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ERBIUM LASER PROPAGATION IN SIMULATED ATMOSPHERES

I. DESCRIPTION OF EXPERIMENTAL APPARATUS AND PRELIMINARY RESULTS

By
R. B. Gomez
and
K. O. White

ATMOSPHERIC SCIENCES LABORATORY
WHITE SANDS MISSILE RANGE, NEW MEXICO

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ABSTRACT

Initial results are presented of an experimental study utilizing an absorption cell facility to determine erbium laser propagation characteristics in simulated atmospheres. The facility consists of a 3.3-meter spectrometer coupled to a 20-meter multipass absorption cell. The cell environment can be controlled over a wide range of pressures, temperatures, humidities, and gas concentrations. Absorption measurements were made with path lengths varying from 400 to 1600 meters in a simulated atmosphere consisting of clean dry air. The initial experimentally measured attenuation of 1.54 micron radiation by clean dry air is less than 25% per km. The results include the discovery of a new emission line of the erbium laser at 1.544 microns and the simultaneous emission of lines at 1.544 and 1.536 microns.

ACKNOWLEDGEMENTS

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In addition, we are indebted to James T. Hall of this laboratory for his helpful technical discussions concerning this program and to Richard Dixon and John Spragins of the White Sands Missile Range Navy machine shop for their help in the construction of the facility. We also wish to acknowledge the assistance of Dr. R. G. Buser of the Institute of Exploratory Research. Grateful thanks are due to Alex Blomerth, Chief of the Atmospheric Physics Technical Area, for his assistance in carrying out the research program.

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1. INTRODUCTION

As the result of a request made by the United States Army Materiel Command, a research program to determine the effects of simulated atmospheres on erbium laser radiation was initiated at the Atmospheric Sciences Office of the Atmospheric Sciences Laboratory, United States Army Electronics Command. This report describes the experimental apparatus and presents the initial results of an investigation of the atmospheric effects on 1.54 micron wavelength laser radiation.

2. SUMMARY OF THEORETICAL INVESTIGATION

Potential atmospheric effects on the propagation of electromagnetic radiation in the 1.54 micron wavelength region were theoretically examined in a previous report (1). It was found that the exact wavelength and width of the laser emission were needed before the effects of the atmospheric absorption lines in the vicinity could be determined. It was reported that the erbium laser may emit anywhere within a $\pm .01\mu$ region about 1.54μ and with a spectral width of as much as $.005\mu$. The atmospheric attenuating mechanisms discussed were the following:

- (1) Molecular selective line absorption.
- (2) Molecular continuum absorption.
- (3) Rayleigh scattering.
- (4) Aerosol absorption.
- (5) Mie scattering.

Utilizing various sources (2-8), an estimate of the attenuation of 1.54 micron radiation was obtained. The data were made applicable to the region of interest by recalculations and interpolations when necessary. Twelve weak absorption bands in the 1.5 to 1.6 micron wavelength region were analyzed including OH, NO, N₂O, O₂, HDO, D₂O, H₂O, and CO₂, with the strongest being the H₂O and CO₂ absorption bands. The main results of the investigation are summarized in Table I and are applicable under the following conditions:

- (1) Temperature: $\sim 20^{\circ}\text{C}$
- (2) Relative humidity: $\sim 70\%$
- (3) Meteorological Range[†]: $\sim 25 \text{ km}$

[†]The meteorological range, V, is that distance for which the transmittance falls to 2%, i.e., $V = 3.912/\alpha$ where α is the attenuation coefficient.

TABLE I. SUMMARY OF THEORETICAL ATTENUATION LOSSES

ATTENUATION	ATTENUATION COEFFICIENT $\alpha(\text{km}^{-1})$	LOSS PER KILOMETER
Molecular Selective Line Absorption (Mainly CO_2 and H_2O)	$3 \times 10^{-3} < \alpha < 3 \times 10^{-2}$	<3%
Molecular Continuum Absorption (H_2O Vapor)	$1.6 \times 10^{-2} < \alpha < 1.6 \times 10^{-1}$	<15%
Rayleigh Scattering	$\alpha < 10^{-4}$	<0.1%
Aerosol Absorption	$\alpha < 10^{-3}$	<1%
Mie Scattering	$8 \times 10^{-3} < \alpha < 1 \times 10^{-1}$	<10%
TOTAL	$2.7 \times 10^{-2} < \alpha < 2.9 \times 10^{-1}$	<25%

The value listed for aerosol absorption was obtained from measurements of dust particles, common to WSMR, utilizing techniques and instrumentation developed by Hoidale (9) and results from the fact that no absorption bands were observed in the 1.54 micron wavelength region.

3. DESCRIPTION OF EXPERIMENTAL APPARATUS

The Atmospheric Sciences Laboratory (ASL) Absorption Cell Facility consists of a 3.3-meter spectrometer coupled to a 20-meter multipass absorption cell. The cell environment is controlled by a combination of systems which are unique in their design and offer a wide range of pressures, temperatures, humidities, and gas concentrations. In view of the wavelength dependence of the absorption mechanism, the spectral characteristics of the laser output are determined as each absorption measurement is made by arranging the experimental apparatus as shown schematically in Fig. 1a. This arrangement of the apparatus will be

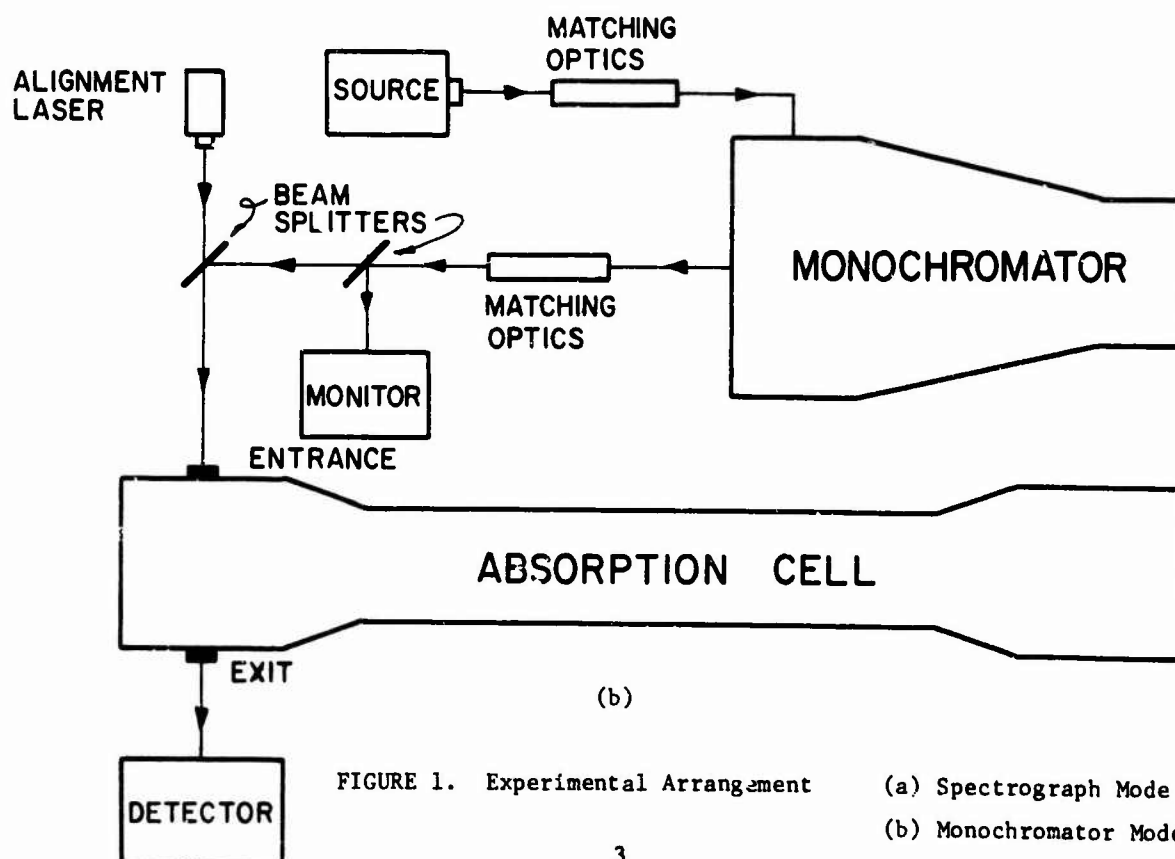
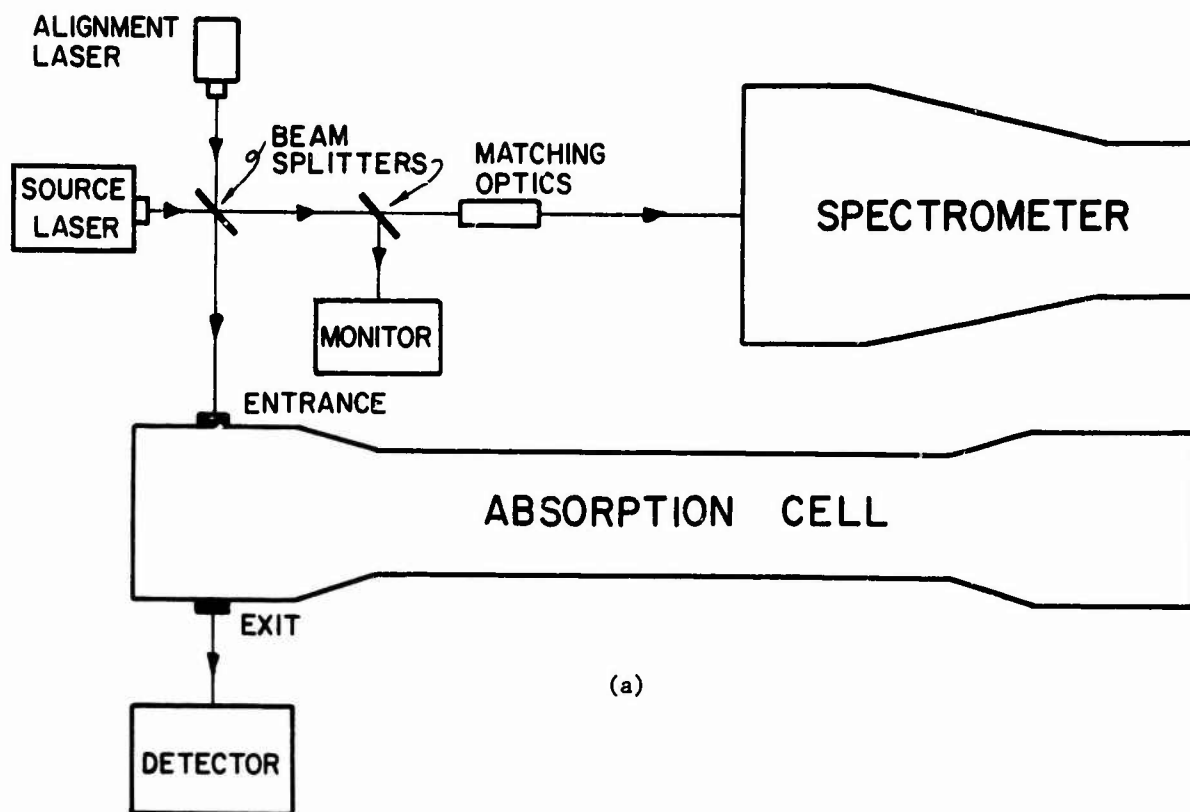


FIGURE 1. Experimental Arrangement

(a) Spectrograph Mode
(b) Monochromator Mode

referred to as the spectrograph mode of operation. In the monochromator mode of operation (see Fig. 1b) the continuous output of a high energy xenon arc lamp or other source is fed through a scanning monochromator prior to the absorption measurement.

3.1. Multipass Absorption Cell

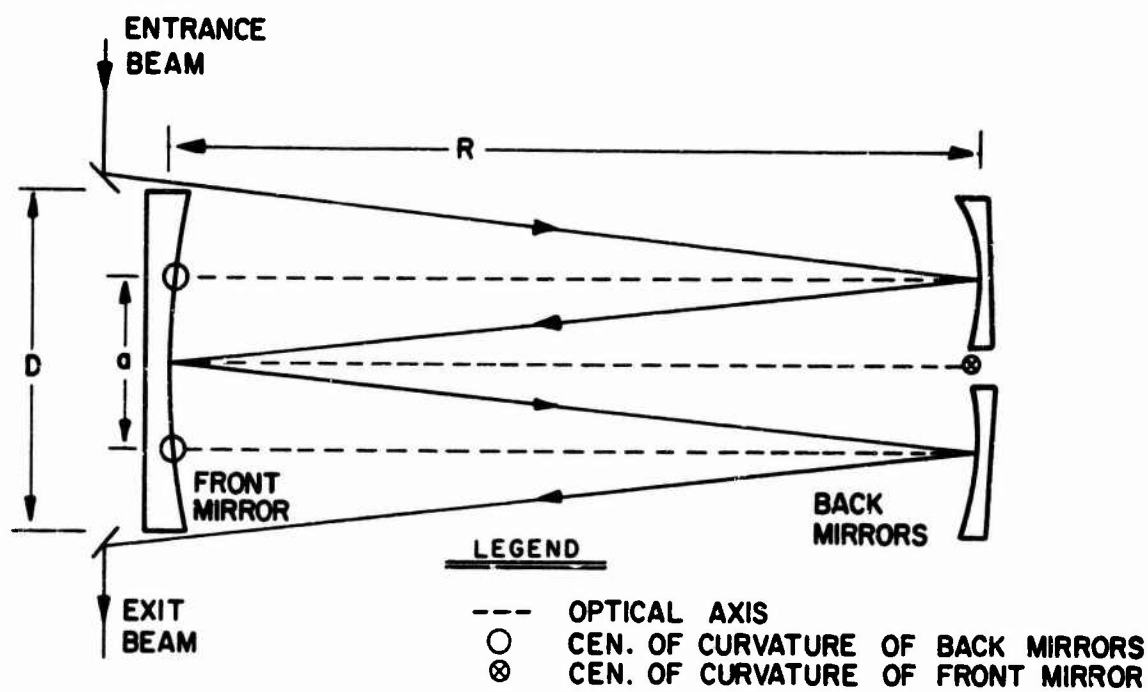
The importance of the multipass absorption cell for investigation of a "simulated atmosphere" is well recognized (10-14). It facilitates the detection and analysis of weakly absorbing components in gas samples. In 1942, White (15) introduced the basic optical principles involved in a multipass gas absorption cell of the type which is discussed here.

The 20 m absorption cell at this laboratory has an inside diameter of 34 cm, a wall thickness of 2 cm, and is fabricated from carbon steel.

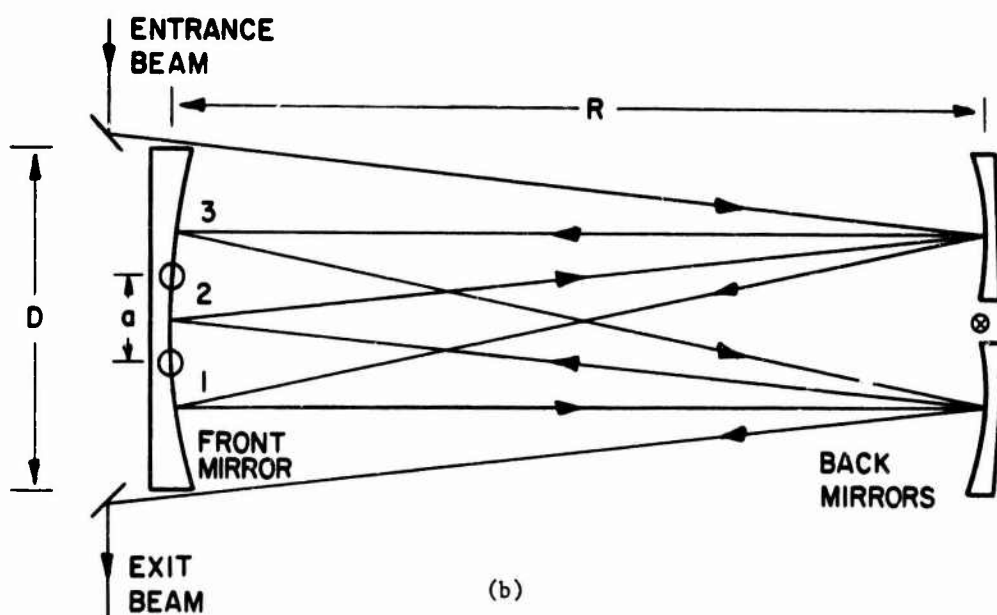
The internal optics of the cell consist of three concave spherical mirrors of equal radii of curvature (20 meters). This optical system is depicted in Fig. 2. The figure illustrates that the centers of curvature of the back mirrors are on the surface of the front mirror, while the center of curvature of the front mirror lies between and in the plane of the back mirrors. The front mirror used in this cell is approximately 21 cm square and each of the back mirrors is 10 cm wide and 21 cm long. Two small diagonal mirrors are used to transfer the electromagnetic radiation into and out of the cell. Figure 2a illustrates that for a single image on the front mirror, the radiation undergoes four passes between the front and back mirrors. In this case the ratio of the distance between the diagonal mirrors, D , to the distance separating the centers of curvature of the back mirrors, a , equals two. The ratio (D/a) can be varied by rotating one (10) or both back mirrors about a vertical axis. (The mirror mechanical adjustment will be half as critical when only one mirror is moved (12).) Increasing the ratio (D/a) results in a greater number of images of the source on the front mirror (see Fig. 2b). The total number of passes, N , can be obtained from the equation

$$N = 2n + 2$$

where n is the number of images on the front mirror. The maximum path length is determined by the number of resolvable images that can be placed on the front mirror. It also depends on the source brightness, the fineness of the mechanical adjustment of the angular separation of the back mirrors, and the fraction of energy loss to reflection. The reflection loss, f_r , is given by



(a)



(b)

FIGURE 2. Optical System of Cell

(a) 4 Passes, one Image

(b) 8 Passes, 3 Images

$$f_r = 1 - r^m$$

where r is the reflection coefficient, and m denotes the number of reflections. The number of reflections is related to the number of images by the relation

$$m = 2n + 1$$

The only energy loss in this system due to transmission through glass occurs at the entrance and exit windows.

The principal aberration to be expected in this optical system is astigmatism (15), which can be calculated by several methods (16,17).

The length of the final sagittal image denoted by ΔL_s was calculated, assuming a point source, from a formula of Edwards (16)

$$\Delta L_s = \frac{wb^2}{12R^2} \left(N - \frac{4}{N} \right)$$

where w is the width of the back mirrors illuminated, b is the distance between the entrance and exit images, R is the radius of curvature of the mirrors, and N is the number of passes. The result for 11 images (480-meter path) is

$$\Delta L_s = 1.1 \times 10^{-2} \text{ mm}$$

and for 39 images (1600-meter path)

$$\Delta L_s = 4.2 \times 10^{-2} \text{ mm}$$

Thus for this case the effect will be negligible, and the entrance image will be considered as conserved in form.

3.2. Cell Environment Control Systems

The cell environment control systems are designed to give a wide range of pressures, temperatures, humidities, and gas concentrations. The

pressure control system allows the cell to be operated over pressures ranging from 10^{-3} to 2×10^3 torr. The temperature control system utilizes an electronic device that regulates the temperature of a liquid flowing through copper tubing wrapped around the cell. Presently the temperature control system is designed to provide a temperature stability of the liquid solution of 0.1°C in the range -48°C to 98°C . Multicomponent atmospheres can be simulated in the cell by the gas handling system.

In the heating mode of operation, valves B, D, G, H are open and A, C, E, F, closed (refer to Fig. 3). Water is circulated through a coil of copper tubing submerged inside the expansion tank. This insures that liquid returning to the cold side of the two-way valve is always cooler than the desired set point value. In the cooling mode of operation, valves A, E, F are open and B, C, D, G, H, closed. Valve C is provided as a means of by-passing the control piping and tanks; it remains closed during normal operation.

In order to stabilize the proportion of hot to cold water flowing into the temperature system, an electronic control supplies commands to a Barber-Colman proportional actuator which operates the two-way valve as shown in Fig. 4. If the temperature of the liquid deviates from the value set on the electronic control, the difference causes a change in resistance of the sensing element which unbalances the resistance bridge circuit. The resulting signal is amplified and trips a relay to operate the actuator. The actuator changes the position of the two-way valve until the correct proportion of hot to cold liquid produces an appropriate change in resistance of the sensing element.

The capability of the system to maintain a constant cell temperature was determined by measuring the output of four copper constantan thermocouples installed inside the cell. Three of them were suspended approximately $1/2$ inch from the cell wall, one at each end and one in the middle. The fourth thermocouple was placed in contact with the cell wall near one end. This arrangement verified that no temperature gradient existed and that the system was capable of maintaining a constant cell temperature with an accuracy of 0.1°C in the range 35°C to 84°C . With the installation of a second sensing element, the cell temperature can be stabilized to the same accuracy throughout the range -48°C to 98°C .

The humidity and gas composition of the cell atmosphere are controlled by the gas handling system schematically illustrated in Fig. 5. A two-phase process determines water vapor content. Gas from header 2 is passed through dispersion tubes immersed in the saturator bath of the temperature and humidity control, producing a steam whose flow

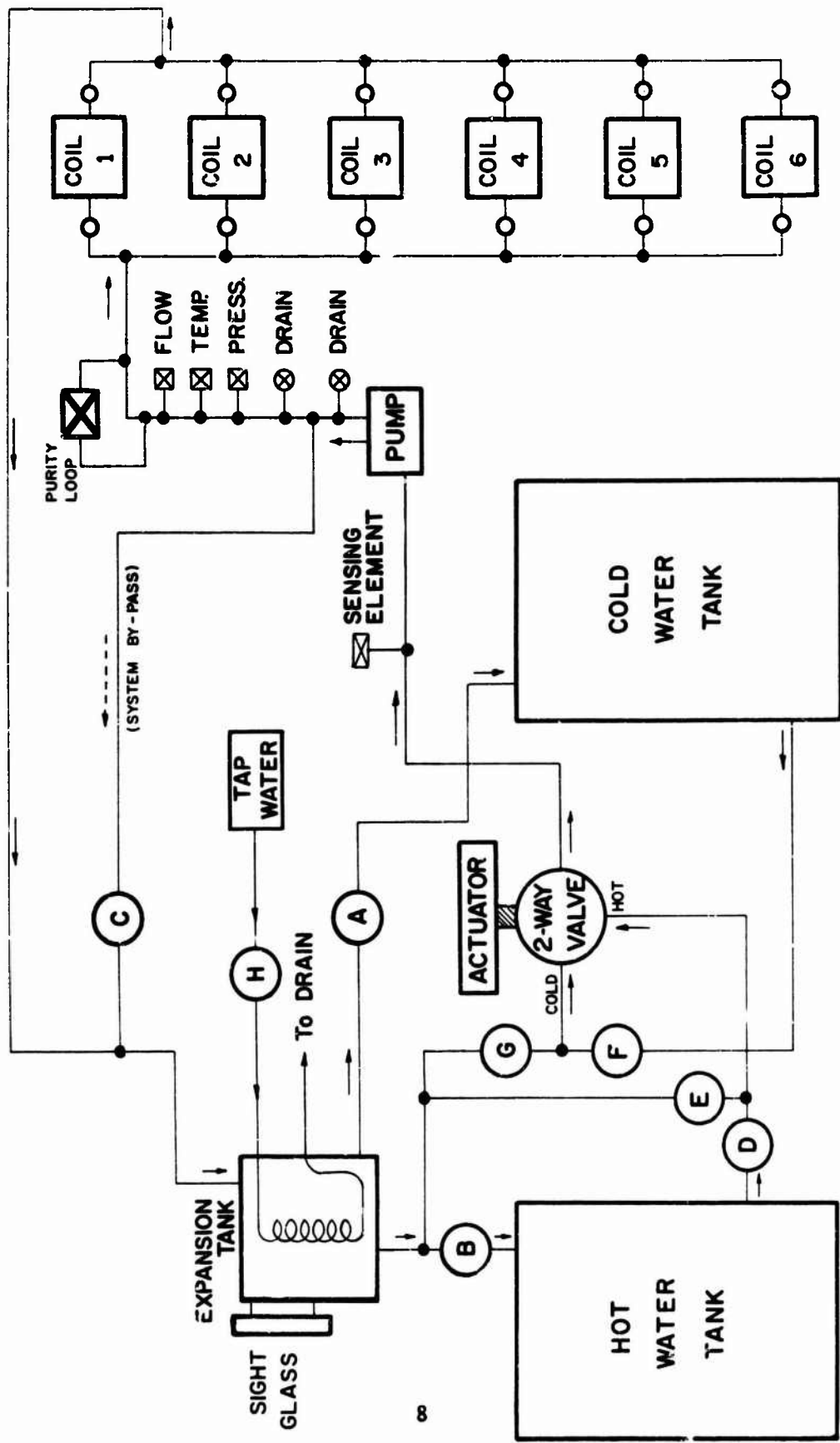


FIGURE 3. Temperature Control System

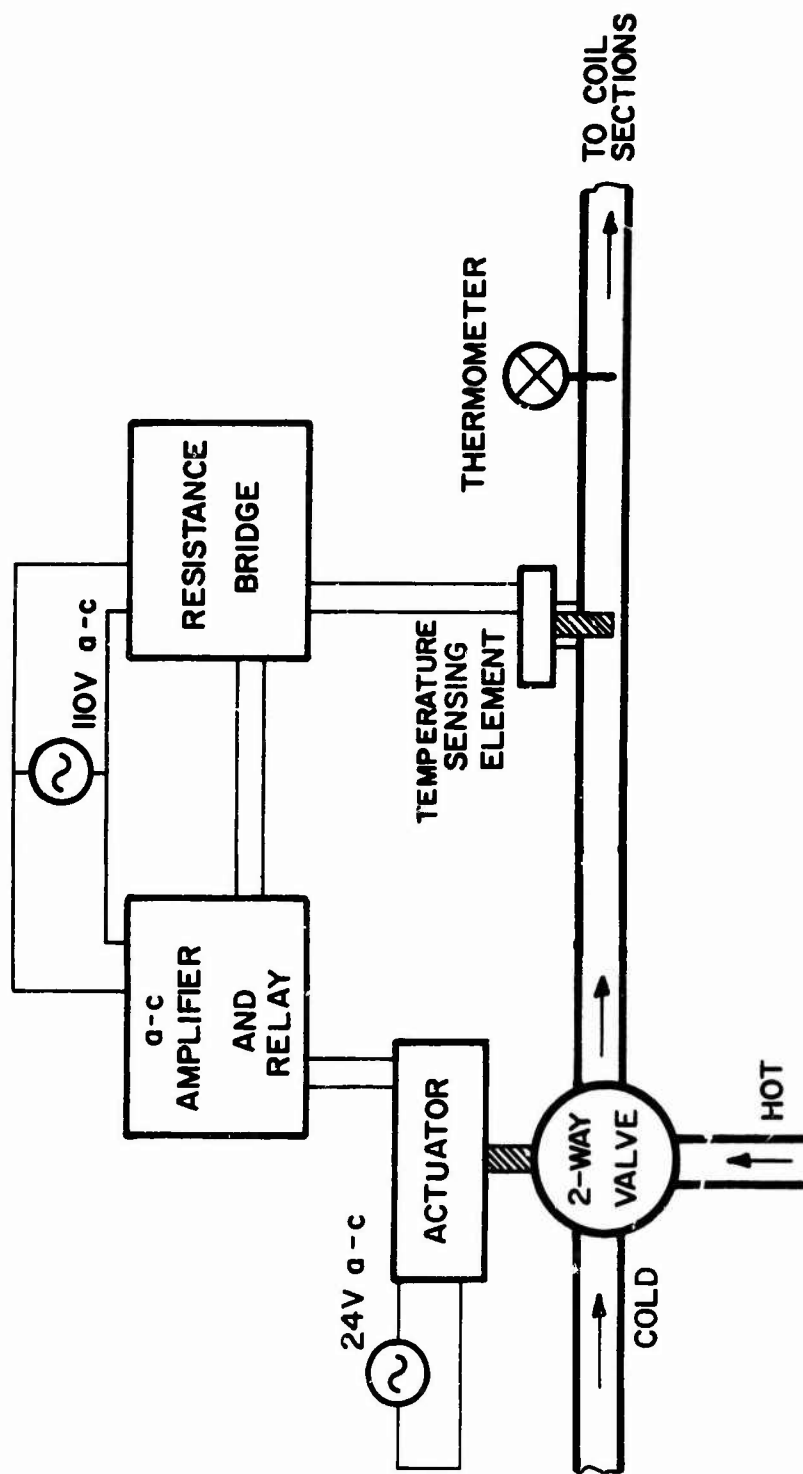


FIGURE 4. Circuit of Temperature Electronic Control

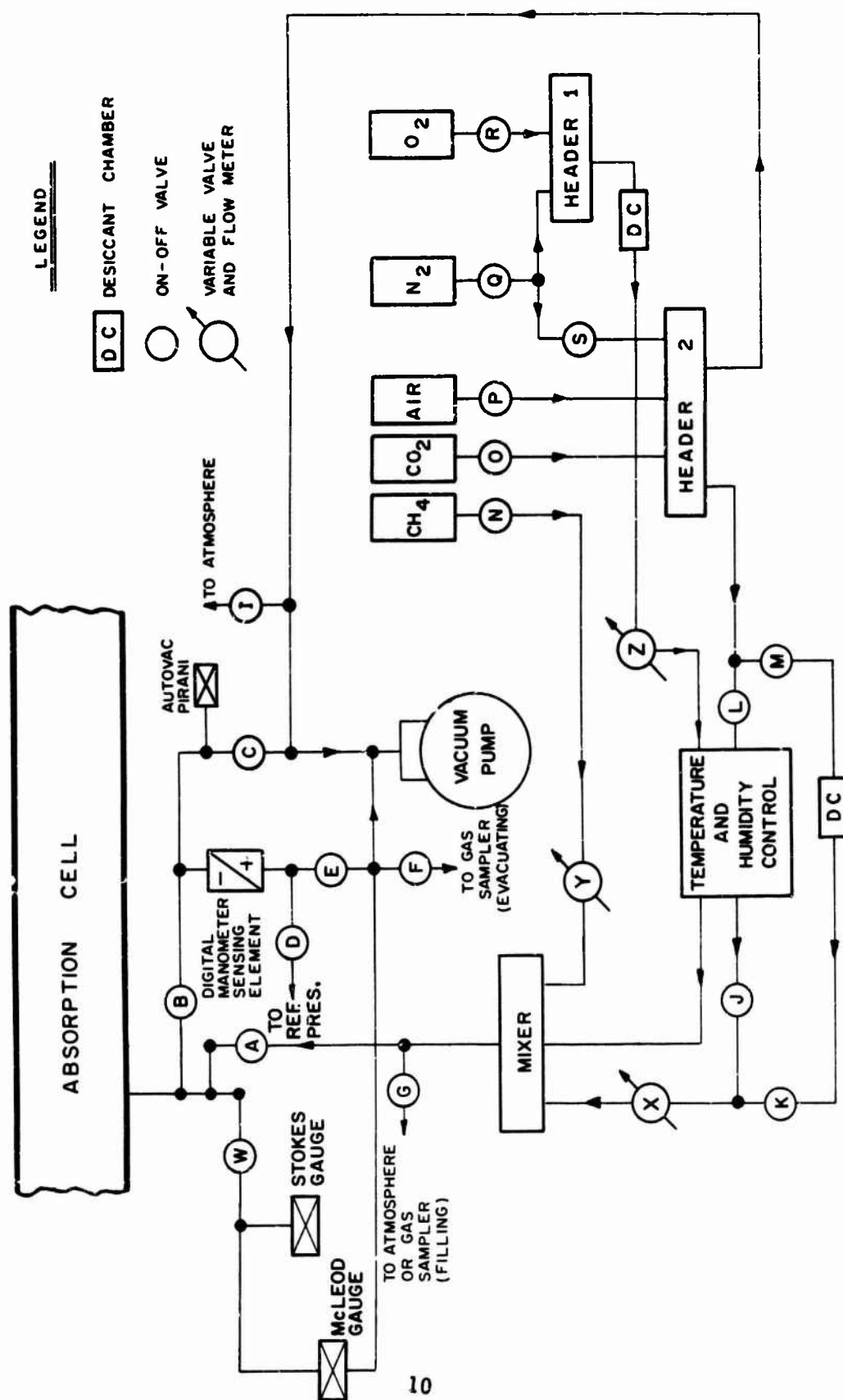


FIGURE 5. Gas Handling System

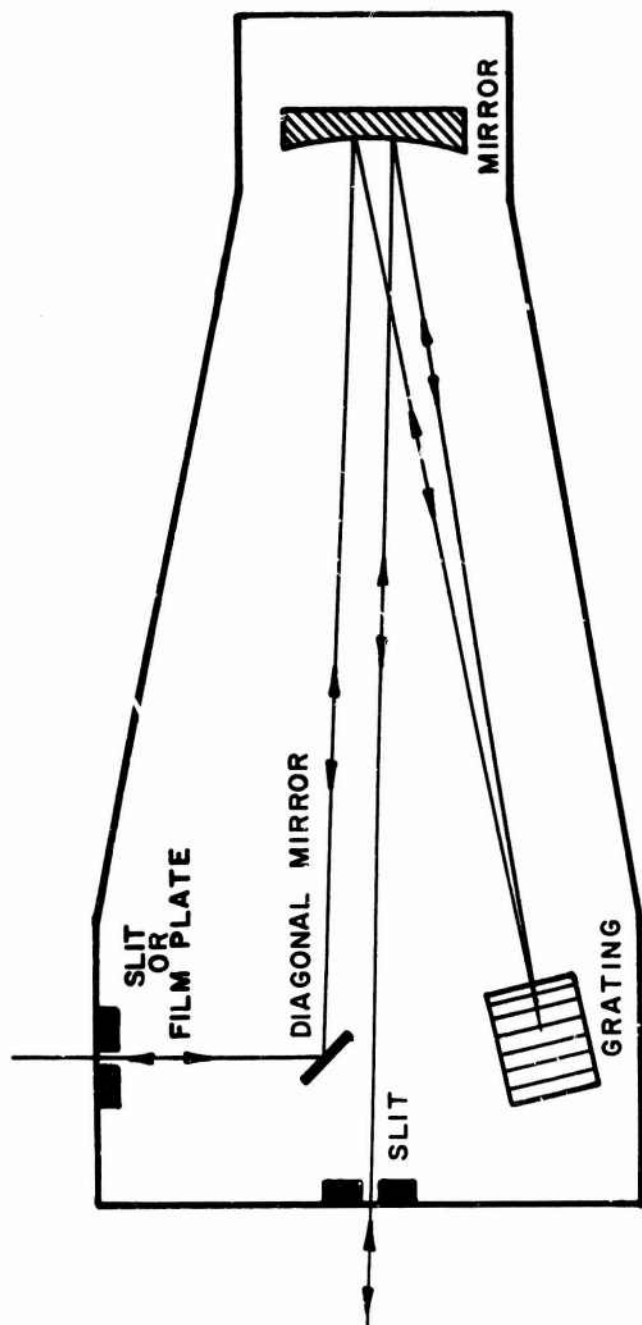
rate is determined by flowmeter X (refer to Fig. 5). Dry gas from header 1, controlled by flowmeter Z, is then mixed with the saturated gas to produce the desired humidity. The temperature of the saturator bath is set to match that of the cell. Due to flowmeter drift, the final value of relative humidity is limited to an accuracy of 2%. The gas handling system is purged by flushing with nitrogen, and a small mechanical pump is used to clear the system of the purging gas and to evacuate gas samplers. By evacuating and filling a 750 ml gas sampler, the composition of the cell atmosphere can be monitored. Infrared absorption spectra run on the sample provide a quantitative analysis of component structure accurate to $\pm 0.5\%$ and determines the accuracy of the system controls over the range of operation.

3.3. Spectrometer

The spectrometer which was constructed in-house uses a Littrow configuration. All the optical components of the spectrometer are mounted on a massive steel frame and mechanically insulated to minimize vibrations. The arrangement of its components and the basic instrument specifications are shown in Fig. 6. The spectrometer can be used both as a spectrograph and as a scanning monochromator. The grating used in this instrument is a 12.5 cm by 25 cm MIT replica on a fused silica blank, with 300 grooves per mm, blazed at 63° . The grating holder is designed to permit scanning about a horizontal axis. The spherical mirror is 30 cm in diameter and has a 3.3 m focal length. At a wavelength of 1.54 microns in 4th order, the reciprocal linear dispersion of this instrument is 0.9 Å/mm, and theoretical resolving power of the grating is 300,000 (0.02 cm^{-1}). The supplier of the grating reported that the actual resolving power would be 90% of theoretical.

3.4. Sources

Various laser rods, cavities, flash lamps, and reflectors were utilized in the construction of a suitable erbium laser source which emits at approximately 1.54-micron wavelength. Three erbium-doped phosphate glass laser rods were available. One was a cylindrical rod with a 6 mm diameter and a 55 mm length. Each of the other rods was rectangular with a 3 mm by 6 mm cross section and a 50 mm length. All three rods had polished ends perpendicular to the rod axis and had rough sides. Each of the rods was used in both cylindrical and elliptical cavities. PEK Model XE5-3.00-.250-C helical flash lamps and EG&G Model FX 42 linear flash lamps were available. The helical flash lamp was used with a cylindrical cavity and operated with a nominal input of 1200



SPECIFICATIONS

SPHERICAL MIRROR: diameter = 30.5 cm
 focal length = 336.1 cm

GRATING (RULE AREA): width = 12.8 cm
 length = 25.6 cm
 ruling = 300 lines/mm

FIGURE 6. Spectrometer Configuration

joules.[†] The linear lamp was used with an elliptical cavity and operated with a typical input of 900 joules. The reflectors utilized in the construction of the erbium laser source were one inch in diameter and were mounted in Lansing optical precision mounts. In general the back reflector (non-output end) of each laser design was a 99% reflectance dielectric coated wedge or a prism.^{††} The front reflectors used included 50%, 80%, and 90% reflectance aluminum coated flats, a 99.7% reflectance dielectric coated flat (used with the prism back reflector) and a 95% reflectance dielectric coated wedge.

3.5. Detection Methods

In this preliminary study, two methods were employed to detect the spectrographically resolved erbium laser emission. A U. S. Radium Corporation IR sensitive phosphor with both a paper and polyethylene backing was used to detect the onset of laser oscillation. The phosphor, when excited by an ultraviolet source, will darken in the region of incident infrared radiation above a certain threshold energy. The darkened spot produced by the incident laser pulse is observable with the unaided eye. The wavelength of the laser emission was determined with this method by placing the phosphor in the focal plane of the spectrograph and selecting reference lines in the region of the expected laser wavelength.

The second detection method utilized an array of ENL653 germanium photovoltaic detectors placed in the focal plane of the spectrometer. The detectors were biased with 1.5 volts and were used with a fixed resistance in series with the detector.^{†††} The signal output from these detectors was displayed on an oscilloscope and photographed.

The arrangement employed to detect the radiation into and out of the cell is illustrated in Fig. 7. The type of detectors used were germanium photovoltaic diodes. Each detector output was displayed on an independent oscilloscope channel and photographed.

[†] A 10,000 joule maximum output power supply was used.

^{††} The prism was incorporated in a TRG model 104A laser head capable of Q-switch operation.

^{†††} The resistance used varied from 10 to 1000 ohms.

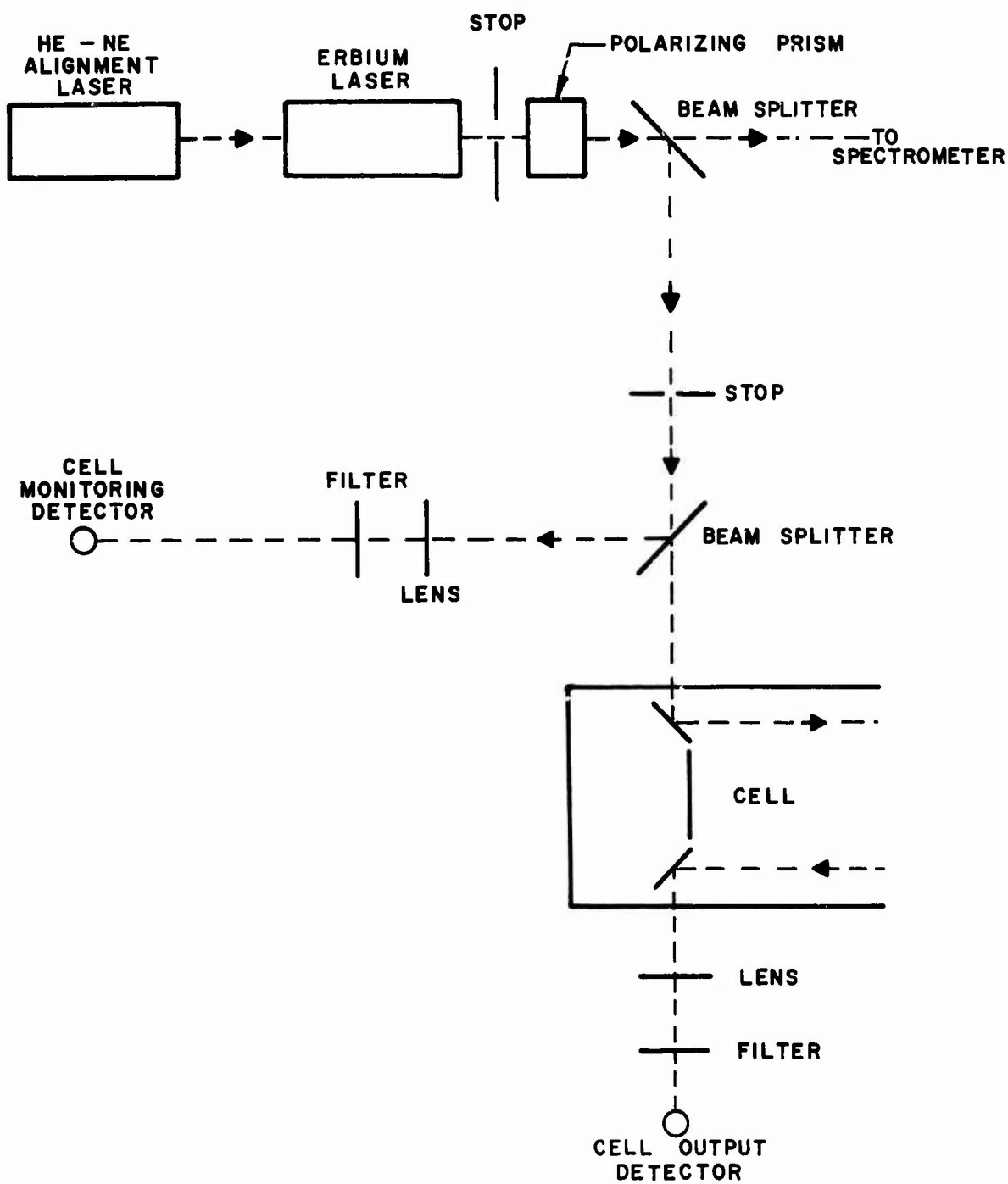


FIGURE 7. Experimental Arrangement with Erbium Laser

4. EXPERIMENTAL PROCEDURES

4.1. Laser Procedure

The spectral characteristics of the laser source are required for adequate analysis of absorption measurements. Therefore the spectrum of the laser emission was determined simultaneously with each absorption measurement. The arrangement of the experimental apparatus used for these measurements is shown schematically in Fig. 7. Since the erbium laser output is pulsed and invisible, a one milliwatt 0.6328μ wavelength helium-neon laser was used for alignment. The laser configuration using the cylindrical cavity with the 5000 joule maximum output helical flash lamp resulted in the most dependable emission. For some cases a polarizing Wollaston prism was used to obtain a linearly polarized beam. Filters (centered at 1.54μ with a 0.05μ bandpass) were employed to eliminate flash lamp light.

The wavelength of the erbium laser emission was calculated by noting its position with respect to four reference lines having a 200 mm spread in the focal plane of the spectrometer. These known lines of wavelengths 0.6096μ , 0.6128μ , 0.6143μ , and 0.6163μ (in 10th order) were isolated from a neon source with a 0.0075μ bandpass filter centered at 0.6130μ . The grating angle α_i for each of these lines was calculated from the grating equation by setting the angle of incidence equal to the angle of reflection, i.e., a Littrow configuration, so that

$$\alpha_i = \arcsin \frac{n \lambda_i}{2d} \quad i = 1, 2, 3, 4$$

where n is the order, λ the wavelength, and d the spacing between rulings. For the case of the erbium laser, the 1.544μ line in 4th order was near the neon 0.6163μ line in 10th order. Hence, with the grating positioned at the grating angle α_4 , corresponding to the 0.6163μ neon line λ_4 , the laser wavelength λ was found by setting $\alpha = \alpha_4$ and $\beta = \alpha_4 + \Delta\alpha$ in the grating equation so that

$$\lambda = \frac{d}{n} [\sin \alpha_4 + \sin (\alpha_4 + \Delta\alpha)].$$

The quantity $\Delta\alpha$ is given by $\Delta L/f$ where ΔL is the distance, in the spectrometer focal plane, between the positions of λ and λ_4 and f is the focal length of the collimating mirror.

An indication of the spectral half-width of the erbium laser output was obtained by scanning its wavelength region in the focal plane of the spectrograph with the photovoltaic germanium diodes.

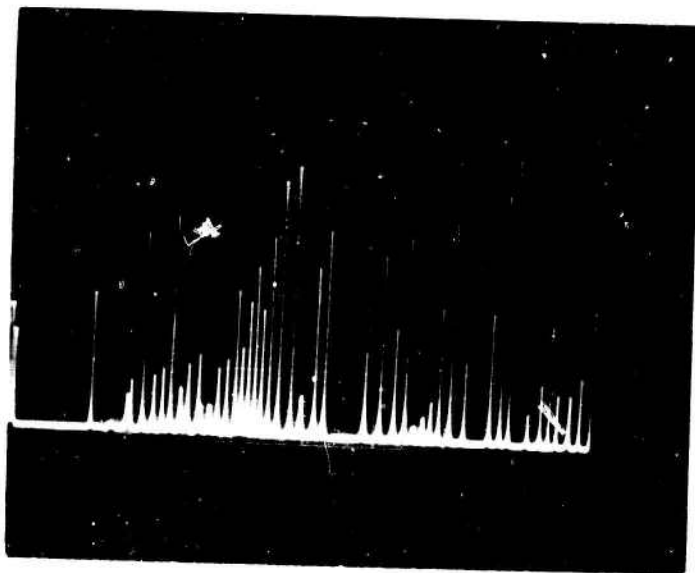
4.2. Absorption Cell Procedures

When the absorption cell was used for the erbium laser propagation studies, the procedures followed permitted the separate measurement of the various attenuating mechanisms present; i.e., cell optics, scattering, and absorption. In preparation for measurements, the cell was outgassed for several hours by raising the temperature to about 95°C and lowering the pressure to about 10^{-2} torr. The constant energy losses (reflection and absorption losses due to the cell optics) were measured at selected temperatures and various path lengths by determining the transmission of the laser while the cell pressure was maintained at about 10^{-2} torr. An estimate of the attenuation due to scattering in the cell was obtained by measuring the transmission in a nonabsorbing gas. For this case, the cell was filled with clean dry nitrogen (no absorption in 1.5 micron wavelength region) to ambient pressure. Any increase in the attenuation, over the corresponding constant energy loss case, can be attributed to Rayleigh scattering by the nitrogen and Mie scattering by particulates. Although the scattering was expected to vary from gas sample to gas sample, the Rayleigh scattering was accurately calculated for the various gases used, and the Mie scattering (from suspended particles picked up from the cell walls) was shown to be negligible. In practice, the results obtained from the nitrogen case were not significantly different from the vacuum case. Finally the cell was filled with the gas or gas mixture of interest and the absorption determined. The measurements were repeated for different path lengths, pressures, and temperatures. Typical data obtained are shown in Fig. 8. The absorption coefficient was obtained by the procedure outlined in the next section.

5. THEORY OF ANALYSIS

Each laser pulse consisted of a sequence of spikes as shown in Fig. 8. The individual spike heights of these pulses were measured before and after transmission, taking into account the different gain settings for the input and output detector channels. The intensity of a transmitted spike I_1^t was related to the intensity of the corresponding incident spike intensity I_1^o by the Lambert-Beer's law

$$I_1^t = I_1^o F_1 \exp [-k_1(\nu)x]$$



Source: Erbium Laser
Sweep Rate: 0.1 millisecond per division

FIGURE 8. Typical Absorption Cell Data

where $k_i(\nu)$ is the extinction coefficient at frequency ν , F_i the reflection and absorption losses due to cell optics and x the path length.

Ideally each spike height H_i is proportional to the detector voltage which in turn is proportional to the intensity I_i . It follows that

$$\frac{R_i^o H_i^t}{R_i^t H_i^o} = F_i \exp [-k_i(\nu)x]$$

where the superscript o designates input, the superscript t designates transmission, and R_i is the detector characteristic for the i^{th} spike. Since the extinction coefficient $k_i(\nu)$ is the sum of the absorption coefficient $\alpha_i(\nu)$ and the scattering coefficient $\beta_i(\nu)$, then the expression solved for the $\alpha_i(\nu)$ becomes

$$\alpha_i(\nu) = -\beta_i(\nu) - \frac{1}{x} \ln \left(\frac{R_i^o H_i^t}{R_i^t H_i^o F_i} \right)$$

In the case of transmission through vacuum, denoted by the superscript v, the absorption and scattering coefficients vanish, and one has

$$F_i^v = \frac{R_i^{ov} H_i^{tv}}{R_i^{tv} H_i^{ov}}$$

Under the assumption of constant energy losses due to optics (no time-varying energy loss due to optics from spike to spike in each measurement), one has

$$F_i^v \approx \overline{F^v}$$

where the overbar denotes the average over M different spikes. In the case of transmission through the absorbing gas mixture, denoted by the superscript g, we see that the average absorption coefficient for M different spikes is given by

$$\overline{\alpha^g(\nu)} = - \overline{\beta^g(\nu)} - \frac{1}{Mx} \ln \prod_{i=1}^M \left(\frac{R_i^{og} H_i^{tg}}{R_i^{tg} H_i^{og} F_i^g} \right)$$

Since the Rayleigh scattering for the gases in question was calculated to be small and the particle concentration measured was small so the Mie scattering was negligible, then

$$\overline{\beta^g(\nu)} \approx 0$$

Now, within the linear range of the detectors[†] one has

$$R_i^{ov} \approx \overline{R^{ov}}, R_i^{og} \approx \overline{R^{og}}$$

$$R_i^{tv} \approx \overline{R^{tv}}, R_i^{tg} \approx \overline{R^{tg}}$$

and again assuming constant energy losses due to optics, one has

$$F_i^g \approx \overline{F^g}$$

Hence the expression for $\overline{\alpha^g(\nu)}$ becomes

$$\overline{\alpha^g(\nu)} = - \frac{1}{Mx} \left[\ln \prod_{i=1}^M \left(\frac{H_i^{tg}}{H_i^{og}} \right) + M \ln \left(\frac{\overline{R^{og}}}{\overline{R^{tg}} \overline{F^g}} \right) \right]$$

If no systematic errors are introduced in going from the transmission measurements in vacuum to those in the absorbing gas mixture, then it follows that

[†]The linear range of the input and output detectors was determined by beam splitting the laser beam onto the two detectors with equal paths between the beam splitter and each detector. The output of one detector was plotted versus the output of the other as the beam in one of the two paths was attenuated with neutral density filters.

$$\overline{F^g} = \overline{F^v}, \overline{R^{og}} = \overline{R^{ov}}, \text{ and } \overline{R^{tg}} = \overline{R^{tv}}$$

so that the expression for $\overline{\alpha^g(v)}$ reduces to

$$\overline{\alpha^g(v)} = -\frac{1}{Mx} \left[\ln \prod_{i=1}^M \left(\frac{H_i^{tg}}{H_i^{og}} \right) - M \ln \left(\frac{1}{M} \sum_{i=1}^M \frac{H_i^{tv}}{H_i^{ov}} \right) \right]$$

or

$$\overline{\alpha^g(v)} = -\frac{1}{Mx} \left[\ln \prod_{i=1}^M \frac{H_i^{tg}}{H_i^{og}} - M \ln \sum_{i=1}^M \frac{H_i^{tv}}{H_i^{ov}} + M \ln M \right]$$

It follows that

$$\overline{\alpha^g(v)} = \frac{1}{x} \left[\ln \left(\frac{H^{tv}}{H^{ov}} \right) - \ln \left(\frac{H^{tg}}{H^{og}} \right) \right]$$

where

$$\ln \left(\frac{H^{tv}}{H^{ov}} \right) = \ln \left[\frac{1}{M} \sum_{i=1}^M \left(\frac{H_i^{tv}}{H_i^{ov}} \right) \right]$$

and

$$\ln \left(\frac{H^{tg}}{H^{og}} \right) = \frac{1}{M} \sum_{i=1}^M \ln \left(\frac{H_i^{tg}}{H_i^{og}} \right)$$

The transmission τ_i for a given path length x_i is given by

$$\tau_i = e^{-\overline{\alpha^g(v)} x_i}$$

Under the assumed conditions it is to be noted that the average absorption coefficient $\alpha^g(\nu)$ is independent of detector characteristics R_1 .

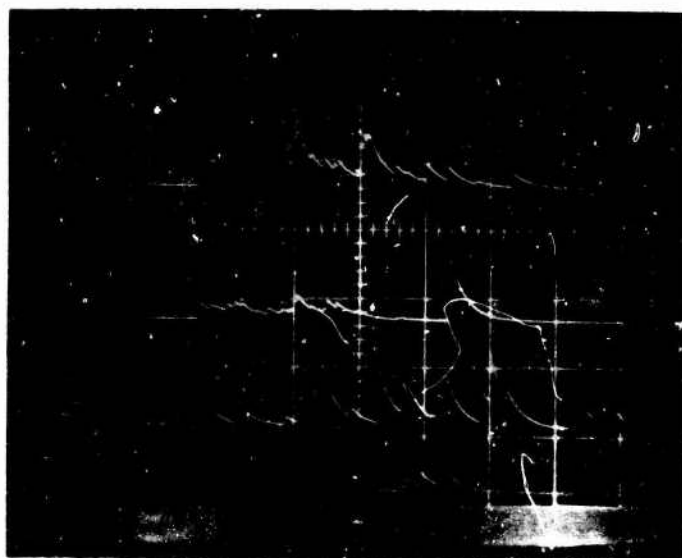
6. RESULTS

6.1. Spectral Measurements

The wavelength of the erbium laser emission, obtained from initial spectral measurements, was $1.544 \pm 0.0005\mu$ with a full width at half maximum of about 0.0015μ . The cylindrical rod-helical flash lamp configuration was used with 99%/95% reflectance wedge dielectric reflectors. This configuration was used for several hundred laser firings and for the initial absorption measurements. The threshold for laser oscillation was about 900 joules. It was subsequently learned that other investigators (18) were obtaining emission at 1.536μ from similar laser rods. The difference between the experimental results was apparently due to the efficiencies of the cavities used by the different investigators. The output reflector was therefore changed to first 80% reflectance and then 50% reflectance (aluminum-coated flats). The emission obtained with the 80% output reflector was still at 1.544μ but with a higher threshold. With the 50% output reflector, however, emission was obtained at 1.536μ with a threshold of about 1300 joules. By choosing the cavity losses appropriately, it was also possible to obtain both wavelengths at once.[†] The two laser emission lines are shown in Fig. 9; the upper two traces are at 1.536μ and the bottom two are at 1.544μ . The fact that both wavelengths were obtained with the 95% output reflector, whereas initially only the 1.544μ line was obtained, is due to additional cavity losses introduced, in time, by pits forming on the rod ends.

It was observed during these measurements that the surface of the rod slowly deteriorated and the ends became pitted. Figure 10 shows the effects of pitting. Figure 10a is a photograph taken under 50X magnification of one end of the rod after about 125 firings and Fig. 10b shows the same area after about 400 firings. The pits had the effect of lowering the efficiency of the cavity so that eventually laser oscillation was not obtainable at the 1.544μ line and finally ceased altogether (maximum pump attempted 1800 joules). The rectangular rods were then used, and oscillation has been obtained at both wavelengths separately and simultaneously.

[†] Simultaneous within the time resolution available ($\approx 10^{-6}$ sec).



λ 1.536 μ , .5V/cm

λ 1.536 μ , .5V/cm

λ 1.544 μ , .5V/cm

λ 1.544 μ , .2V/cm

Pump: 1450 joules
Reflectance: 99%/95%
Sweep Rate: 0.5 millisec/cm

FIGURE 9. Simultaneous Emission of lines at 1.544 and 1.536 μ .



(a) 125 firings, 50X magnification



(b) 400 firings, 50X magnification

FIGURE 10. Effects of Pitting

In order to retard the degradation of the laser rods, careful cleaning of their surfaces and shielding of their ends from the flash lamp output was necessary. The cleaning procedure consisted of washing the rods with a mild soap and water solution, rinsing with distilled water, and then baking at around 50°C under about 100 torr pressure for one to two hours. A more detailed discussion of this problem has been published elsewhere (19).

6.2. Cell Measurements

The aerosol contribution to the attenuation in the cell was investigated by measuring the dust concentration in the cell with a Royco particle counter. This was done by flowing clean dry nitrogen through the cell and then sampling directly in the cell with the Royco. It was found that there were fewer than 1.76×10^4 particles/m³ (500 particles/ft³) with a diameter larger than 0.3 micron, fewer than 4.24×10^3 particles/m³ (120 particles/ft³) larger than 0.5 micron, and none larger than 5 microns. Under good atmospheric conditions the concentrations are at least 1000 times larger and result in about 10% loss per km of 1.54 micron radiation. Therefore, the aerosol attenuation in the cell is negligible.

Erbium laser atmospheric absorption measurements in clean dry air (78% N₂, 21% O₂, 0.2% CO₂, and noble gases) were made with path lengths varying from 400 to 1600 meters, a cell temperature normally around 37°C, and a cell pressure of 660 torr. Since the aerosol attenuation was shown to be negligible, the average absorption coefficient

$\alpha^g(v)$ was determined from these measurements as outlined in Section 5. The transmission obtained using this average absorption coefficient was $87\% \pm 10\%$ per km.

7. SUMMARY

A new emission line of the erbium laser at 1.544 μ and the simultaneous emission of lines at 1.544 μ and 1.536 μ are reported. Preliminary absorption measurements using clean dry air yielded a transmission of $87\% \pm 10\%$ per km of 1.54 micron radiation.

A laboratory facility for the investigation of the absorption of electromagnetic energy by simulated atmospheres is also described. The facility consists of a combined 3.3-meter grating spectrograph-monochromator and a 20-meter multipass absorption cell. Control of the temperature, pressure, humidity, and gaseous composition of the medium under study is provided.

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Initial results are presented of an experimental study utilizing an absorption cell facility to determine erbium laser propagation characteristics in simulated atmospheres. The facility consists of a 3.3-meter spectrometer coupled to a 20-meter multipass absorption cell. The cell environment can be controlled over a wide range of pressures, temperatures, humidities, and gas concentrations. Absorption measurements were made with path lengths varying from 400 to 1600 meters in a simulated atmosphere consisting of clean dry air. The initial experimentally measured attenuation of 1.54 micron radiation by clean dry air is less than 25% per km. The results include the discovery of a new emission line of the erbium laser at 1.544 microns and the simultaneous emission of lines at 1.544 and 1.536 microns.		

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