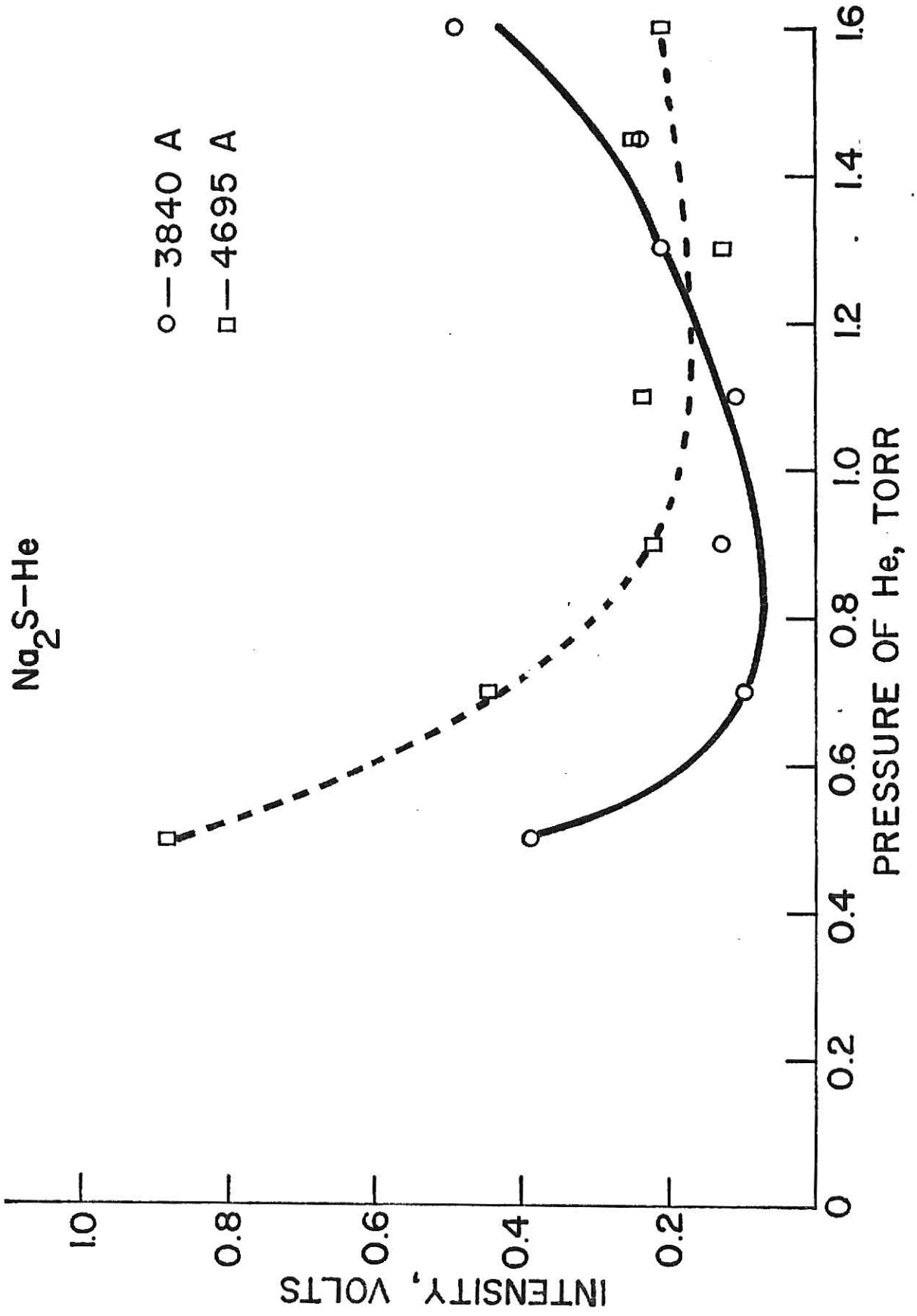
Figures 33-38 are representative curves showing the optimum pressures of the sulfur containing gases. The remaining data are in Tables A-2 and A-3 of the appendix. The optimum pressure varies for individual gases and wavelengths but was usually 0.3 to 0.5 torr.

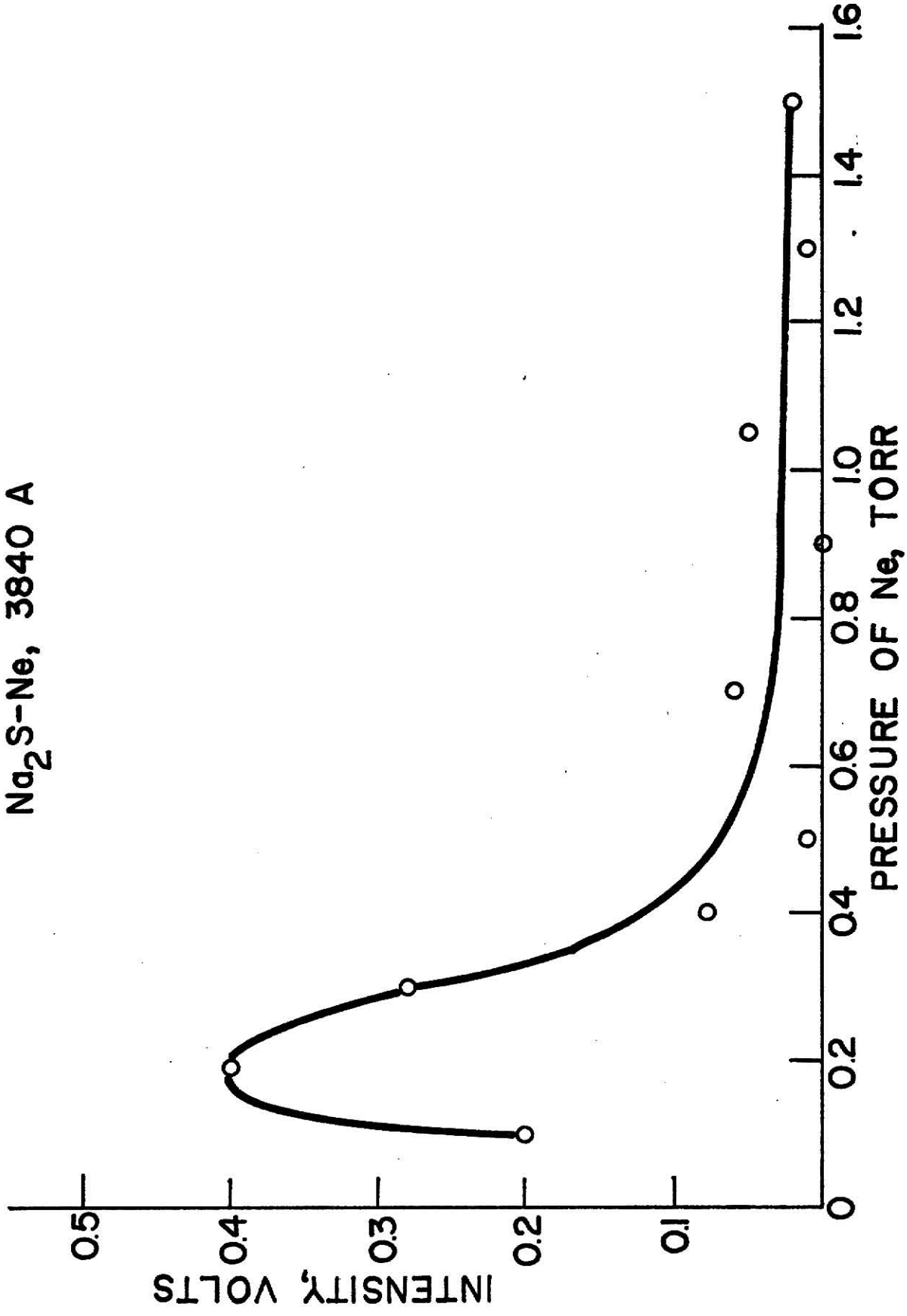
Inspection of the plots of intensity versus fill gas pressure indicates some scattered points. (It must be remembered that each point is a separate lamp.) These scattered points

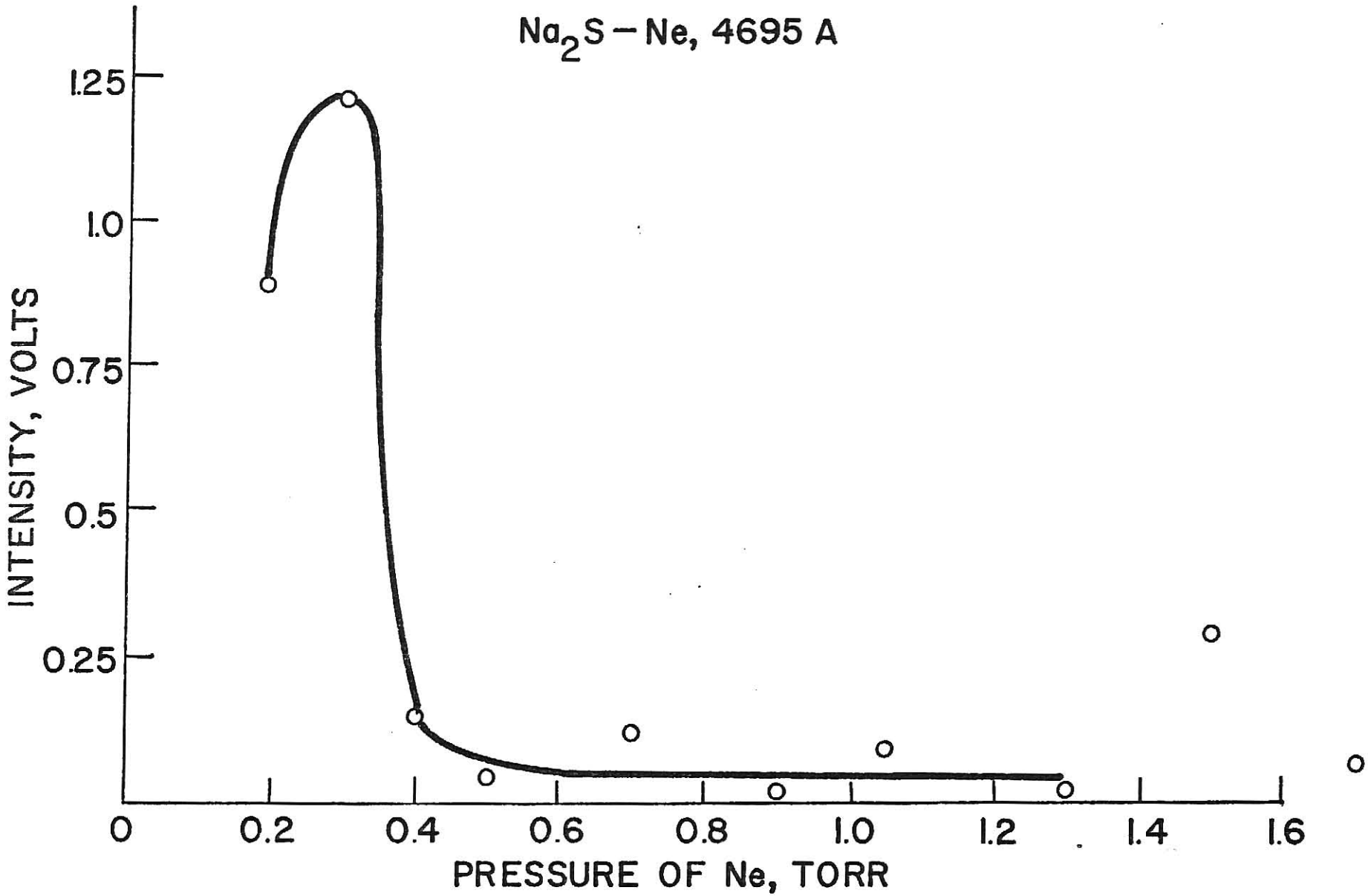
EXPLANATION: FIG. 27-29

27: Helium, 3840 A° and 4695 A°
28: Neon, 3840 A°
29: Neon, 4695 A°

The intensities of these Na_2S containing lamps were plotted versus fill gas pressure.


Na_2S–He
○—3840 A
□—4695 A
INTENSITY, VOLTS
0.2
0.4
0.6
0.8
1.0
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
PRESSURE OF He, TORR

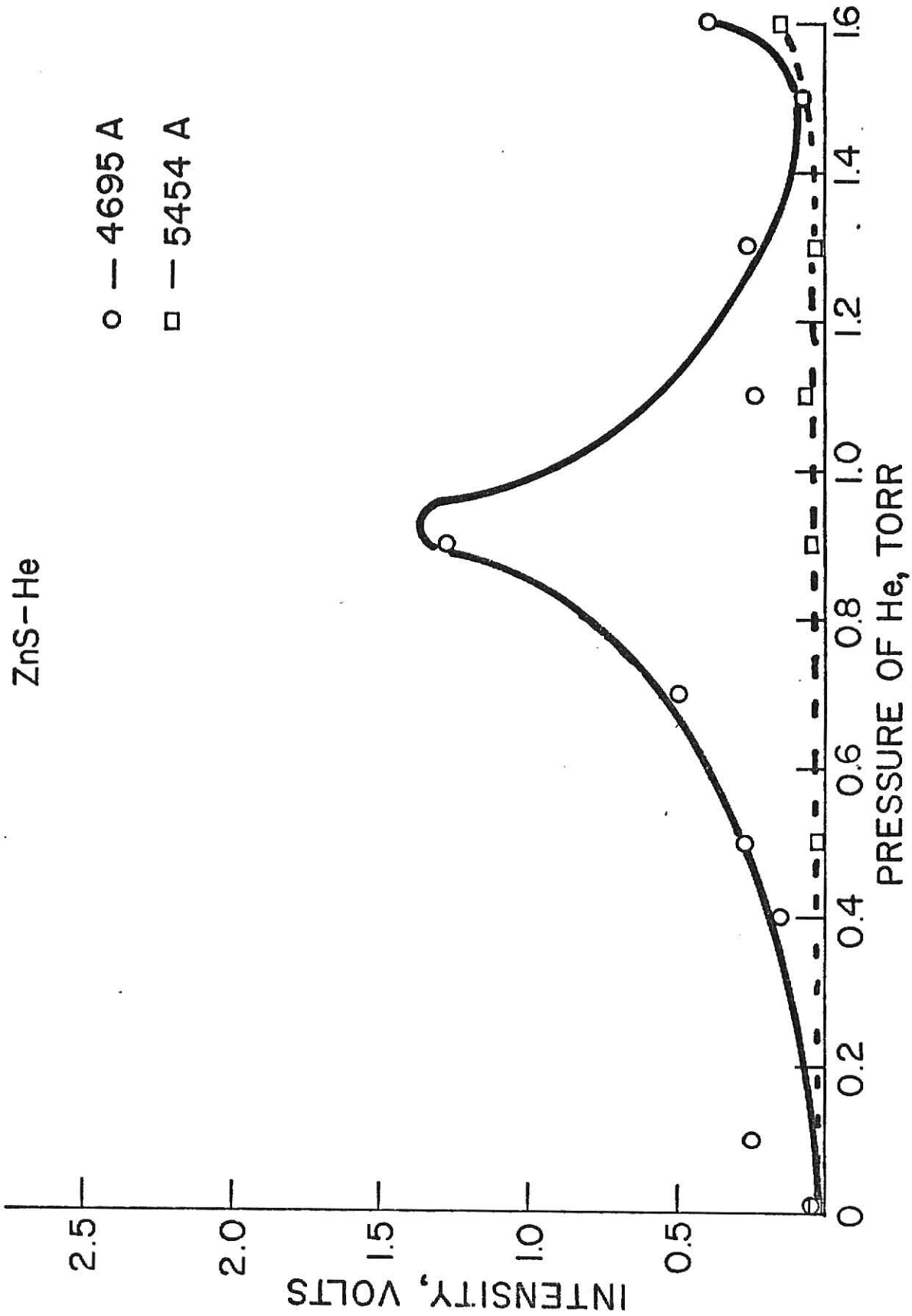

Na_2S-Ne, 3840 A
INTENSITY, VOLTS
0.5
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
PRESSURE OF Ne, TORR

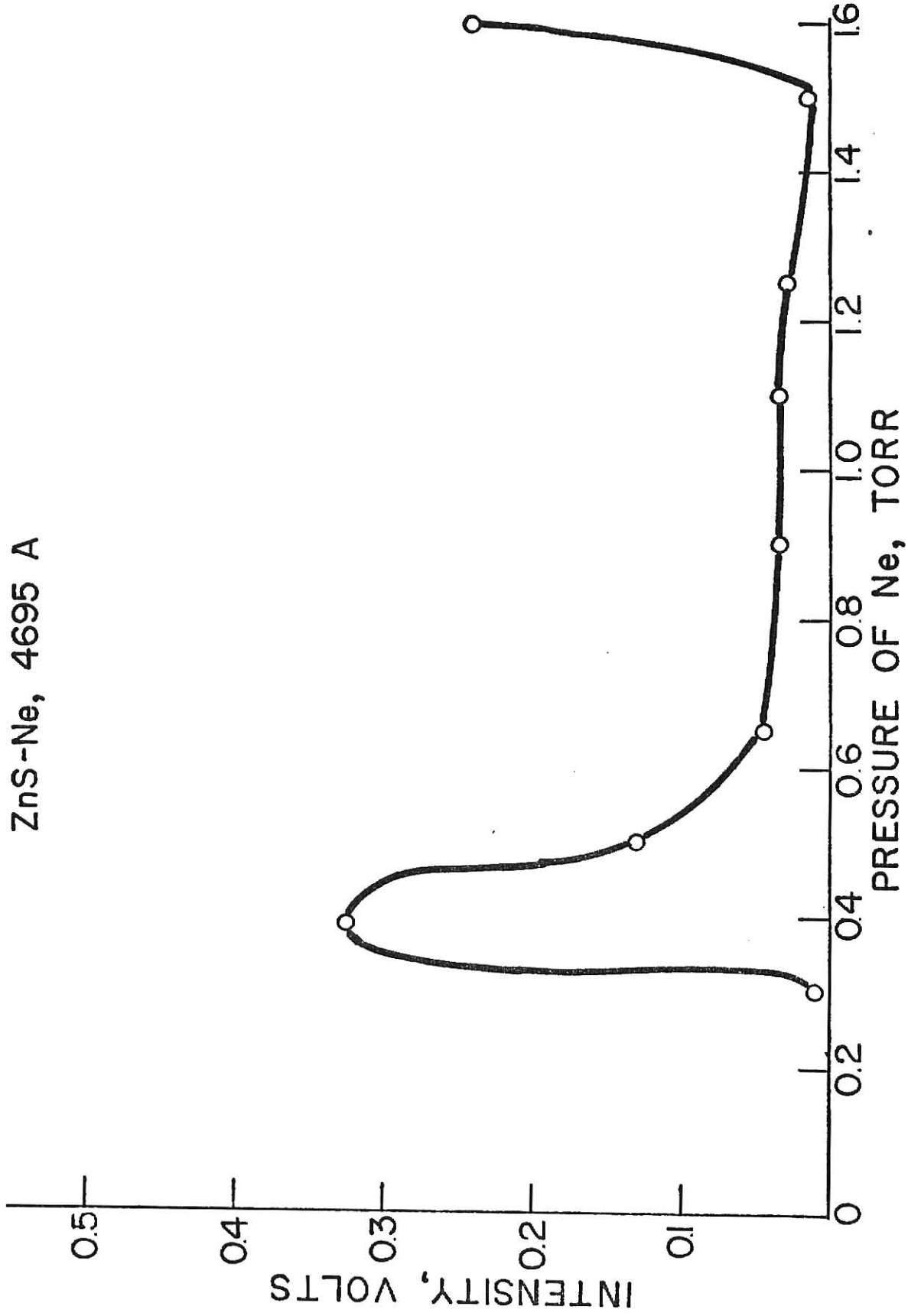

$Na_2S - Ne$, 4695 A
INTENSITY, VOLTS
1.25
1.0
0.75
0.5
0.25
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
PRESSURE OF Ne, TORR

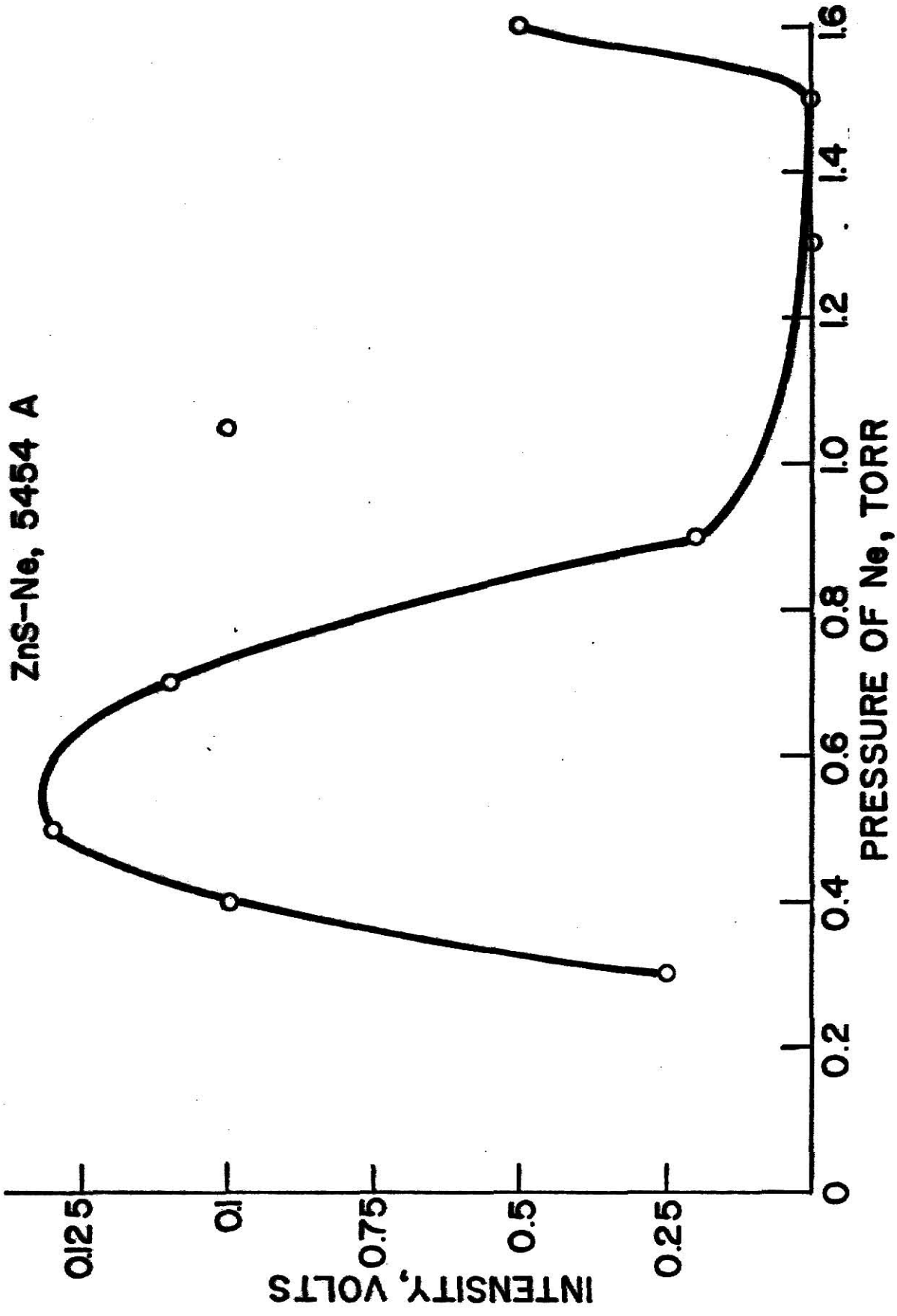
EXPLANATION: FIG. 30-32

30: Helium, 4695 A° and 5454 A°
31: Neon, 4695 A°
32: Neon, 5454 A°

The intensities of these ZnS containing lamps were plotted versus fill gas pressure.


ZnS–He
o — 4695 A
□ — 5454 A
INTENSITY, VOLTS
2.5
2.0
1.5
1.0
0.5
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
PRESSURE OF He, TORR

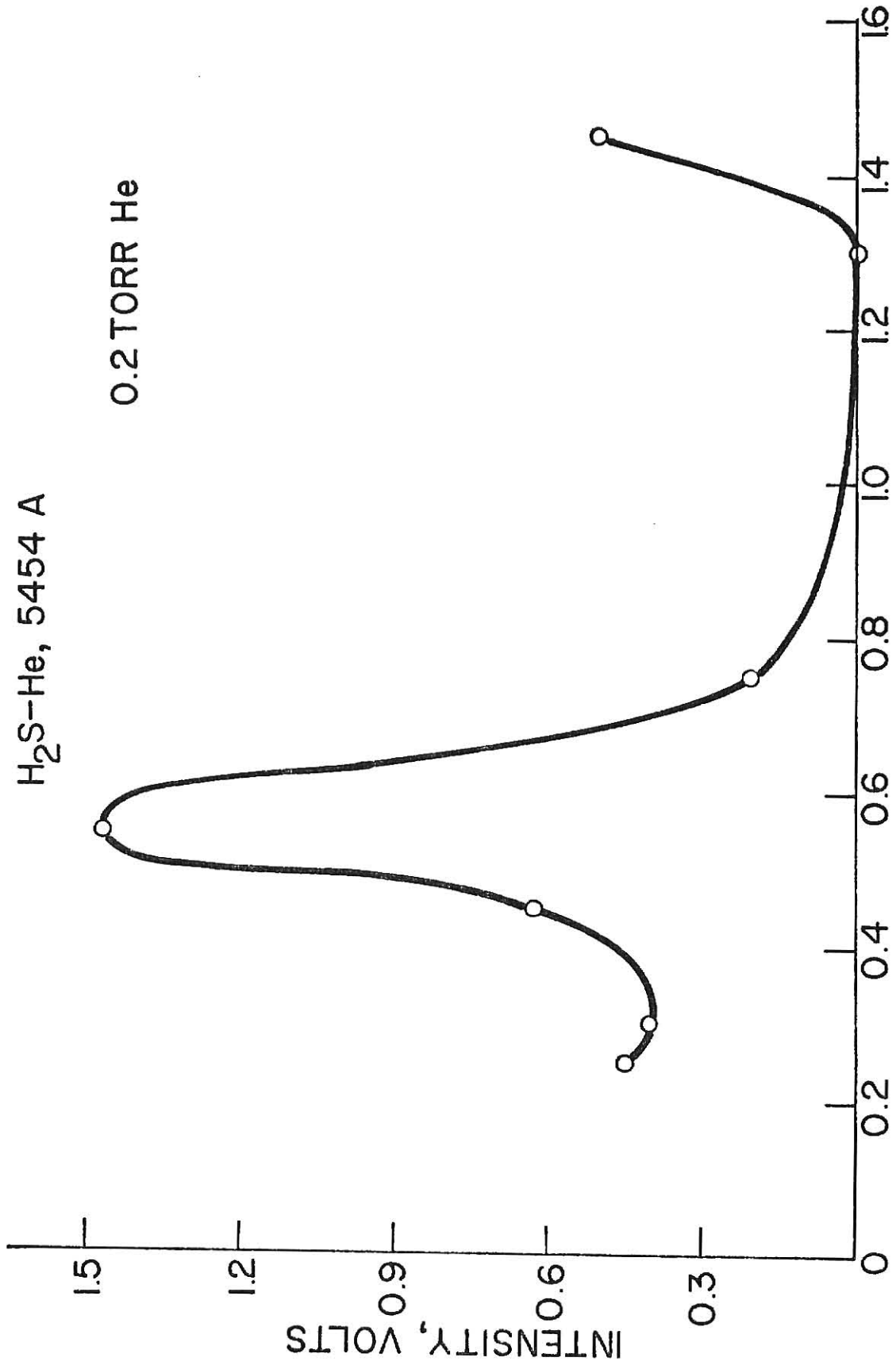

ZnS-Ne, 4695 A
INTENSITY, VOLTS
0.5
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
PRESSURE OF Ne, TORR

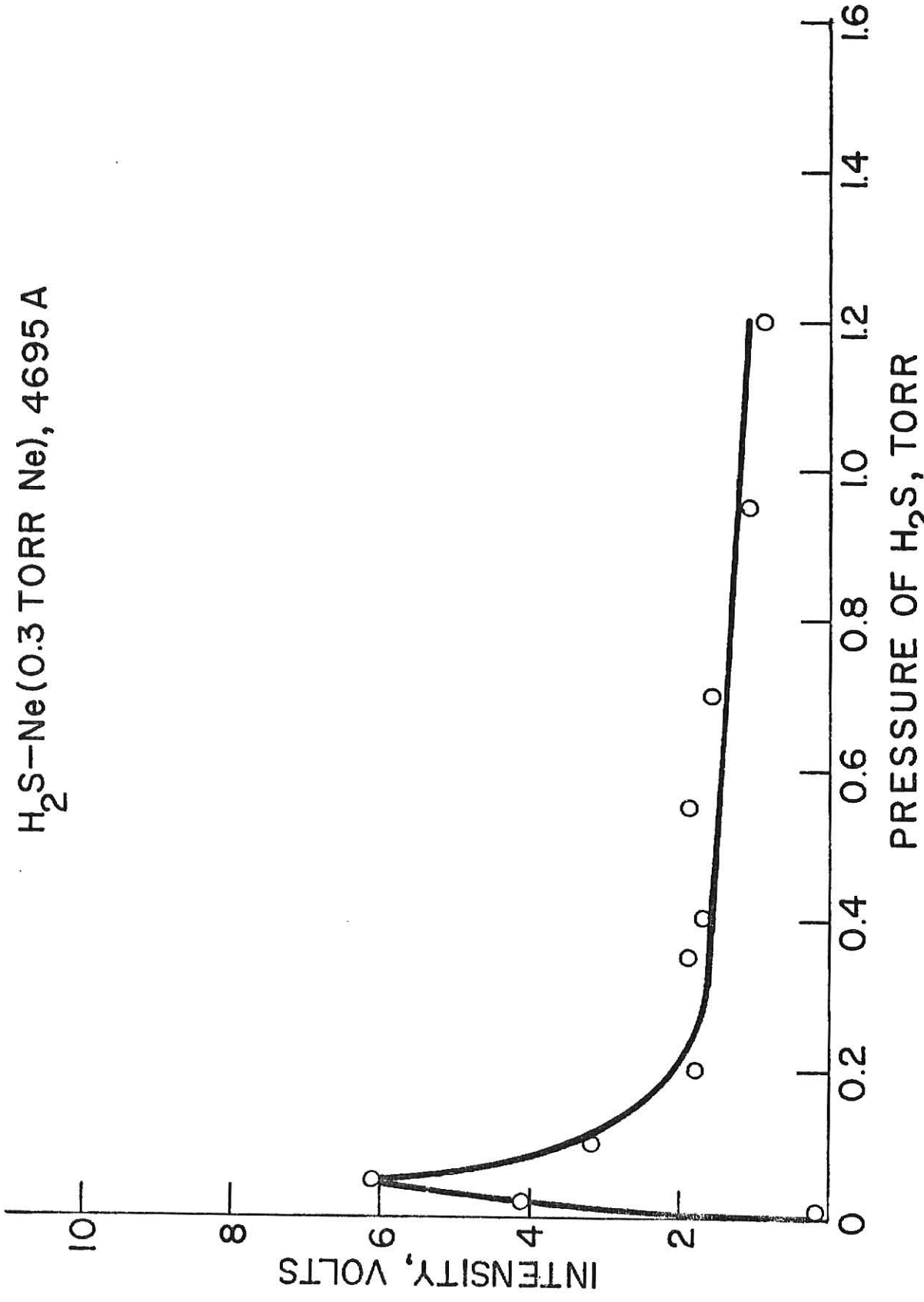

ZnS-Ne, 5454 A
INTENSITY, VOLTS
0.25
0.5
0.75
1.0
1.25
PRESSURE OF Ne, TORR
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6

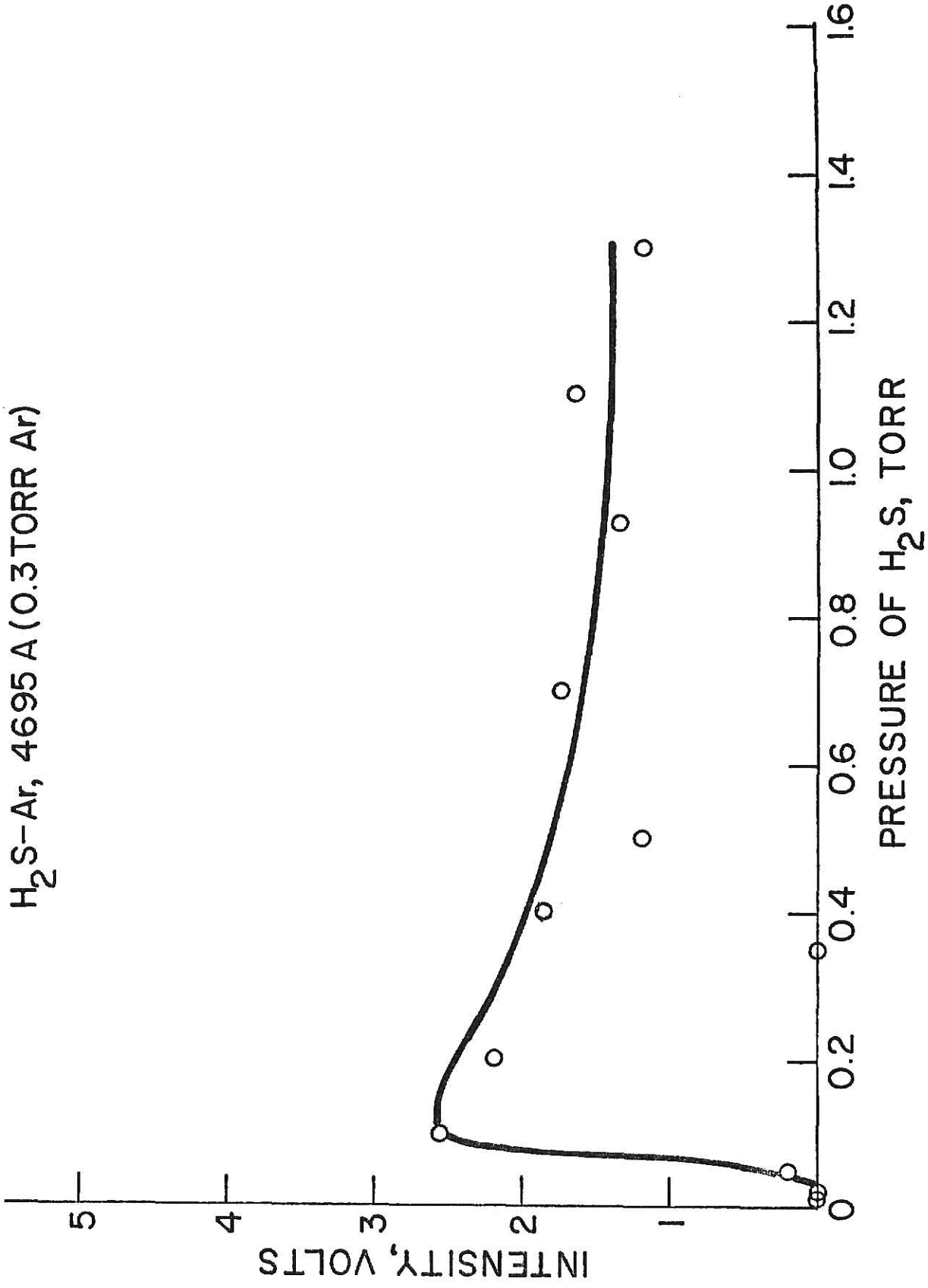
EXPLANATION: FIG. 33-38

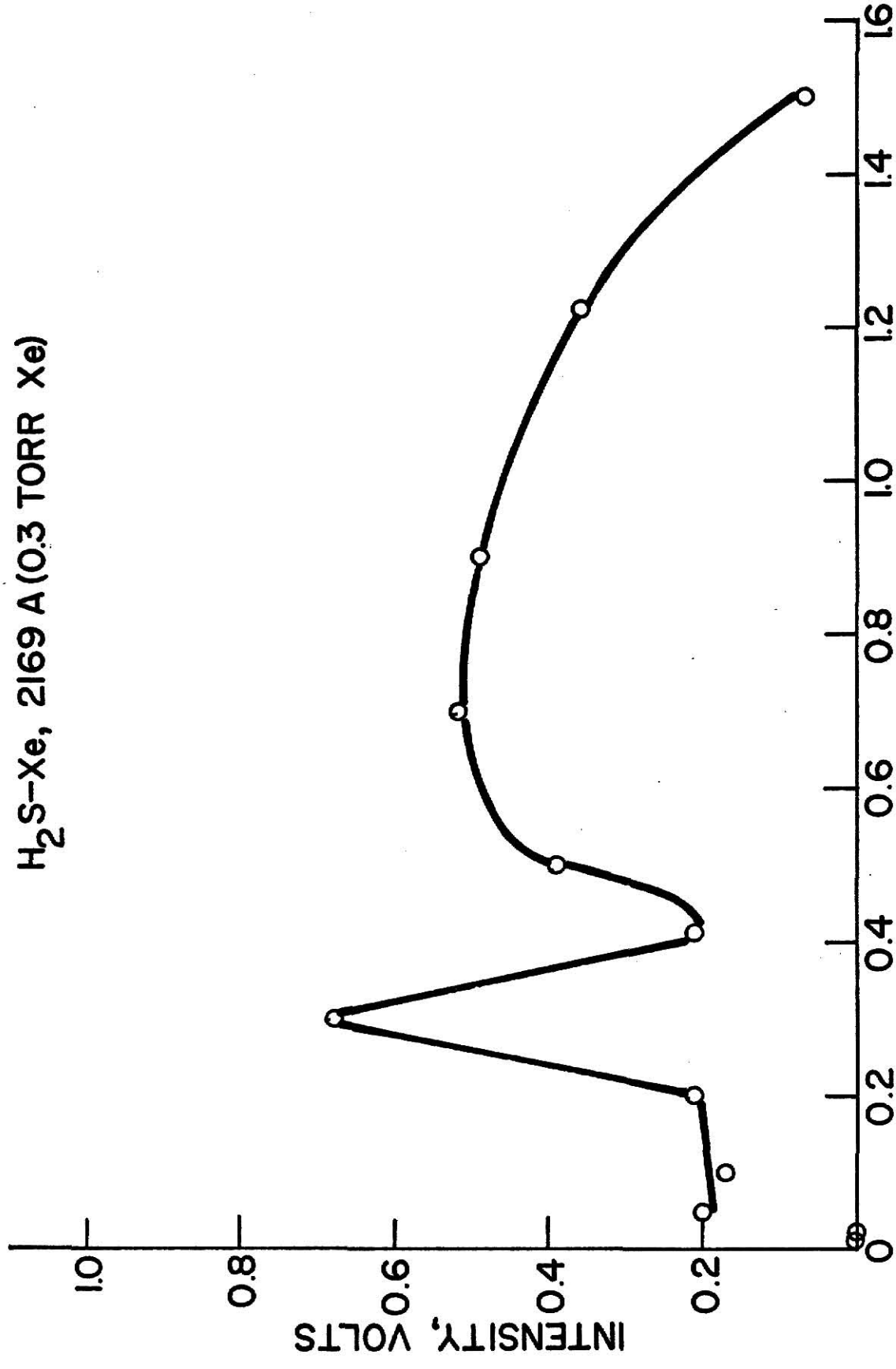
33: H_2S-He, 5454 A°
34: H_2S-Ne, 4695 A°
35: H_2S-Ar, 4695 A°
36: H_2S-Xe, 2169 A°
37: SO_2-Kr, 3840 A°
38: SO_2-Kr, 4695 A°

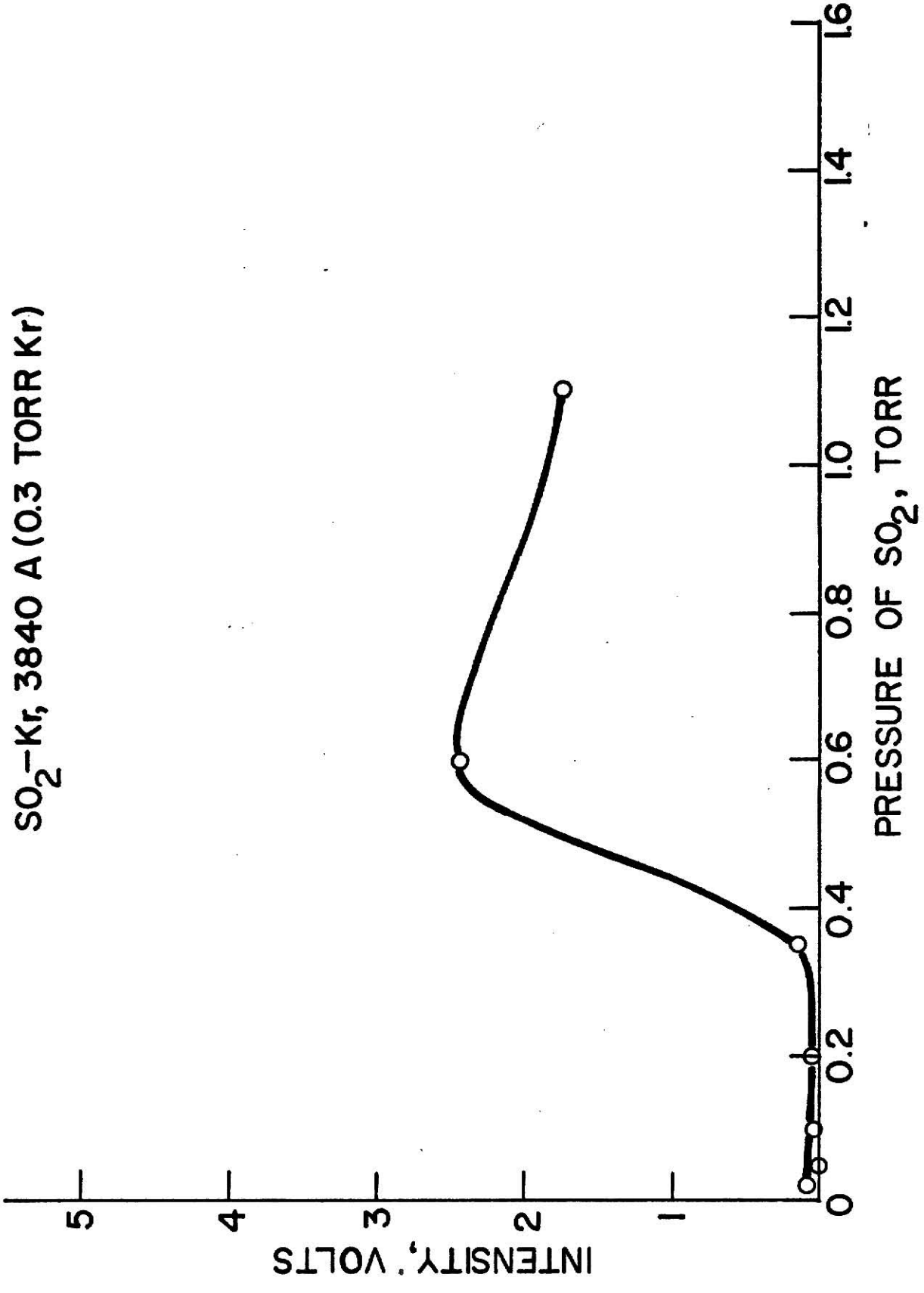
The sulfur gas pressure was varied and plotted versus the lamp intensity.

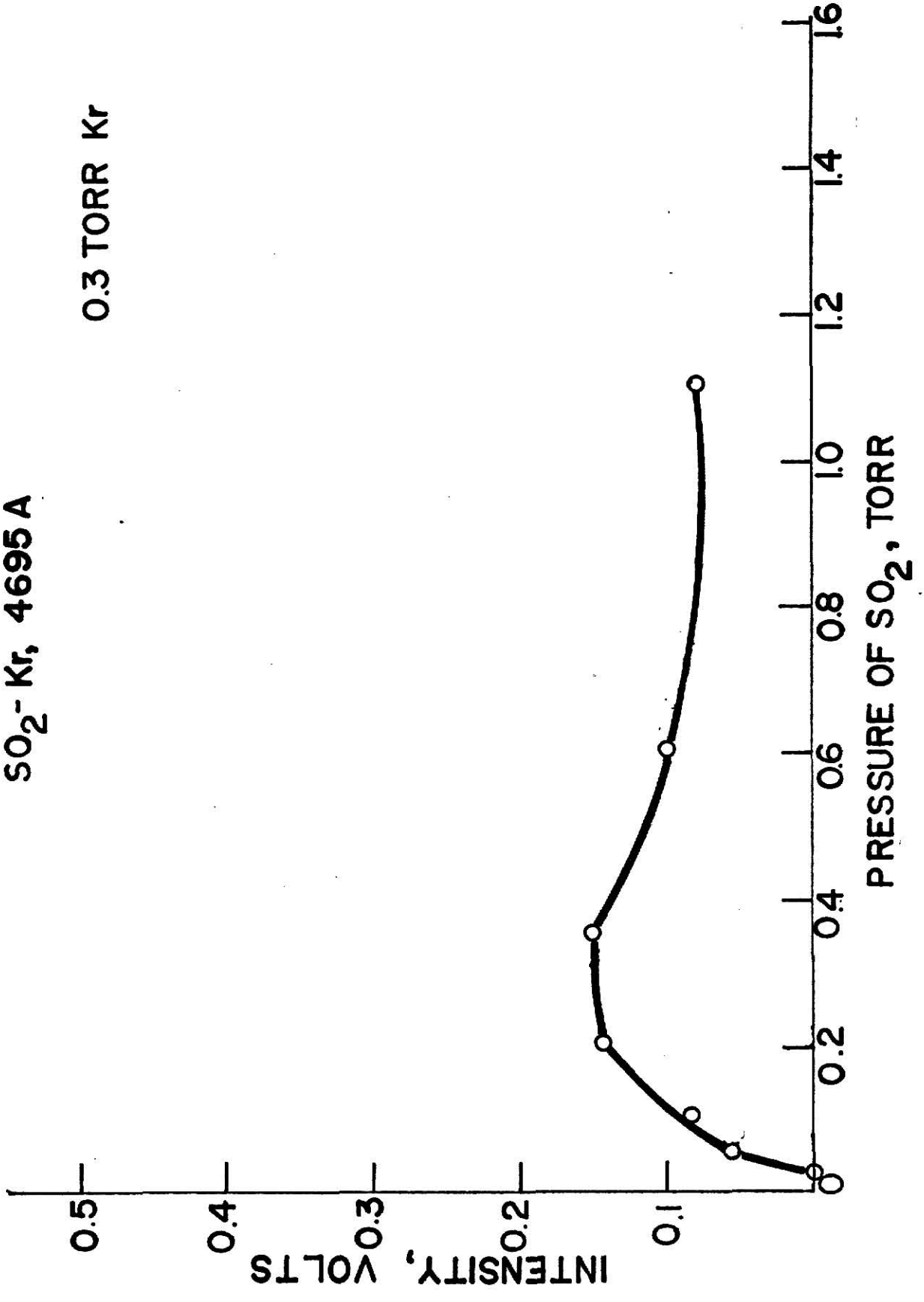

H_2S–He, 5454 A
0.2 TORR He
INTENSITY, VOLTS
1.5
1.2
0.9
0.6
0.3
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
PRESSURE OF H_2S, TORR


H_2S–Ne(0.3 TORR Ne), 4695 A
INTENSITY, VOLTS
PRESSURE OF H_2S, TORR
0
2
4
6
8
10
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6


H_2S-Ar, 4695 A (0.3 TORR Ar)
INTENSITY, VOLTS
5
4
3
2
1
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
PRESSURE OF H_2S, TORR


H_2S–Xe, 2169 A (0.3 TORR Xe)
INTENSITY, VOLTS
0.2
0.4
0.6
0.8
1.0
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
PRESSURE OF H_2S, TORR


SO_2–Kr, 3840 A (0.3 TORR Kr)
INTENSITY, VOLTS
0
1
2
3
4
5
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
PRESSURE OF SO_2, TORR


SO_2- Kr, 4695 A
0.3 TORR Kr
INTENSITY, VOLTS
0.1
0.2
0.3
0.4
0.5
PRESSURE OF SO_2, TORR
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6

could be in error because in manufacture it is difficult to control all variables. For example, the amount of sulfur compound in the lamp could be more critical than originally thought because of its volatility. Another factor, pointed out by Mansfield (65) in his study, is that the length (as it relates to volume) of the lamp is an important parameter in obtaining the maximum intensity. Since the lamps are hand blown, this is a difficult parameter to control precisely. Mansfield observed that small changes could be tolerated. Since he did not study sulfur, the length of the lamp could be more important in this case.

Temperature Effects

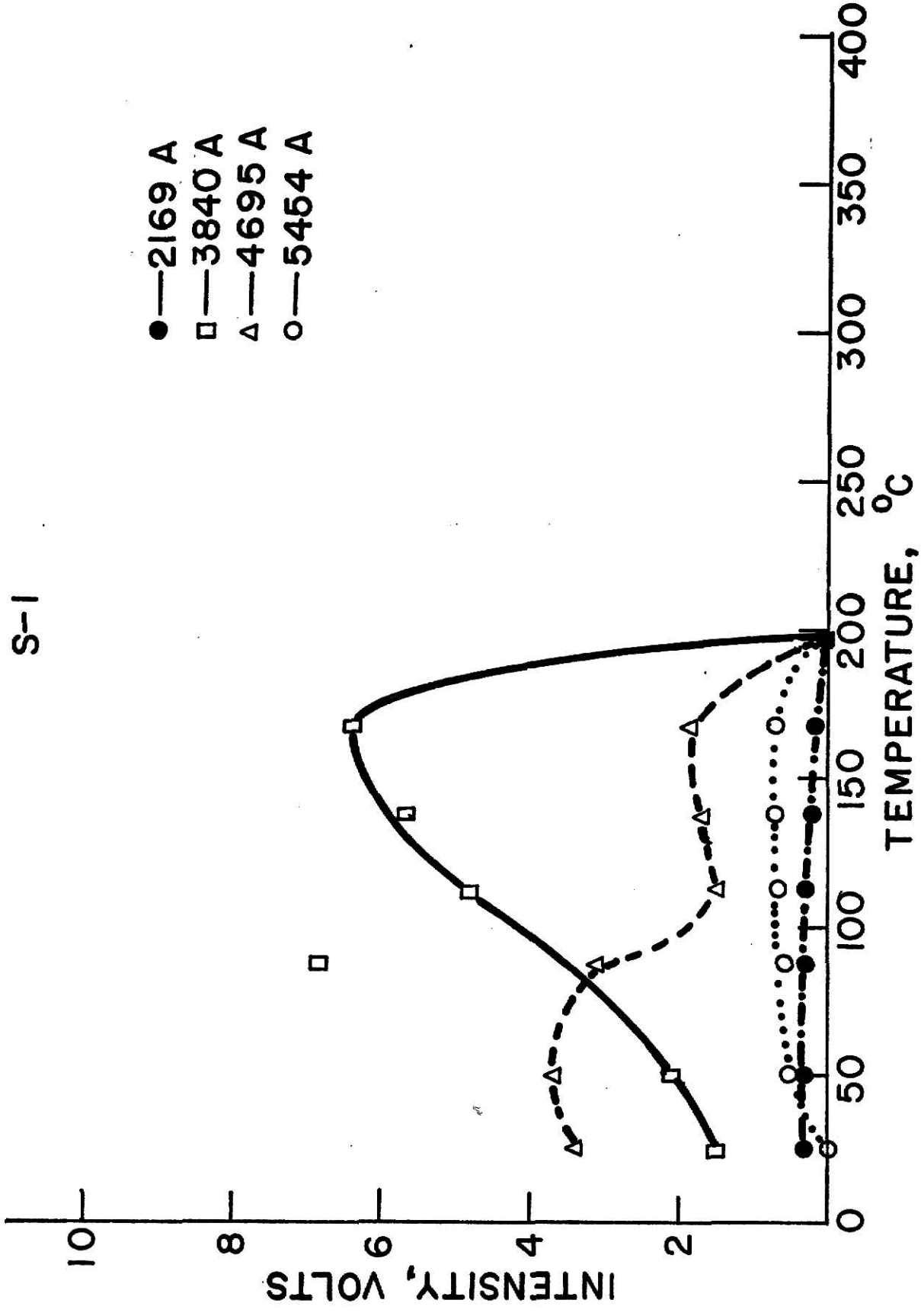
The next experiment was to place a 1.5 cm diameter-13 cm long quartz tube around the lamp for an air jacket. Quartz wool was placed in the top to minimize air currents. The lamps were operated at the same conditions as previously used for comparison. With the exception of very few lamps, the intensity was lowered (see Table A-7 of the appendix). In some cases the lamp would extinguish.

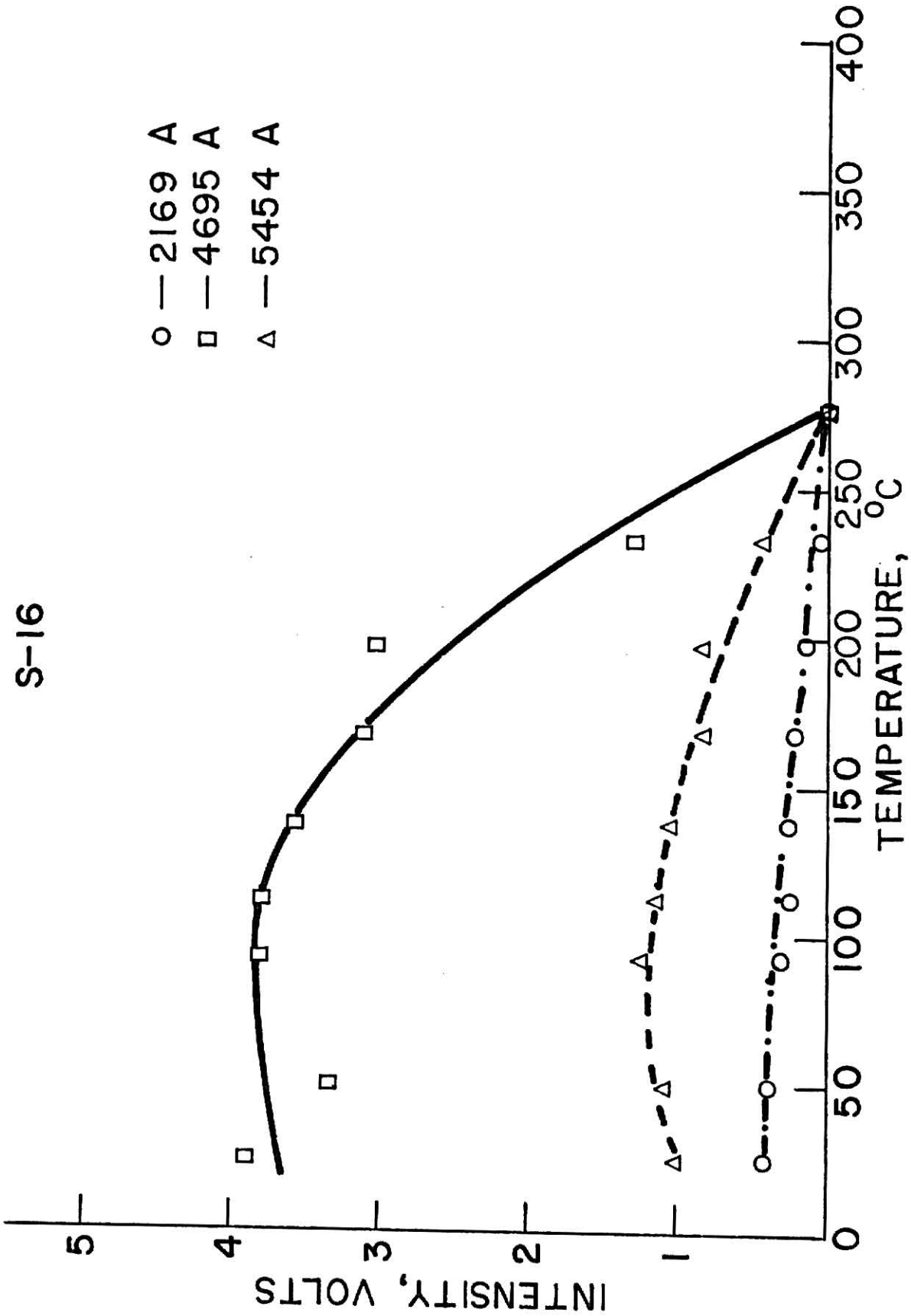
This was further confirmed with data presented in Figures 39-42, where intensity was measured as a function of temperature. The optimum temperature was the same for most wavelengths and was around 100-150°C depending on the lamp.

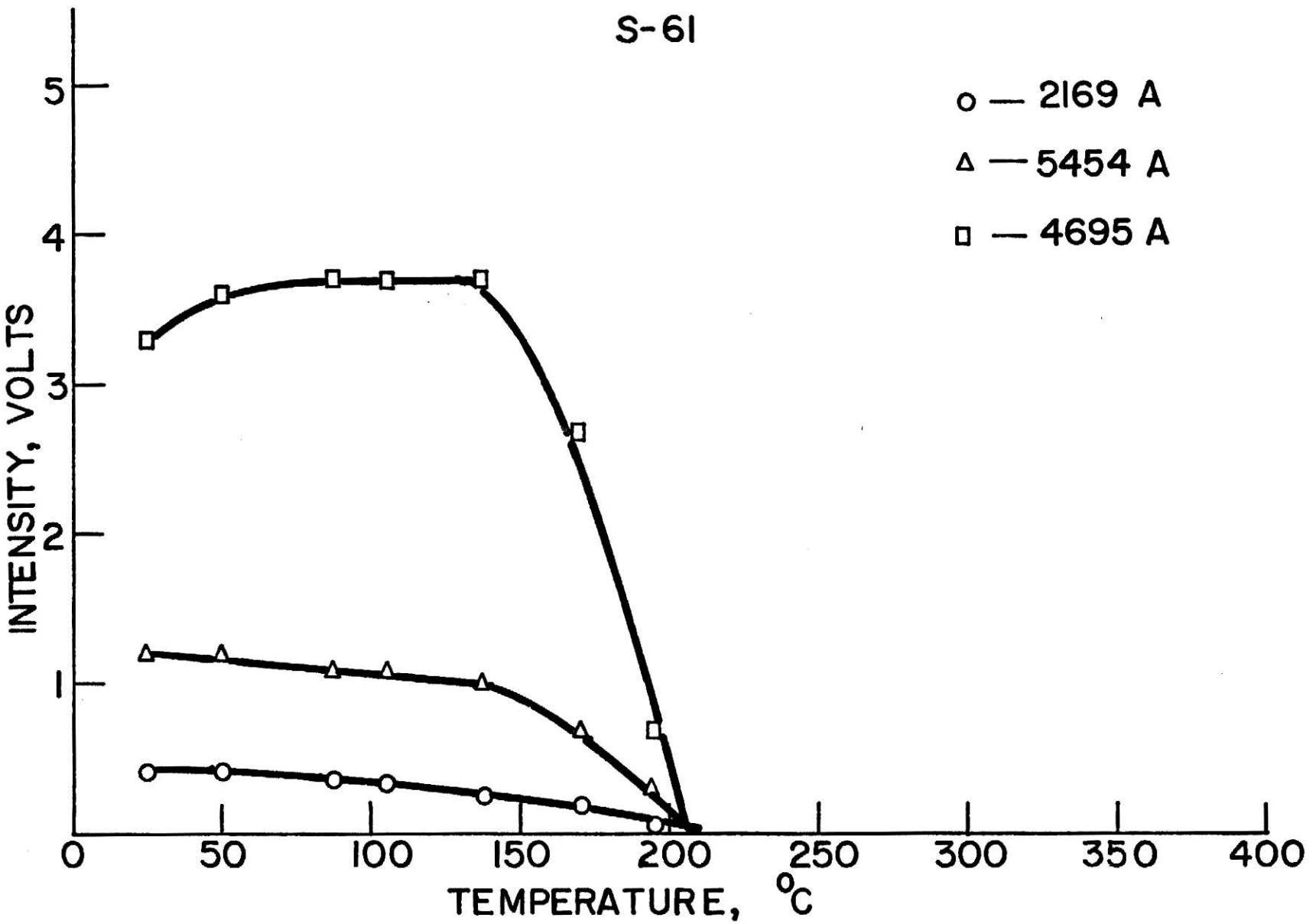
EXPLANATION: FIG. 39-42

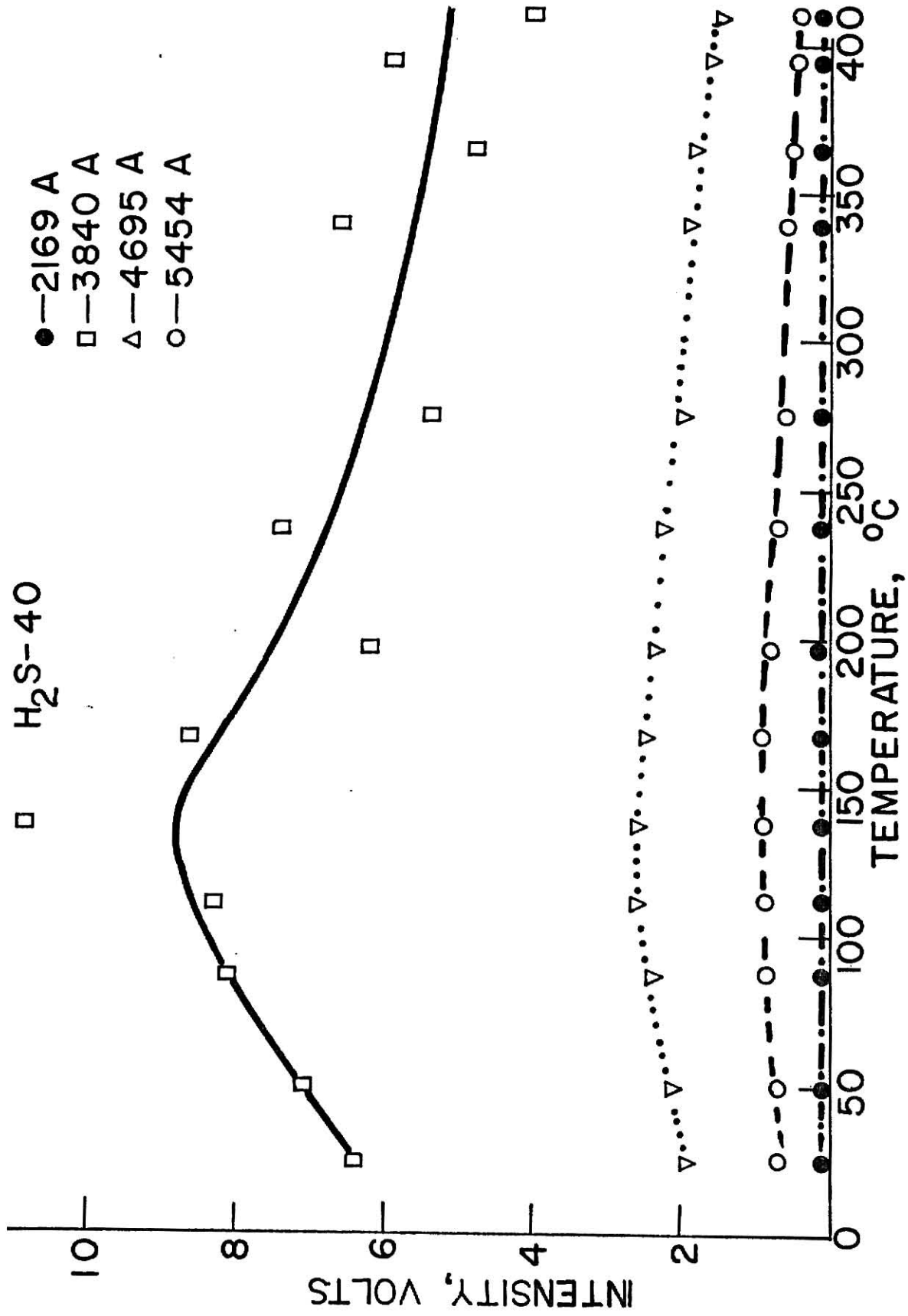
39: S-1
40: S-16
41: S-61
42: H_2S-40

The lamp intensity is plotted versus temperature.


S-1
●—2169 A
□—3840 A
△—4695 A
○—5454 A
INTENSITY, VOLTS
TEMPERATURE, °C
0
50
100
150
200
250
300
350
400
2
4
6
8
10


S-16
o — 2169 A
□ — 4695 A
Δ — 5454 A
INTENSITY, VOLTS
TEMPERATURE, °C
0
50
100
150
200
250
300
350
400
1
2
3
4
5


S-61
o — 2169 A
Δ — 5454 A
□ — 4695 A
INTENSITY, VOLTS
1
2
3
4
5
0
50
100
150
200
250
300
350
400
TEMPERATURE, °C


H2S-40
●—2169 A
□—3840 A
△—4695 A
○—5454 A
INTENSITY, VOLTS
TEMPERATURE, °C
0
50
100
150
200
250
300
350
400
2
4
6
8
10

Stability

The stability of several of the more intense lamps was determined in air for a period of one-half hour using the same settings as previously used. The drift in the intensity varied from two to four precent for the duration of the half hour. The lamps were given a five minute warm-up time.

Lamp Reproducibility

The next experiment was to determine how reproducible the lamps are. Two of the better lamps, one with elemental sulfur and one with H_2S, were each reproduced three times. The results of this study are shown in Table 1. The widely varying results observed may be due to differences in lamp volumes as stated by Mansfield (65). The amount of sulfur may also be contributing to the differences observed.

Table A-8 of the appendix shows the reproducibility of the intensity upon relighting the same lamp at a later time. The variation seen is a repositioning problem in most cases.

Atomic Absorption Study

Flameless atomic absorption was briefly studied using one of the better EDL's as a line source. Solutions of 2000 ppm H_2SO_4 and 0.1M Na_2S, and solid elemental sulfur were

Table 1: Reproducibility in manufacturing lamps.

EDL	2169 A	3840A	4695 A	5454 A
S	0.36	14.7	3.95	1.14
S′	0.4	8.7	2.42	0.78
S″	0.39	14.6	3.0	1.10
S‴	0.35	10.2	2.12	0.62
H_2S	0.39	9.5	6.35	0.75
H_2S'	0.68	6.4	2.86	0.52
H_2S''	1.46	1.3	8.5	0.1
H_2S'''	0.48	7.4	2.46	0.76

INTENSITY, VOLTS

atomized on a tantalum boat. Elemental sulfur was the only form of sulfur to give an absorption signal at any of the four wavelengths investigated. Lack of time prevented further investigation of sulfur absorption signals.

CONCLUSIONS

The electrodeless discharge lamps manufactured for this investigation have shown that intense line sources for sulfur can be made. Elemental sulfur or H_2S, with helium, neon, or argon as a fill gas will produce the most intense sulfur line sources.

Sulfur lamps have their maximum intensities at low temperatures. Temperature studies were preformed only on sulfur and H_2S containing lamps.

The reproducibility of the intensity upon relighting a lamp is good for most lamps. However reproducibility in remanufacturing a lamp is not good.

The lifetime of the lamps have not been studied rigorously. However it seems that the less intense lamps (ZnS, Na_2S, and some of the others) fail first. One of the more intense lamps has operated for 20 hours, of which 8 hours were continuous, without any problems.

The major problem at present is the stability of the lamp. A variation of 2 to 4 percent may be usable, but it should be closer to 0.25 percent to be truly acceptable.

Some preliminary studies using flameless techniques show absorption for elemental sulfur. Other results indicate that dissociation of sulfates, sulfides, and other sulfur containing compounds to produce atomic sulfur or S_2 is a very inefficient process.

APPENDIX

Table A-1. Lamps containing elemental sulfur.

Lamp	Fill gas pressure torr	Intensity 2169 A° volts	Intensity 3840A° volts	Intensity 4695 A° volts	Intensity 5454 A° volts
Helium					
S-1	1.6	0.8	7.0	5.5	0.96
S-2	0.95	0.25	7.45	2.0	0.25
S-3	0.45	0.32	5.8	2.05	0.37
S-4	0.21	0.5	14.7	4.8	0.55
S-5	0.1	0.62	14.7	4.55	1.05
S-6	0.05	0.29	14.7	2.75	0.9
S-7	0.25	0.24	9.0	1.65	0.3
S-8	0.01	0.58	14.7	3.9	1.35
Argon					
S-9	0.25	0.13	5.3	0.37	0
S-10	1.15	0.55	14.0	2.1	0.97
S-11	1.7	0.7	14.7	3.25	0.97
S-12	0.625	0.54	13.75	2.5	0.83
S-13	0.1	0.65	14.0	3.35	1.05
Neon					
S-14	0.125	0.15	14.7	3.15	0.5
S-15	0.55	0.4	6.0	3.95	1.4
S-16	1.0	0.36	14.7	3.95	1.5
S-17	1.7	0.21	10.5	2.55	0.95
Krypton					
S-18	0.425	0.66	3.1	1.55	0.34
S-19	0.225	0.78	5.5	1.95	0.51
S-20	0.125	0.67	5.9	3.5	0.76
S-21	0.05	0.74	5.5	3.25	0.63
S-22	1.15	0.46	2.5	3.1	0.43
S-23	0.7	0.8	5.0	0.75	0.47
S-24	1.7	0.41	0.14	2.4	0.04
S-25	1.275	0.35	1.95	0.32	0.18
S-26	0.9	0.57	3.45	1.04	0.25
S-27	0.8	0.4	11.9	1.2	0.32
S-28	0.025	0.24	6.5	0.98	0.43
S-29	0.01	0.24	11.5	1.9	0.68
Argon					
S-30	1.6	0.01	1.65	0.21	0.08
S-31	1.4	0.2	6.0	0.51	0.35

Lamp	Fill gas pressure torr	Intensity 2169 A° volts	Intensity 3840 A° volts	Intensity 4695 A° volts	Intensity 5454 A° volts
Argon					
S-32	1.0	0.29	7.35	2.57	0.73
S-33	0.8	0.37	3.05	2.82	0.63
S-34	0.5	0.36	4.5	1.78	0.62
S-35	0.2	0.27	8.15	3.11	0.8
S-36	0.05	0.75	8.9	2.95	0.75
S-37	0.025	0.46	1.95	2.47	0.33
S-38	0.01	0.66	10.2	3.65	1.13
Neon					
S-39	1.4	0.02	0.61	0.27	0.07
S-40	1.2	0.11	6.1	2.12	0.75
S-41	0.7	0.14	6.1	2.12	0.67
S-42	0.3	0.08	5.2	1.22	0.42
S-43	0.05	0.01	2.55	0.4	0.07
S-44	0.025	0.2	10.9	1.9	0.95
S-45	0.01	0.14	6.2	2.17	0.72
Helium					
S-46	0	0.03	0.31	0.4	0.03
S-47	0.8	0.61	4.45	2.83	0.68
S-48	0.6	0.35	4.15	2.72	0.73
S-49	0.3	0.55	6.3	3.25	0.89
Xenon					
S-50	1.7	0.72	2.65	0.8	0.25
S-51	1.5	0.03	0.3	0.02	
S-52	1.3	0.48	7.0	1.77	0.20
S-53	1.1	0.53	13.85	1.76	0.5
S-54	0.9	0.49	14.6	1.38	0.75
S-55	0.7	0.35	13.9	1.87	0.69
S-56	0.5	0.4	14.6	3.28	1.22
S-57	0.4	0.44	14.6	3.68	1.13
S-58	0.295	0.5	14.6	3.4	1.29
S-59	0.21	0.3	14.6	2.95	1.06
S-60	0.095	0.46	14.6	3.68	1.36
S-61	0.05	0.36	14.6	3.82	1.46
S-62	0.025	0.33	14.6	2.78	1.38
S-63	0.01	0.36	14.6	3.57	1.13

Table A-2. Lamps containing H_2S.

Lamp	Fill gas pressure torr	Intensity 2169 A° volts	Intensity 3840 A° volts	Intensity 4695 A° volts	Intensity 5454 A° volts
Helium, 0.2 torr, vary the pressure of H_2S.					
H_2S-1	0.55	0.43	13.75	4.5	0.85
H_2S-2	0.3	1.19	7.7	13.9	———
H_2S-3	0.1	———	———	———	———
H_2S-4	1.3	0.13	0.04	1.0	0.07
H_2S-5	0.275	0.45	13.6	3.3	0.18
H_2S-6	0.45	0.7	11.3	3.1	0.38
H_2S-7	0.75	0.3	3.85	1.43	0.15
H_2S-8	1.45	0.34	10.0	1.33	0.15
Helium, 0.3 torr of H_2S					
H_2S-9	0.1	0.45	4.55	3.55	0.1
H_2S-10	0.3	0.67	12.0	4.4	0.55
H_2S-11	0.5	0.25	0.17	0.03	0
H_2S-12	1.0	0.69	1.33	9.5	0
H_2S-13	1.325	0.84	6.95	5.05	0.23
Argon, 0.3 torr of H_2S					
H_2S-14	1.1	2.75	1.75	0.1	
H_2S-15	0.675	0.27	1.5	0	
H_2S-16	0.1	3.75	1.85	0.28	
H_2S-17	0.5	5.45	4.25	0.48	
Argon, 0.5 torr of H_2S					
H_2S-18	0.5	5.4	1.3	0.12	
H_2S-19	0.725	2.8	0.75	0.05	
H_2S-20	1.0	7.85	1.1	0	
Neon, 0.3 torr of H_2S					
H_2S-21	0.1	0.43	0.67	0.19	0.09
H_2S-22	0.6	0.71	0.5	0.3	0.04
H_2S-23	0.925	0.38	0.8	0.14	0.04
H_2S-24	1.4	0	0.09	0.03	0.02
H_2S-25	0.05	0.22	1.1	0.1	0.13

Lamp	Fill gas pressure torr	Intensity 2169 A° volts	Intensity 3840 A° volts	Intensity 4695 A° volts	Intensity 5454 A° volts
Krypton, 0.5 torr, vary the pressure of H_2S					
H_2S-26	0.3	0.09	0.2	0.95	0.41
H_2S-27	0.6	0	0.3	0.3	0.05
H_2S-28	1.05	0.03	0.18	0.91	0.11
Krypton, 0.3 torr of H_2S					
H_2S-29	0.1	0.36	0.3	2.3	0.11
H_2S-30	0.3	0.58	0.2	3.4	0.13
H_2S-31	0.75	0.02	0.1	0.5	0.13
H_2S-32	1.3	0	0.15	1.4	0.15
H_2S-33	0.05	0.65	8.2	1.64	0.42
H_2S-34	0.2	0.27	0.75	2.09	0.22
H_2S-35	0.95	0.57	6.4	2.55	0.3
H_2S-36	1.4	0.25	1.95	1.76	0.14
Argon, 0.3 torr of H_2S					
H_2S-37	0.01	0.35	4.6	1.62	0.54
H_2S-38	0.025	0.35	7.4	2.32	1.01
H_2S-39	0.05	0.38	5.1	1.99	0.68
H_2S-40	0.1	0.39	9.5	6.35	0.76
H_2S-41	0.2	0.54	7.2	2.45	0.78
H_2S-42	0.3	0.59	2.0	1.5	0.17
H_2S-43	0.4	0.6	3.9	1.55	0.23
H_2S-44	0.525	0.68	0.43	1.65	0.07
H_2S-45	0.75	5.0	0.35	0.18	0.06
H_2S-46	0.975	1.75	0.73	0.7	0.02
H_2S-47	1.1	3.7	5.35	0.55	0.19
H_2S-48	1.4	3.4	0.28	0.02	0
Neon, 0.3 torr of H_2S					
H_2S-49	0.3	0.61	2.4	1.85	0.2
H_2S-50	0.5	0.39	1.28	1.35	0.08
Helium, 0.3 torr of H_2S					
H_2S-51	0.05	0.03			
H_2S-52	0.7	0.09	4.35	1.88	0.32
H_2S-53	0.95	0	0.18	0.64	0.04
H_2S-54	1.125	0.05	1.88	1.23	0.19
H_2S-55	1.4	0.07	1.33	1.28	0.16
Helium, 0.2 torr, vary the pressure of H_2S					
H_2S-56	0.1	1.8	2.9	3.82	
H_2S-57	0.3	0.36	3.4	1.58	0.41

Lamp	Fill gas pressure torr	Intensity 2169 A° volts	Intensity 3840 A° volts	Intensity 4695 A° volts	Intensity 5454 A° volts
Xenon, 0.3 torr of H_2S					
H_2S-58	0.01	0.28	6.0	1.65	0.23
H_2S-59	0.025	0.42	8.75	1.95	0.55
H_2S-60	0.05	0.83	3.65	2.85	0.2
H_2S-61	0.1	0.32	10.0	2.15	0.68
H_2S-62	0.225	0.28	2.15	2.15	0.29
H_2S-63	0.3	0.42	11.7	2.45	0.73
H_2S-64	0.4	0.44	13.0	0.62	0.58
H_2S-65	0.5	0.29	5.15	0.6	0.26
H_2S-66	0.7	0.61	0.99	0.14	0.04
H_2S-67	0.96	0.82	3.9	0.75	0.29
H_2S-68	1.09	0.5	0.9	0.43	0
H_2S-69	1.25	0.7	1.1	0.43	0
Xenon, 0.3 torr, vary the pressure of H_2S					
H_2S-70	0.01	0	0	0	0
H_2S-71	0.25	0	0	0	0
H_2S-72	0.05	0.2	3.45	0,22	0.02
H_2S-73	0.11	0.18	3.1	0.9	0
H_2S-74	0.21	0.21	10.0	1.73	0.53
H_2S-75	0.3	0.68	6.6	1.8	0.5
H_2S-76	0.425	0.21	9.2	0.98	0.55
H_2S-77	0.5	0.39	9.75	1.38	0.38
H_2S-78	0.7	0.52	7.95	1.38	0.48
H_2S-79	0.9	0.49	9.75	1.33	0.49
H_2S-80	1.24	0.37	8.25	1.18	0.47
H_2S-81	1.5	0.07	3.15	0.53	0.5
Argon, 0.3 torr, vary the pressure of H_2S					
H_2S-82	0.01	0	0.05	0	
H_2S-83	0.025	0	0.02	0	0
H_2S-84	0.05	0	0.68	0.18	0.04
H_2S-85	0.1	0	1.95	2.55	0.03
H_2S-86	0.2	0.23	4.45	2.1	1.05
H_2S-87	0.35	0.01	0.48	0	
H_2S-88	0.4	0.1	2.56	1.88	0.38
H_2S-89	0.5	0.27	1.95	1.16	0.46
H_2S-90	0.7	0.47	1.55	1.78	0.72
H_2S-91	0.925	0.26	0.65	1.33	0.58
H_2S-92	1.1	0.31	2.35	1.67	0.44
H_2S-93	1.3	0.21	1.75	1.18	0.42

Lamp	Fill gas pressure torr	Intensity 2169 A° volts	Intensity 3840 A° volts	Intensity 4695 A° volts	Intensity 5454 A° volts
Neon, 0.3 torr, vary the pressure of H_2S					
H_2S-94	0.025	0.02	0.16	0.25	0.08
H_2S-95	0.05	0.63	0.25	4.15	0.09
H_2S-96	0.085	0.22	2.55	6.15	0.31
H_2S-97	0.1	0.4	0.65	3.25	0.04
H_2S-98	0.2	0.32	2.5	1.85	0.37
H_2S-99	0.325	0.45	2.65	1.85	0.47
H_2S-100	0.4	0.49	1.75	1.68	0.49
H_2S-101	0.575	0.38	1.05	1.83	0.54
H_2S-102	0.7	0.47	1.15	1.59	0.54
H_2S-103	0.925	0.21	3.35	1.1	0.48
H_2S-104	1.125	0.15	3.0	0.88	0.4
H_2S-105	1.4	0.06	5.25	0.88	0.3

Table A-3. Lamps containing SO_2

Lamp	Fill gas pressure torr	Intensity 2169 A° volts	Intensity 3840 A° volts	Intensity 4695 A° volts	Intensity 5454 A° volts
Helium, 0.5 torr of SO_2					
SO_2-1	0.2				
SO_2-2	0.45				
SO_2-3	0.6	0.04	0.12	0.06	0
SO_2-4	0.1				
Helium, 0.2 torr, vary the pressure of SO_2					
SO_2-5	0.2	0.04			
SO_2-6	0.95	0.16			
SO_2-7	0.475	0.16			
SO_2-8	1.425	0.15	7.55	0.5	0.45
Argon, 0.5 torr of SO_2					
SO_2-9	1.1	0.02	0.1	0.11	0
SO_2-10	0.2	0.3	0.4	0.98	0.05
SO_2-11	0.4	0.4	0.26	1.5	0.02
SO_2-12	0.9	0.35	0.26	0.5	0.01
SO_2-13	0.1	0.15	0	0.4	0
SO_2-14	0.6	0.35	0.37	1.4	0.02
SO_2-15	1.15	0.25	0.3	0.75	0
Neon, 0.3 torr of SO_2					
SO_2-16	0.35	0.29	1.9	2.15	0.2
SO_2-17	0.5	1.25	0.7	3.25	0
SO_2-18	0.85	1.0	1.9	5.55	0.65
SO_2-19	1.35	1.8	0.85	5.65	0.25
SO_2-20	0.125	1.5	0.6	1.55	0
Krypton, 0.3 torr of SO_2					
SO_2-20'	0.6	0	2.1	2.0	0.15
SO_2-21	1.05	0	0.5	0.3	0.08
SO_2-22	2.0	0	0.12	0	0.11
SO_2-23	0.3	0	11.0	0.33	0.16

Lamp	Fill gas pressure torr	Intensity 2169 A^0 volts	Intensity 3840 A^0 volts	Intensity 4695 A^0 volts	Intensity 5454 A^0 volts
Krypton, 0.3 torr, vary the pressure of SO_2					
SO_2-24	0.325	0	0.12	0.18	0.1
SO_2-25	0.6	0	3.45	0.1	0.1
SO_2-26	1.1	0	1.75	0.08	0.15
SO_2-27	0.01	0			
SO_2-28	0.025	0	0.08	0	0
SO_2-29	0.05	0	0	0.06	
SO_2-30	0.1	0	0.03	0.09	
SO_2-31	0.2	0.04	0.05	0.15	0.08
Krypton, 0.3 torr of SO_2					
SO_2-32	0.4	0.01	0.39	0.17	0.04
SO_2-33	0.51	0.07	11.8	2.05	0.15
SO_2-34	0.65	0.15	12.85	1.0	0.29
SO_2-35	0.11	0.1			
SO_2-36	0.25	0.6	0.09		
SO_2-37	0.3	0.06	0.29	0.27	0.03
SO_2-38	0.875	0.05	0.09	0.03	0.01
SO_2-39	1.01	0.01	1.75	0.57	0.07
SO_2-40	1.15	0.07	8.0	1.13	0.44
SO_2-41	1.3	0.03	0.39	0.02	
SO_2-42	0.01	0.16			
SO_2-43	0.05	0.05			
SO_2-44	0.075	0.02	0.31	3.35	0.15
SO_2-45	1.4	0	0.01	0	0
Neon, 0.3 torr of SO_2					
SO_2-46	0.01	0.39	0.4	4.09	0.03
SO_2-47	0.03	0			
SO_2-48	0.05	0			
SO_2-49	0.075	0.11	0.48	2.18	0.05
SO_2-50	1.5	0.03	0.05	3.0	0
Argon, 0.5 torr of SO_2					
SO_2-51	0.01	0			
SO_2-52	0.025	0.01	0.11	2.8	0.02
SO_2-53	0.06	0.27	0.53	4.35	0.04
SO_2-54	1.2	0.11	0.4	1.69	0.02

Lamp	Fill gas pressure torr	Intensity 2169 A° volts	Intensity 3840 A° volts	Intensity 4695 A° volts	Intensity 5454 A° volts
Helium, 0.2 torr, vary the pressure of SO_2					
SO_2-55	0.025	0.02			
SO_2-56	0.05	0.03			
SO_2-57	0.105	0.03			
SO_2-58	0.225	0.04			
SO_2-59	0.3			0.5	0.01
SO_2-60	0.425			0.4	0.04
SO_2-61	0.55			0.6	0
SO_2-62	0.7				0.33
SO_2-63	0.99				
SO_2-64	1.1				0.26
SO_2-65	1.3	0.16	14.6	0.38	0
SO_2-66	1.5			0.5	0.3
Helium, 0.5 torr of SO_2					
SO_2-67	0.01				0.22
SO_2-68	0.03				0.25
SO_2-69	0.05				0.22
SO_2-70	0.11				0.2
SO_2-71	0.2				0.28
SO_2-72	0.3	0.05			0
SO_2-73	0.4	0.04	0	0.06	0
SO_2-74	0.5	0.03	0.07	0.03	0.2
SO_2-75	0.7	0.02	0.02	0	0.1
SO_2-76	0.9	0.01	0.03	0	0.18
SO_2-77	1.1	0.01	0.02	0	0.01
SO_2-78	1.2	0.01	0.07	0.05	0.1
Xenon, 0.3 torr of SO_2					
SO_2-79	0.01				0.06
SO_2-80	0.025				0.11
SO_2-81	0.05				0.17
SO_2-82	0.1				0.11
SO_2-83	0.2			0.13	0
SO_2-84	0.3	0	0.34	0	0
SO_2-85	0.4	0	0	0	0
SO_2-86	0.6	0	0.41	0.02	0
SO_2-87	0.75	0	0	0	0
SO_2-88	0.925	0	0	0	0
SO_2-89	1.1	0	0	0	0
SO_2-90	1.35	0	0	0	0

Lamp	Fill gas pressure torr	Intensity 2169 Å volts	Intensity 3840 Å volts	Intensity 4695 Å volts	Intensity 5454 Å volts
Xenon, 0.3 torr, vary the pressure of SO_2					
SO_2-91	0.01	0	0	0	0.04
SO_2-92	0.025	———	0	0	0
SO_2-93	0.05	0	0	0	0
SO_2-94	0.1	0	0	0	0
SO_2-95	0.25	0	0	0	0
SO_2-96	0.32	0.21	3.45	0.97	1.2
SO_2-97	0.4	———	0	0	0.01
SO_2-98	0.5	0	0	0.05	0
SO_2-99	0.7	0	4.95	0.08	0
SO_2-100	0.92	0	3.85	0.02	0
SO_2-101	1.1	0	12.75	0.53	0
SO_2-102	1.3	0	1.05	0.07	0
Argon, 0.3 torr, vary the pressure of SO_2					
SO_2-103	0.01	0	0	0.58	0
SO_2-104	0.03	0	0	0	0
SO_2-105	0.05	0	0	0	———
SO_2-106	0.1	0	0	0	0
SO_2-107	0.205	0	0.2	0.3	0
SO_2-108	0.3	0.14	0.38	0.38	0.03
SO_2-109	0.4	0.05	0.28	0.5	0.02
SO_2-110	0.55	0.05	0.29	0.45	0.05
SO_2-111	0.07	0.06	0.26	0.53	0.03
SO_2-112	0.95	0.06	0.27	0.73	0.03
SO_2-113	1.11	———	———	———	———
SO_2-114	1.4	0.02	0.1	0.28	0.05
Neon, 0.3 torr, vary the pressure of SO_2					
SO_2-115	0.01	0	0	0	0
SO_2-116	0.025	0	0	0	0
SO_2-117	0.06	0.03	0.05	0.18	0
SO_2-118	0.11	0.03	0	0.28	0
SO_2-119	0.19	0.15	0.6	1.6	0
SO_2-120	0.3	0.17	0.31	0.78	0.02
SO_2-121	0.425	0.11	0.33	1.18	0.04
SO_2-122	0.5	0.26	0.36	1.06	0.03
SO_2-123	0.7	0.01	0.18	1.08	0
SO_2-124	0.925	0	0.15	1.84	0.01
SO_2-125	1.1	0	0.14	0.68	0.01
SO_2-126	1.325	0	0.19	0.65	0.02

Table A-4. Lamps containing Na_2S.

Lamp	Fill gas pressure torr	Intensity 2169 A° volts	Intensity 3840 A° volts	Intensity 4695 A° volts	Intensity 5454 A° volts
Argon					
Na_2S-1	1.7	0	0.49	0.17	0.13
Na_2S-2	1.5	——	——	——	——
Na_2S-3	1.3	——	——	——	——
Na_2S-4	1.1	——	——	——	——
Na_2S-5	0.9	0	0.03	0.05	0.02
Na_2S-6	0.7	0	0.03	0.01	0
Na_2S-7	0.6	0	0.32	0.63	0
Na_2S-8	0.425	——	——	——	——
Na_2S-9	0.31	0	——	——	——
Na_2S-10	0.2	0	——	——	——
Na_2S-11	0.1	0	0.02	0.01	0
Na_2S-12	0.05	0	0	——	——
Na_2S-13	0.025	——	——	——	——
Na_2S-14	0.01	0	0.03	0	0
Krypton					
Na_2S-15	1.7	0	0.01	0.01	0
Na_2S-16	1.5	0	0.9	0.08	0
Na_2S-17	1.3	0	0	0	0
Na_2S-18	1.075	0	0.01	0.01	0
Na_2S-19	0.9	0	0.1	0.01	0
Na_2S-20	0.71	0	——	——	——
Na_2S-21	0.5	0	0.03	0.02	0
Na_2S-22	0.4	0	0	0.09	0.01
Na_2S-23	0.3	0	0.07	——	——
Na_2S-24	0.2	0	——	——	——
Na_2S-25	0.1	0	——	——	——
Na_2S-26	0.075	0	——	——	——
Na_2S-27	0.04	——	——	——	——
Na_2S-28	0.01	0	——	——	——
Neon					
Na_2S-29	1.7	0	0.01	0.07	0.01
Na_2S-30	1.5	0	0.02	0.3	0.01
Na_2S-31	1.3	0	0.01	0.04	0
Na_2S-32	1.075	0.02	0.06	0.1	0.01
Na_2S-33	0.9	0	0.01	0.04	0

Lamp	Fill gas pressure torr	Intensity 2169 A° volts	Intensity 3840 A° volts	Intensity 4695 A° volts	Intensity 5454 A° volts
Neon					
Na_2S-34	0.7	0	0.07	0.14	0
Na_2S-35	0.51	0	0.01	0.06	0.01
Na_2S-36	0.4	0.06	0.07	0.15	0.01
Na_2S-37	0.3	0	0.28	1.23	0.01
Na_2S-38	0.19	0	0.4	0.9	—
Na_2S-39	0.1	0	0.2	—	—
Na_2S-40	0.05	0.01	—	—	—
Na_2S-41	0.025	0	—	—	—
Na_2S-42	0.01	—	—	—	—
Helium					
Na_2S-43	1.7	0.01	0.7	0.23	0.03
Na_2S-44	1.49	0	0.24	0.25	0.1
Na_2S-45	1.3	0	0.21	0.13	0.03
Na_2S-46	1.1	0	0.11	0.24	0.03
Na_2S-47	0.91	0	0.13	0.22	0.05
Na_2S-48	0.7	0	0.1	0.44	0.03
Na_2S-49	0.5	0	0.39	0.86	0.03
Na_2S-50	0.4	0	—	—	—
Na_2S-51	0.3	0	—	—	—
Na_2S-52	0.2	0	—	—	—
Na_2S-53	0.1	—	—	—	—
Na_2S-54	0.05	—	—	—	—
Na_2S-55	0.025	—	—	—	—
Na_2S-56	0.01	0	—	—	—
Xenon					
Na_2S-57	0.01	—	0	—	—
Na_2S-58	0.035	—	—	—	—
Na_2S-59	0.055	—	—	—	—
Na_2S-60	0.12	—	—	—	—
Na_2S-61	0.205	0	—	—	—
Na_2S-62	0.325	0	—	—	—
Na_2S-63	0.405	0	1.35	0.18	0.17
Na_2S-64	0.53	0	0	0	0
Na_2S-65	0.7	0	0	0	0
Na_2S-66	0.915	0	0	0	0
Na_2S-67	1.11	0	0	0	0
Na_2S-68	1.3	0	0	0	0
Na_2S-69	1.5	0	0	0	0
Na_2S-70	1.7	0.02	4.0	0.7	0

Table A-5. Lamps containing ZnS.

Lamp	Fill gas pressure torr	Intensity 2169 A° volts	Intensity 3840 A° volts	Intensity 4695 A° volts	Intensity 5454 A° volts
Krypton					
ZnS-1	1.7		0.04	0.06	0.28
ZnS-2	1.5	0.12	0.27	0.24	0.05
ZnS-3	1.3	0.1	0.03	0.11	0.05
ZnS-4	1.1	0.1	0.08	0.03	0.01
ZnS-5	0.9	0.02	0.08	0.3	0.03
ZnS-6	0.7	0.02	0.05	0.02	0.01
ZnS-7	0.5	0	0.18	0.05	0.01
ZnS-8	0.4	0.08	0.21	0.05	0
ZnS-9	0.3	0	0	0.02	0
ZnS-10	0.2	0	0	0.06	0.08
ZnS-11	0.1	0	2.8	0.71	0.1
ZnS-12	0.05	0	—	—	—
ZnS-13	0.025	0.04	—	—	—
ZnS-14	0.01	0	—	—	—
Argon					
ZnS-15	1.675				
ZnS-16	1.5	0	0.2	0.1	0.04
ZnS-17	1.3	0	0.2	0.06	0.01
ZnS-18	1.1	0	0	0.01	0.01
ZnS-19	0.9	0	0.05	0.1	0.03
ZnS-20	0.69	0	0.75	0.15	0.03
ZnS-21	0.5	0.01	0.08	0.4	0.02
ZnS-22	0.4	0			
ZnS-23	0.3	0	1.13	0.15	0.33
ZnS-24	0.2	0	0.2	—	—
ZnS-25	0.1	0.02	—	—	—
ZnS-26	0.05	0.04			
ZnS-27	0.025	0	0.11	0.85	0.62
ZnS-28	0.01	0.01	—	—	—
Neon					
ZnS-29	1.7	0	0.05	0.4	0.1
ZnS-30	1.5	0	1.15	0.02	0
ZnS-31	1.275	0	0.03	0.03	0
ZnS-32	1.1	0	1.88	0.04	0.1
ZnS-33	0.9	0	0.54	0.04	0.02
ZnS-34	0.675	0	0.62	0.05	0.11
ZnS-35	0.5	0.05	0.16	0.13	0.17
ZnS-36	0.39	0.03	0.1	0.33	0.11

Lamp	Fill gas pressure torr	Intensity 2169 A° volts	Intensity 3840 A° volts	Intensity 4695 A° volts	Intensity 5454 A° volts
Neon					
ZnS-37	0.29	0.01	0.5	0.01	0.03
ZnS-38	0.2	0	0.07	——	——
ZnS-39	0.1	0	0.4	——	——
ZnS-40	0.05	0	——	——	——
ZnS-41	0.025	——	——	——	——
ZnS-42	0.01	——	——	——	——
Helium					
ZnS-43	1.7	0	0.48	0.93	0.27
ZnS-44	1.475	0	7.1	0.07	0.08
ZnS-45	1.3	0	0	0.16	0.02
ZnS-46	1.1	0	0.52	0.14	0.05
ZnS-47	0.89	0	1.38	1.28	0.06
ZnS-48	0.69	0	0.22	0.5	——
ZnS-49	0.49	0	0.87	0.17	0.03
ZnS-50	0.4	0	0.03	0.15	——
ZnS-51	0.3	0	0.1	——	——
ZnS-52	0.2	0	0.1	——	——
ZnS-53	0.09	0	0.02	0.25	——
ZnS-54	0.05	0	0.39	——	——
ZnS-55	0.025	——	——	——	——
ZnS-56	0.01	0	0.01	0.05	0
Xenon					
ZnS-57	0.01	——	——	——	——
ZnS-58	0.025	——	——	——	——
ZnS-59	0.05	——	——	0	0
ZnS-60	0.11	——	0	0.06	0
ZnS-61	0.2	0	0	0	0
ZnS-62	0.3	0	0	0	0
ZnS-63	0.4	0	0	0.02	0
ZnS-64	0.575	0	0	0	0
ZnS-65	0.71	0	0	0	0
ZnS-66	0.9	0	0	0	0
ZnS-67	1.11	0	0	0	0
ZnS-68	1.3	0	0	0	0
ZnS-69	1.5	0	0	0	0
ZnS-70	1.7	0	0	0	0

Table A-6. Lamps containing CS_2 which lit.

Lamp	Fill gas pressure torr	Intensity 2169 A° volts	Intensity 3840 A° volts	Intensity 4695 A° volts	Intensity 5454 A° volts
Krypton	all	___	___	___	___
Argon					
CS_2-17	1.3	0.01	0.21	0.24	0.01
Helium					
CS_2-32	1.09	0.12	2.21	1.15	0.52
Xenon					
CS_2-46	1.06	0.11	1.55	0.58	0.09
CS_2-47	0.9	0.12	4.95	1.0	0.38
CS_2-48	0.7	0.01	1.75	0.11	0.01
CS_2-49	0.5	0.13	3.15	0.27	0.12
CS_2-51	0.3	0.08	7.05	0.29	0.31
CS_2-52	0.2	0.01	2.05	0.18	0.22
CS_2-53	0.1	0.03	1.65	0.29	0.25
CS_2-54	0.055	0	0.01	0	0
CS_2-55	0.025	0	___	0	0
Neon					
CS_2-57	1.7	0.05	1.35	0.14	0.13
CS_2-60	1.1	0	0	___	___
CS_2-62	0.7	0	0	0	0
CS_2-66	0.2	0	0	___	0
CS_2-68	0.055	0.04	1.05	0.22	0.11

___ indicates where a lamp has failed to light.

Table A-7. Intensities of lamps with an air jacket.

Lamp	Intensity 2169 A° volts	Intensity 3840A° volts	Intensity 4695 A° volts	Intensity 5454 A° volts
S-1	0.56	4.9	3.1	0.31
S-2	0.14		1.1	0.02
S-5	0.29	10.0	4.35	0.51
S-7	0.12		1.8	
SO_2-3	0.04	0.23		0.03
SO_2-8	0.11		0.12	
H_2S-10	0.49	5.1	1.03	0.23
H_2S-11			0	0.02
H_2S-13	0.84	1.1	1.55	0.05
S-9	0.04	3.0	0.72	0.11
S-11	0.1	10.0	2.5	0.5
H_2S-15	0.17	0.23	0.33	0.08
H_2S-17	0.35	1.8	0.85	0.05
H_2S-20	0.12	2.5	1.02	0.15
SO_2-9	0.12	0.14	0.04	0.01
SO_2-10	0.1	0.22	0.07	0.03
SO_2-13	0.09	0	0	0
S-14	0.35	10.0	3.05	
S-15	0.18	9.0	2.58	0.5
SO_2-16	0.36	0.4	1.26	0.04
SO_2-18	0	0	0	0
SO_2-20	0	0	0.22	0
H_2S-22	0.45	0	0	0
H_2S-24	0	0	0	0
H_2S-25	0.05	0.45	0.08	0.02
S-18	0.06	2.35	1.1	0.12
S-20	0.08	3.95	1.11	0.19
S-22	0.06	2.7	0.99	0.06
S-23	0.07	2.0	1.55	
H_2S-27	0.02	2.6	0.96	0.06
H_2S-30	0.01	0.2	0.11	0.02
H_2S-31	0.01	0.03	0.03	0
H_2S-32	0.02	0.25	0.1	0

Lamp	Intensity 2169 Å volts	Intensity 3840 Å volts	Intensity 4695 Å volts	Intensity 5454 Å volts
SO_2-20'	0.02	13.0	0.43	0.13
SO_2-22	0	0.15	0.04	0.06
SO_2-25	0		—	
ZnS-9	0	0.09	0	—
ZnS-11	—	—	—	—
S-26	0.15	8.0	2.0	0.3
S-29	0.2	10.0	3.0	0.4
H_2S-33	0.35	4.3	2.25	0.16
H_2S-34	0	0.55	3.2	0.04
S-30	0.03	0.6	0.21	0.01
S-36	0.15	9.2	2.05	0.29
SO_2-29	—	—	0.21	0
SO_2-31	—	—	0.08	0.03
ZnS-21	0	0	0	0.03
ZnS-27	0	0	0	0
Na_2S-1	0	0.3	0.25	0.03
Na_2S-11	0	0	0	0
SO_2-34	0	0.5	0.35	0.47
SO_2-45	0	0	0	0
Na_2S-16	0	0	0	0
Na_2S-22	—	—	0	0
CS_2-17	0	0	0	0
H_2S-38	0.3	4.0	0.01	0.3
H_2S-48	0	0	0	0.01
S-39	0.15	2.1	0.55	0.08
S-44	0.2	6.0	—	—
Zns-32	0	1.0	0.01	0.12
ZnS-35	0	0.02	0	0
Na_2S-36	0	0.05	0.02	0.01
Na_2S-38	—	0	0.06	0.01
S-46	0	1.1	—	0
S-49	0.2	5.5	1.15	0.12

Lamp	Intensity 2169 A° volts	Intensity 3840 A° volts	Intensity 4695 A° volts	Intensity 5454 A° volts
ZnS-43	0	0.25	0.03	0.24
ZnS-56	____	____	0	0
H_2S-52	0.28	2.3	1.0	0.09
H_2S-53	0	0.02	0	0
Na_2S-45	0	0.08	0.02	0
Na_2S-49	0	0.3	0.03	0.02
SO_2-65	0.09	11.5	1.7	0.48
SO_2-74	0	0.02	0.01	0
SO_2-73	0	0.06	0	0.01
CS_2-32	0	1.4	0.85	0.45
S-50	0.2	5.0	0.3	0.08
S-53	0.15	2.0	0.6	0.2
ZnS-61	0	0	0	0
ZnS-70	0	0	0	____
SO_2-86	0.1	0.6	0.12	0.01
SO_2-90	0	0	0	0
H_2S-60	0	2.0	0.53	0.07
H_2S-62	0.03	1.25	0.2	0
SO_2-95	0	0	0	0
SO_2-96	0.03	0.8	0.35	0.06
H_2S-70	____	____	____	____
H_2S-75	0.2	6.2	1.0	0.06

____ indicates where a lamp has failed to light.

Table A-8. Intensity reproducibility upon relighting the lamp at a later time.

Lamp	Intensity 2169 A^{o} volts first	Intensity 2169 A^{o} volts second
S-1	0.8	0.89
SO_2-3	0.04	0.02
H_2S-2	1.19	2.0
H_2S-5	0.45	0.33
H_2S-16	0.71	0.67
S-11	0.7	0.59
SO_2-9	0.13	0
SO_2-19	1.8	0.1

ACKNOWLEDGMENT

The author wishes to acknowledge the aid and encouragement of the faculty, staff, and graduate students of the Chemistry Department of Kansas State University. A very special word of thanks and appreciation is extended to Dr. W. G. Schrenk for his guidance, assistance, patience, and friendship which were always there whenever needed.

The Teaching and Research Assistantships granted to the author by the chemistry department, NSF, and the Kansas Agriculture Experiment Station are gratefully acknowledged.

The suggestions and aid of Mr. Rick Everson, Dr. Don Smith, and Dr. Ken Smith are also gratefully acknowledged.

The author also wishes to acknowledge Dr. O. L. Chapman and Dr. J. W. Mitchell who encouraged him to obtain a graduate degree.

Finally, the author wishes to thank his parents and grandparents, for without their aid, encouragement, and love throughout the years he could not have attained the goals that he has.

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PRODUCTION AND EXAMINATION OF LOW PRESSURE SULFUR MICROWAVE EXCITED ELECTRODELESS DISCHARGE LAMPS

BY

ALLAN HAROLD CHILDS

B. S., Iowa State University, Ames, 1970.

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Chemistry

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1973

Sulfur, because of its role as a trace element and as a pollutant in the environment, has recently come under increased interest as far as the need for faster means of analysis and better detection limits. Only within the past decade has sulfur been determined by flame emission spectroscopy using the S_2 species. Atomic absorption has been tried on sulfur only within the past five years. Because a good sulfur hollow cathode has not been developed, the production and examination of electrodeless discharge lamps (EDL) containing sulfur was investigated.

The EDL is a quartz tube approximately 30 mm long by 8 mm i.d. into which is placed about 1 mg of one of the following sulfur containing compounds: elemental sulfur, Na_2S, ZnS, and CS_2. If H_2S or SO_2 were used, 0.3 to 0.5 torr of the gas was used. For fill gases He, Ne, Ar, Kr, and Xe were used from 0.01 to 1.7 torr.

The lamps were evacuated using a vacuum system capable of obtaining a pressure of 10^{-6} torr. The EDL was then filled with the respective fill gas-compound mixture.

The lamps were evaluated at a microwave frequency of 2450 MHz and 100 watts of power with a standing wave ratio of one. An "A" antenna was used to couple the microwave power to the lamp.

The sulfur intensity was measured at four different wavelengths: 2169 A° (S I), 3840 A° (S_2 band head), 4695 A° (S I), and 5454 A° (S II).

All lamps were evaluated in air, sometimes with the use of a small cooling fan. The better lamps were evaluated using an air jacket and a heater. Most showed a cool operating temperature, 100-150°C.

The stability of the more intense lamps was checked for a preiod of one-half hour and was found to vary from 2 percent to 4 percent.

The reproducibility upon relighting the lamp was checked. Repositioning was the major cause of intensity variation. The reproducibility of remanufacturing of individual lamps was also checked. The results of this were not good. Some of the lamps were only half the intensity of the other lamps.

Elemental sulfur and H_2S with He, Ne, and Ar as a fill gas in the EDL gave the strongest intensities.