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**THE CONSTANT PRESSURE DECOMPOSITION OF
NITROUS OXIDE, $N_2O + .88N_2$, AND $N_2O +$
AIR MIXTURES AT 11.2 ATMOSPHERES AND
INITIAL TEMPERATURES FROM 772 TO 1233°K**

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FOREWORD

This interim technical documentary report was prepared by J. R. Nicholson, E. S. Fishburne and R. Edse of the Department of Aeronautical and Astronautical Engineering of The Ohio State University on Contract Number AF 33(657)-8951, Project 7065, Aerospace Simulation Techniques Research, Task 7065-01, Fluid Dynamics Facilities Research. The research on this task was administered under the direction of the Aerospace Research Laboratories, Office of Aerospace Research, United States Air Force, with Mr. John Goresh, Fluid Dynamics Facilities Laboratory, as Contract Monitor.

ABSTRACT

The thermal decomposition of N_2O , $N_2O + .88N_2$, and $N_2O + AIR$ has been investigated in a flowing system. These studies were conducted at 11.2 atmospheres over the temperature range from $772^\circ K$ to $1233^\circ K$, and total flow rates from 1.0 to 3.76 liters/sec. Total residence times in the heated section range from approximately .1 to 2.5 sec. A maximum reacted gas temperature of $1588^\circ K$ was obtained. Chromatographic analysis of the products of decomposition showed that the maximum nitrogen dioxide yield was 4.44% for the $N_2O + AIR$ mixture, 5.09% for the $N_2O + .88N_2$, mixture, 7.55% for the pure N_2O decomposition. Spectrographic observations of the emitted radiation from the decomposition reactions showed the presence of nitrogen dioxide in the reaction. Nitrogen dioxide absorption bands were found. There was no evidence of any discrete bands in emission.

A reaction rate constant of $4.15 \times 10^{10} \exp \left\{ - \frac{51,000}{R T} \right\}$ was calculated

for the decomposition of nitrous oxide in the $N_2O + .88N_2$ mixture.

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LIST OF SYMBOLS

a	Indicates after the reaction	
A	Heater cross-sectional area	(cm ²)
b	Indicates before the reaction	
c	Frequency factor	(sec ⁻¹)
E _a	Activation energy	(cals/mole)
h	Planck's constant - 6.623 x 10 ⁻²⁷	($\frac{\text{gm cm}^2}{\text{sec}}$)
k	First order reaction rate	(sec ⁻¹)
K ₀	Equilibrium constant for $\frac{1}{2} \text{O}_2 \rightarrow \text{O}$ reaction	(atm ^{1/2})
L	Length of the heater	(cm)
\dot{m}	Mass flow rate	(gm/sec)
n	Specific molality	(moles/gm)
p	Pressure	(atm)
P ₀ , P _{O₂}	Partial pressure of atomic and molecular oxygen	(atm)
R	Universal gas constant - 1.986	($\frac{\text{cal}}{(\text{mole}) (^\circ\text{K})}$)
	82.06	($\frac{(\text{atm}) (\text{cm}^3)}{(\text{mole}) (^\circ\text{K})}$)
T	Gas temperature	(°K)
\bar{T}	Average gas temperature in heater	(°K)
\bar{u}	Average linear gas velocity through heater	(cm/sec)
ΔH ₀ ⁰	Standard heat of formation at 0°K	(cal/mole)
ΔH _f ^T	Heat of formation at indicated temperature	(cal/mole)
\bar{M}	Molecular weight of the mixture	(gms/mole)
η_i	Mole fraction	

LIST OF SYMBOLS (CONT'D)

$\bar{\rho}$	Average gas density	(gms/cm ³)
τ_R	Residence time of the gas in the heater	(sec)
ν	Frequency of emitted radiation	(sec ⁻¹)
\dot{V}	Standard volume flow rate	(liters/sec)
(N ₂ O)	Concentration	(moles/c _c)
*,**	Excited states	
3*, 3**	3Σ or 3 _π states	

SECTION I

INTRODUCTION

The advent of hypersonic flight and re-entry flight into the earth's atmosphere has introduced experimental difficulties in adequate simulation of the aerodynamic characteristics for these conditions. Current materials technology has limited the maximum stagnation temperature to which air can be heated by conventional methods on a steady state basis to approximately 2000°K. Transient tests with zirconia pebble bed heat exchangers have been conducted with stagnation temperatures to approximately 2500°K; however, it is desirable to establish steady state conditions for extended periods of time so that more reliable measurements in the test cabin can be made. For the complete simulation of hypersonic flow characteristics, stagnation temperatures and pressures must be sufficiently high to permit not only Mach number simulation but also adequate Reynolds number simulation. Due to the high expansion ratio of the high Mach number nozzles, the static temperature of the exit gas is quite low, and in some cases, the gas (i.e., nitrogen and oxygen) may liquify. Obviously this phenomenon prevents us from achieving homogeneous flow.

The primary interest for the use of nitrous oxide as a wind tunnel testing medium results from the fact that the heat of reaction from the decomposition of nitrous oxide is approximately 20,000 cal/mole, assuming complete decomposition. Based on the results presented in Ref. 1 through 3, it appears that a completely self-sustaining decomposition of nitrous oxide is practical and possible. The resulting products of decomposition of nitrous oxide are 66% nitrogen and 33% oxygen for the complete decomposition. The adiabatic temperature rise for the pure nitrous oxide decomposition based on theoretical calculations (Appendix I) is approximately 1600°K. Assuming a preheat temperature of 1200°K, final gas temperatures of 2800°K are possible. Current state-of-the-art techniques allow heating pure nitrogen to a temperature of approximately 3000°K with graphite heaters. The temperature of the resulting mixture will be approximately 2900°K. This permits the attainment of steady state stagnation temperatures considerably higher than the highest currently being employed in the simulation of hypersonic conditions. For the complete decomposition reaction, $N_2O + .88N_2$, the products are $1.88 N_2 + .50 O_2$. This composition duplicates that of air.

The decomposition reaction of nitrous oxide has been investigated rather extensively by constant volume bomb methods; however, this does not provide adequate information for a flowing system or a constant pressure decomposition. The fundamental purpose in the design of this system was to permit the investigation of the decomposition reaction of nitrous oxide for constant pressure conditions. It is necessary, therefore, to determine the conditions which lead to complete decomposition of nitrous oxide, the species concentration and maximum achievable temperatures.

The constant pressure decomposition of nitrous oxide has been investigated (Refs. 1-3, 12). Investigation of the constant volume decomposition of nitrous oxide has been conducted by various investigators (Refs. 4 through 12). In general, the primary interest has been in the area of the constant volume reaction. Investigations into the processes of decomposition during the constant pressure process at elevated pressures has not been investigated in detail. It is also of interest to determine the temperature of the reaction and the effects of the heating medium and the wall surfaces. It has been determined by other investigators (Refs. 1, 9-11) that nitric oxide is a fundamental product of the decomposition reaction. Since this occurs as a product of one of the steps of the reaction, it is most probable that any system using nitrous oxide must accept the existence of the nitric oxide; however, it would be expected that certain experimental techniques could be utilized to minimize the formation of nitric oxide.

Various methods of initiating the decomposition reaction were considered. Among these were electrothermal heat addition, electric arc energy addition, or by the addition of a nitrous oxide stream (heated to just below the decomposition temperature) to a high temperature stream of nitrogen. It was decided that the appropriate approach to this experimental program was to obtain the results from direct electrothermal heat addition to the nitrous oxide. The effects of various additives to the gas are considered (i.e., nitrogen and air). The latter approach considered will be the approach taken in a future investigation at this Laboratory.

SECTION II

EXPERIMENTAL APPARATUS

The experimental apparatus utilized in this investigation was discussed in detail in Ref. 8. A brief discussion of the apparatus will be included.

The reaction vessel is illustrated in Fig. 1. This vessel is made of stainless steel pipe, 8-1/2" I. D. x 1-1/8" wall thickness, 10 feet long. It was designed to withstand a maximum working pressure of up to 200 atm. The flanges on each end provide ready access to the internal heaters in the reaction chamber section.

The heaters are constructed of 1" I. D. alumina tube with a 1/8" wall. The tubes are wrapped with approximately 90 turns of .040" Kanthal A-1 resistance wire. The maximum operating temperature of this heater is approximately 1600°K. A coating of alumina cement was placed on the outer surface of the tube to provide structural support to the resistance wire and to increase the heat transfer coefficient from the wire to the tube. Each of the four sections of the heater have a power dissipation of 3 kilowatts at 220 volts AC. It was found that

this power input was completely adequate and in most cases created thermal overshoot problems. A rather serious disadvantage to this heater design was the small wire size. The lifetime of the smaller diameter wire is reduced considerably. A more appropriate design would have utilized large diameter wire, with a low-voltage, high-current power supply.

Heater temperature control was obtained with four Simplytrol thermocouple actuated temperature controllers. The schematic diagram is shown in Fig. 2. The chromel/alumel thermocouples for control of the wall temperatures were imbedded in the outer surface of the ceramic cement coating at the downstream end of the heater. The percentage on-time of the heaters is controlled by means of conventional percentage timers. This permitted control of the average rate of power input into the system at a constant supply of voltage, helping to eliminate the effects of thermal overshoot.

A similar arrangement was utilized for the reaction section. There are a total of 5 sections in the reaction zone. The original concept was that the first four sections which are heated sections would act as a preheater, and the reaction would occur in the first five sections of the reaction zone. Due to the extremely rapid reaction, it was impossible to shift the reaction from the heater into the reaction zone. This problem will be discussed in further detail in Section III.

In the original design of the system, a fixed orifice for exhausting the gases to the atmosphere was used. It was found, however, that due to the combined effects of increased temperature and volume flow rate caused by the decomposition, the pressure level could not be adequately controlled to maintain a constant internal pressure. A variable pressure switch was used in conjunction with a solenoid valve to pressurize or depressurize a pneumatically operated Annin valve. This arrangement worked quite well and maintained the pressure in the reaction vessel to within ± 2 psig of the desired operating pressure.

An observation window with a 1" diameter opening is located on the upstream flange. This provides visual observation of the reaction and the heaters. It was originally anticipated that optical pyrometer temperature measurements of the probe might be made; however, due to the luminosity of the reaction, it was impossible to observe the probe. For normal experiments, a window made of Herculite glass, 1-1/4" thick, was utilized; however, during some of the spectrographic measurements, a quartz window was used to eliminate the absorption effects in the short wave length regions.

A water-cooled probe is used to obtain gas temperatures and gas samples. This probe can be moved axially throughout the entire length of the reaction chamber and heater assembly. The positioning arrangement and locking mechanism for the probe is illustrated in Fig. 1. The gases removed for sampling are quenched by the internal water cooling. Since the water temperature at no time exceeded 120°F, the quenching effect was quite adequate. Original design of the thermocouple probe incorporated a

tungsten/tungsten-26% rhenium thermocouple for temperature measurements above 2000°K. Since the observed temperatures were well within the temperature range of chromel/alumel thermocouples, a sheathed chromel/alumel thermocouple was used in place of the tungsten/tungsten-26% rhenium thermocouple. Better measurement accuracy was obtained in the lower temperature region observed.

Gas samples are withdrawn from the reaction tube into evacuated 250 ml Pyrex flasks. These flasks are connected to the vacuum pump until the sample is obtained. A three-way solenoid valve is used to divert the sampling stream from a vent into the sampling flasks. The flasks are then flushed approximately 15 to 25 seconds for a total volume change of approximately 10 to 15 times. This virtually eliminates the presence of impurities in the sample. These flasks are evacuated to an absolute pressure of approximately 100 microns before the samples are taken.

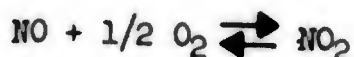
An F and M Scientific Corporation Model 500 Linear Temperature Programmed Gas Chromatograph is used to analyze the gas samples. A molecular sieve 5A column, 42 inches long is used. Various methods of determining the composition of mixtures of nitrogen, oxygen and the oxides of nitrogen (i.e., nitric oxide, nitrogen dioxide and nitrous oxide) are given in Ref. 13 through 16. Since the mixture of the oxides of nitrogen in the presence of oxygen is very reactive at room temperature, this makes the complete analysis of these gases extremely difficult by gas chromatography. However, when analyzing mixtures containing nitrogen, oxygen, nitrogen dioxide and nitrous oxide, it was observed that there were 4 distinct indications of the various constituents. Comparisons with mixtures of nitrogen, oxygen, nitrous oxide showed that three of the peaks could definitely be identified as produced by these constituents. The fourth peak was considered to be that corresponding to the composite of the equilibrium mixture of the oxides of nitrogen at room temperature. In an attempt to obtain a direct calibration for the percentage of the oxides of nitrogen, equilibrium mixtures of nitric oxide and air were made. At room temperature nitric oxide in the presence of a large excess of oxygen reacts nearly completely to form an equilibrium mixture of nitrogen dioxide and nitrogen tetroxide. Equilibrium constants for the reaction



were obtained from Ref. 17. At room temperature (20°C) and a very small concentration of nitrogen dioxide, this reaction is almost completely shifted to the left side. According to the Le Chatelier principle, high pressures will shift the reaction to the right. Increasing temperatures will shift the reaction to the left. For total percentages of the oxides of nitrogen less than 5%, the reaction is shifted approximately 95% to the left.

Calibration of the detector response to various percentages of the oxides of nitrogen were performed to determine if the total percentage could be determined directly. Quite interestingly enough, the height of

the composite peak was linearly related to the number of moles of the equilibrium mixture of the oxides of nitrogen and air; however, at very low concentrations, the slope of the calibration curve shifted quite drastically. The sensitivity of the detector to extremely small amounts of the oxides of nitrogen at very low partial pressures was much higher than for higher percentages. This was corroborated by observations of the analyses of the mixtures of nitrous oxide which had obviously not decomposed. In some cases where there was approximately 1/2% of oxygen present in the sample, a slight peak was observed before the nitrous oxide peak. Since the equilibrium constant at room temperature for the reaction



is approximately 10^6 , effectively all of the nitric oxide will be oxidized to nitrogen dioxide in the presence of excess oxygen.

Visual observation of these sample flasks showed that the presence of nitrogen dioxide must be less than .01% since no brown color could be detected. It is felt, therefore, that if nitric oxide is formed in the reaction, its concentration was less than .01%. Calibration for the other constituents in the gas (i.e., nitrogen, oxygen and nitrous oxide) was performed with dry high pressure air and a calibration gas which consisted of nearly equal parts of oxygen, nitrogen, and nitrous oxide. In Ref. 8, a method of determining the amount of nitrogen dioxide in the sample was outlined. This method required dry ice-alcohol traps to freeze out the nitrogen dioxide, and analyze the mixture by difference. It was found by subsequent analyses, that the small percentage of nitrogen dioxide in the mixture (i.e., from 1% to 5%) lead to rather serious errors in the determination of this percentage. The analysis for the mixture of the oxides of nitrogen was conducted as described above. In addition, the nitrous oxide percentage was determined directly. The total percentage of nitrogen plus oxygen was then determined by difference, and the individual percentages of nitrogen and oxygen were determined by area ratios. The appropriate correction for thermal conductivity differences between the two gases was applied to the area ratio.

The spectrographic techniques utilized in the study involved four basic pieces of equipment. Initial observations were made with a small Bausch and Lomb hand spectroscope. Those observations clearly revealed the presence of various band systems. For a more refined spectral analysis a Hilger-Watts quartz prism spectrograph was used. This instrument utilized 3-1/4" x 4-1/4" glass plates. It was found, however, that due to the characteristics of the quartz prism and the fact that the spectral regions of primary interest was above 4500 Å, the dispersion of the quartz prism was insufficient to permit any adequate interpretation of the spectra. Subsequently, a Bausch and Lomb Medium Cornu Spectrograph was used. This spectrograph was placed immediately adjacent to the reaction tube. This instrument was used primarily to determine the existence of the continuum cut-off point.

Greater resolution was obtained with a Jarrell-Ash 21-foot Grating Spectrograph. Various films and plates were used. Eastman Kodak Tri-X, Type I-N, and I-O Spectroscopic 35mm films were used. Type I-N, II-F, and IV-O 4" x 10" glass plates were also used. The geometric arrangement of the light path is shown in Fig. 3.

SECTION III

EXPERIMENTAL RESULTS

(1) Pure N₂O Decomposition

The decomposition reaction of pure nitrous oxide was investigated at a pressure level of 11.2 atmosphere. Flow rates of 1.0 to 2.0 liters per second were used. Initial temperature levels from 772°K to 1138°K were investigated. The results are tabulated in Tables I through III.

Initial experiments were conducted with an air purge to stabilize the temperature of the heaters. It was found, however, that the samples were taken before the nitrous oxide had completely eliminated the air from the test section. Subsequent experiments were conducted with pure nitrogen as the stabilizing medium. Air leaks into the reaction chamber were also observed. These leaks were apparently caused by an aspiration effect at the junctions of the heater sections. During the remainder of the experiment, the annular cooling air was terminated during the experiments to eliminate this problem.

The procedure followed during these experiments was to stabilize the heaters at some temperature level with pure nitrogen at a flow rate of approximately 1.0 liters/sec. After the temperature had stabilized, the nitrogen flow was terminated, and the nitrous oxide flow was started immediately. There was a rather long lag time (approximately 15 seconds) before any reaction was observed. This lag occurred at all temperature levels. Most likely this lag was caused by the long distance (approximately 35 feet) between the flow control panel and the reaction vessel, and the initially high concentration of nitrogen in the reaction chamber. Approximately 30 seconds after the nitrous oxide flow was started, the sample was taken. Approximately 15 to 25 seconds were needed to insure adequate flushing of the sample flask. Upon completion of sampling, the nitrous oxide flow was terminated and nitrogen was introduced.

During the experiments with pure nitrous oxide, some rather interesting results were noted. The luminosity from the reaction generally appeared to begin at the far end of the heater section, and then very rapidly traveled back to the area of the injectors and observation window. Visual observation of the color of the emitted radiation showed that there are apparently two distinctly different types of radiation. During the "initiation period", the time between the first indication of a reaction and the transition into a stable decomposition reaction, the color is a brilliant yellow. After the

reaction is stabilized, the color is more reddish-orange. The results of the spectrographic studies will be discussed more completely in a later section.

Great difficulties in obtaining a partial decomposition of the nitrous oxide were experienced with all experiments with pure nitrous oxide. Associated with the "transition" phenomena discussed above, was the virtual impossibility of obtaining a partial decomposition. All samples taken showed that the nitrous oxide either did not decompose, or that the reaction had gone virtually to completion.

The measured temperature of the reacted gases was always much less than indicated by theoretical calculations. The adiabatic decomposition temperature rise for this reaction should be approximately 1600°K (Appendix I and Figure 4), assuming that there is no dissociation of the oxygen and that no intermediate compounds, such as nitric oxide and nitrogen dioxide, are formed. Existence of the latter constituents in the system will lower the calculated value of the temperature. Experimental results tabulated in Tables I-III show that the maximum observed temperature rise was 688°K or about 40% of the theoretical values. This temperature was observed at the outlet of the first heater section, with a total flow rate of 2.0 liters/second.

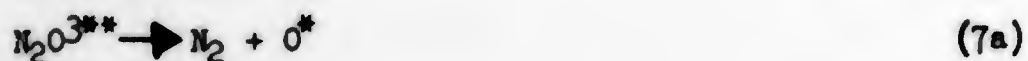
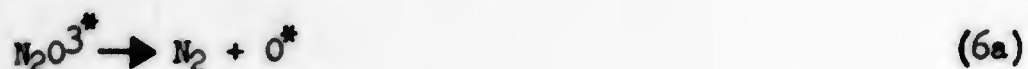
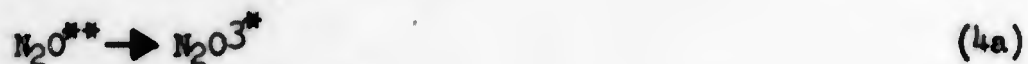
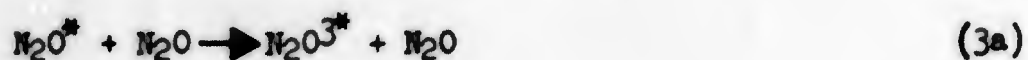
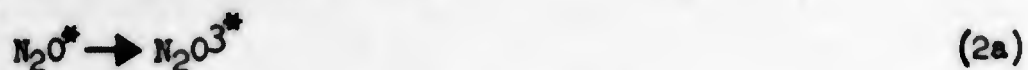
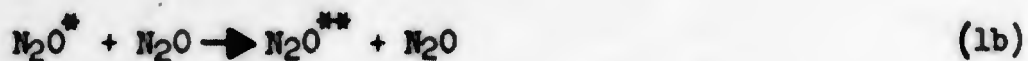
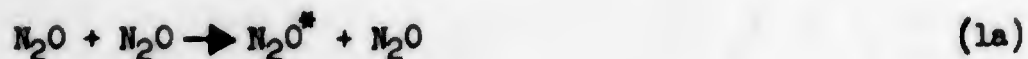
The data on the results with the pure nitrous oxide system are somewhat scattered; however, the formation of nitrogen dioxide in this system increases with increasing initial temperature and with increasing flow rates.

Reference 10 presents a set of reactions as follows



where $\Delta H_{\text{f}}^{\circ}$ = heat of formation at 0°K

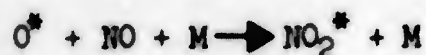
According to this set of reactions, it is difficult to explain the presence of the radiation. Kaufman, et al (Ref. 10), observed the radiation and ascribed it to the fluorescence of the electronically excited nitrogen dioxide molecule. Reuben and Linnett (Ref. 9) have postulated that the set of activation equations are



where 3^* and 3^{**} are the 3Σ and 3Π states, although not necessarily in that order, and the symbols $*$ and $**$ are used to designate an excited state. Assuming that nitrous oxide decomposes according to reactions (1) through (6), and that the unimolecular decomposition reaction of nitrous oxide occurs as indicated in (1a) through (7a), reaction (1) will be modified to



Assuming that excited atomic oxygen atoms are formed, equation (4) can be written as



The radiation would then originate from the excited nitrogen dioxide molecule



where h = Planck's constant

ν = Frequency of the emitted radiation

Based on the observed experimental results, it is expected that the rate of reaction (3) increases faster with increasing temperature than that of equation (2).

As determined by other investigators (Ref. 10), nitric oxide is formed during the early stage of the reaction and subsequently inhibits

the formation of additional nitric oxide. These results are in agreement with the results obtained for increasing flow rate, i.e., larger amounts of nitrogen dioxide formed.

The existence of wall effects or a wall reaction is indicated by the observed reactions and maximum temperature increases observed. As would be expected, if the effects of a wall reaction are present, the temperature rise will decrease with increasing temperature, and will increase with increasing flow rate. An increasing wall temperature will cause the wall reaction to accelerate, thereby increasing the amount of heat transfer to the wall. Increasing flow rate will shift the reaction downstream, thereby causing more energy transfer to the gas stream. In addition, further verification of this effect is shown by the increasing temperature rises obtained as the probe is moved towards the inlet.

It was demonstrated that a self-sustaining reaction could very easily be maintained for the initial conditions and flow rates considered. This self-sustaining reaction was accomplished several times and it continued after all electrical energy had been cut-off; however, these experiments were not allowed to reach a stable state since the observed wall temperature rose to approximately 1300°K. This temperature is approaching the maximum safe usable limit of the heaters.

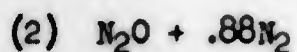
During the experiments in which the probe was positioned at the exit of the first and second heaters, observations of the reaction vessel showed that a reaction was occurring downstream of the probe. Since this occurred at temperatures lower than previously determined required for initiation of the reaction (859°K), it was expected that there might possibly be catalytic effects present. Sample probes of stainless steel, copper and silver solder covered stainless tubes were constructed. Interestingly, conditions which lead to no decomposition with stainless steel and copper tubes, produced a decomposition reaction when the rods were coated with silver solder. After causing a single decomposition, no further reactions could be initiated. Removal of the probe and repolishing the surface of the probe led to initiation of a reaction when re-inserted into the reaction tube.

The reactions on the surface of the probe most probably lead to the initiation of the reaction; however, the possibility of the probe acting as a "flame holder" may also play an important role in this effect. Corresponding to these effects is the low temperature required for initiation of the reaction when the probe was positioned at the outlet of the first heater. Characteristics of the vortex flow may also explain the low observed temperature required for initiation. Since the length-diameter ratio was from 12 to 24, a fully developed turbulent flow is probably not established. Large temperature gradients may exist in the gas stream under these conditions.

During visual observations of the reaction, it was noticed that a pulsation in the luminosity occurred. The frequency of the oscillation increased with increasing flow rate, and indeed, the luminous zone extended completely to the inner surface of the window. The presence of the

radiation at the window is quite difficult to understand, since the gas temperature in this region is not higher than 450 - 500°K. This observation can possibly be explained by a catalytic effect. The origin of the pulsations is not clear.

To consider the factors leading to the pulsation, the characteristics of the flow must be analysed. The injectors are designed to create a vortex flow necessary to provide maximum heat transfer to the gas. One of the four injectors is bent so that direct impingement of the gas on the window is effected to eliminate a possible "pocket" of cold reacted gases. Due to the high tangential peripheral velocity, a stagnant region in the center of the tube will exist for a short distance downstream of the inlet. In this region, which is somewhat cooler than the gases at the periphery due to the lower heat transfer rate, the reaction will occur at a slower rate. Products of the reaction zone around the periphery of the tube surface will be carried into the center of the tube, accelerating the reaction in the center. After completion of the reaction, the effect of the inert diluents (nitrogen and oxygen) in the center of the tube will be transported downstream, being continually replenished with fresh nitrous oxide. When the composition of the gases along the centerline of the tube becomes suitable, rapid reactions will again occur. This will then lead to a periodic reaction along the centerline of the tube.



Experiments were conducted with mixtures of $N_2O + .88N_2$, in a similar manner as described previously for the pure nitrous oxide experiments. The results are presented in Tables IV through VI. The maximum amount of nitrogen dioxide found during this investigation was 5.09%, although, in general, the amount determined was somewhat less than found in the pure nitrous oxide experiments. A larger temperature rise was obtained with the $N_2O + .88N_2$ mixture for flow rates corresponding to the pure nitrous oxide decomposition. In addition, since the theoretical temperature rise for the $N_2O + .88N_2$ mixture is approximately 1000°K (compared to 1500°K for the pure nitrous oxide decomposition), the percentage of the theoretical temperature rise for the $N_2O + .88N_2$ mixture was always greater than that observed for the pure nitrous oxide reaction.

Difficulties in obtaining a stable partial decomposition reaction were also encountered with this mixture. With the exception of three cases, the reaction went nearly 100 per cent to completion. Evaluation of the partial reactions permitted the calculation of a reaction rate constant.

The calculation of the first-order reaction rate constant is given in Appendix II; the value obtained is

$$k = 4.15 \times 10^{10} \exp\left\{-\frac{51,000}{R T}\right\}$$

The first-order reaction rate is of the form

$$k = c \exp\left\{-\frac{E_a}{R T}\right\}$$

where

$$c = \text{frequency factor} = 4.15 \times 10^{10} \text{ sec}^{-1}$$

$$E_a = \text{activation energy} = 51,000 \text{ cal/mole}$$

$$T = \text{initial temperature}$$

This first-order reaction rate agrees rather well with the data obtained in Ref. 18. The activation energy is somewhat lower than values obtained by other investigators. This is probably due to the effects of the wall reactions. The frequency factor which was determined is also low. This is in agreement with the data obtained by many other investigators.

Visual observations of the reaction vessel showed that the radiation was nearly optically transparent, as compared to the pure nitrous oxide decomposition which was optically opaque. In addition, the color of the gas was much more yellow. These results can be explained by the decreased nitrogen dioxide formation.

(3) N₂O + AIR

Results of the experiments with N₂O + AIR are presented in Table VII. Total gas flow rates of 2.0 and 3.0 liters/sec were used, with the probe positioned at the outlet of the fourth heater. The maximum temperature rise for this particular position and flow rate is higher than that obtained either with the pure nitrous oxide or the N₂O + .88N₂ reactions. It is therefore concluded that the reaction rates follow the following scheme:

$$k_{N_2O} > k_{N_2O + .88N_2} > k_{N_2O + AIR}$$

At the maximum flow rate, and temperatures considered, no decomposition was obtained for this mixture.

Visually, the radiation from this reaction appeared to be similar to that obtained with N₂O + .88N₂ mixtures.

(4) Spectrographic Observations

Initial investigations of the radiation from the decomposition reaction of pure nitrous oxide were made using a small hand spectroscope. The results of these investigations indicated that it would be worthwhile to attempt to identify the origin of the radiation. For this purpose, a rather elaborate optical path was constructed, shown in Fig. 3, to utilize the Jarrell-Ash 21-foot grating spectrograph. Since there appeared to be two distinctly different colors (i.e., bright yellow during the starting process and reddish-orange during stable decomposition) attempts were made to obtain the spectra of each phase. Figure 4 shows the spectra obtained with Eastman Kodak Tri-X film. Although the film sensitivity decreased quite rapidly for wavelengths longer than 6500 Å, in the region of primary interest (5500 Å), it was sufficient to obtain the spectrum.

The radiation during the starting process was photographed by repeated exposures. No bands in absorption were found in this phase of the reaction; however, the steady state reaction produced a band spectrum in absorption as shown in Fig. 4. In both cases, however, a continuum background was observed. The intensity of the continuum was apparently much greater for the case of the steady state reaction.

To identify the system observed, it was necessary to obtain a reference spectrum of possible constituents. A small absorption cell, with a path length of 1" was filled with either nitrous oxide, nitric oxide or nitric oxide plus excess air. Light from a tungsten filament blackbody source was passed through the cell. Virtually no absorption was observed with the nitrous oxide and very slight absorption around 4000 Å was observed with the nitric oxide; however, the equilibrium mixture of nitric oxide plus excess air at approximately 100 psig resulted in a very complex absorption system. Comparison of the absorption spectra obtained from the reaction vessel with the reference spectra, indicated that the nitrogen dioxide molecule gave rise to the observed absorption spectra.

To obtain an absorption spectrum, the presence of a background source is necessary. Great care was taken to eliminate the blackbody radiation of the heater walls as a source of the continuum background. Repeated exposures for very short intervals (10 seconds), produced similar results to the longer exposures, i.e., identical absorption bands were observed with a continuum background. It is, therefore, concluded that the observed continuum was produced in the reaction rather than being caused by the blackbody radiation of the heaters.

A Bausch and Lomb Medium Cornu Spectrograph was positioned directly at the reaction vessel to determine if the apparent continuum had a cut-off at any particular wavelength. For cumulative exposure times of 90 seconds at 15 seconds per exposure, slit widths of 10, 50 and 200 microns, and type IV-0 spectroscopic plates, a continuum was observed down to approximately 3200 Å; however, no discrete cut-off point was observed.

A spectrogram of the stable decomposition reaction obtained by this spectrograph is shown in Fig. 5. Since the recombination continuum of the $\text{NO} + \text{O} \rightarrow \text{NO}_2$ reaction should cut-off at about 4000 Å, it is believed that this reaction is not the principle reason for the radiation. Kaufman, et al (Ref. 10) have postulated that the radiation is caused by chemiluminescence rather than thermal nitrogen dioxide molecule radiation. Since the nitrogen dioxide lines have been identified, the absorption bands are most probably due to self-absorption phenomena.

The mechanism of chemiluminescence of the $\text{NO} + \text{O}$ recombination reaction was studied by Clyne and Thrush (Ref. 19). The absorption spectra of an equilibrium mixture of nitrogen dioxide and nitrogen tetroxide in the spectral region from 2400 to 5000 Å was determined by Hall and Blacet (Ref. 20). Fluorescence spectra of the nitrogen dioxide molecule were investigated in the region above 4000 Å by Neuberger and Duncan (Ref. 21) using Raman spectrum techniques. The results obtained by Ref. 20 and 21 are of considerable interest in confirmation of the observed spectra.

The absorption spectra of nitrogen dioxide has a maximum at approximately 4000 Å with decreasing absorptivity towards longer and shorter wavelengths. The spectra showed the presence of some fine structure. The intensity of the absorption decreases continually with decreasing wavelengths down to approximately 2500 Å, although the absorptivity at 4000 Å is approximately 45 times as great as at 2500 Å; on the other hand, the absorptivity at 4000 Å is approximately 2-1/2 times as great as at 5000 Å. Neuberger and Duncan (Ref. 21) indicate that an absorption spectrum against a continuum background was obtained for relatively low nitrogen dioxide pressures (approximately 12 microns).

The observed results are in agreement with Refs. 20 and 21. Since the observed continuum extended to approximately 3200 Å, this may be caused by the radiation of the hot nitrogen dioxide molecule. Based on the absorption characteristics of nitrogen dioxide, similar emission characteristics due to thermal effects should be possible. The precise shape and position of the curve would probably be different due not only to different transition probabilities, but also due to the higher temperatures encountered in this investigation, 1000 - 1200°K, as compared to 300°K in Ref. 20. The higher vibration levels will be more highly populated due to the increased temperature level; thereby, shifting the maximum of the curve. The curve should also be flattened providing a more nearly constant emission spectra, over a broader spectral range.

This is, in fact, in agreement with the observed spectra. Since nitrogen tetroxide will be non-existent at the temperature levels obtained, no effect due to the short wavelength absorption will be encountered, and nitrogen dioxide will be the only source of the observed spectrum. It is somewhat questionable as to whether the total spectrum is only a function of the hot nitrogen dioxide radiation, or whether fluorescence may also account for some of the radiation in the region above 4000 Å (Ref. 21).

(5) Conclusions

The use of nitrous oxide as a working medium for a hypersonic wind tunnel requires a maximum total temperature rise (minimum heat loss) with a minimum formation of nitric oxide and nitrogen dioxide. Due to the characteristics of the decomposition reaction, it was impossible to achieve reaction temperatures approaching the theoretical values. This is primarily due to the effects of the wall on the reaction. Since, for nearly all cases, virtually complete decomposition was obtained in this temperature range and pressure level, acceleration of the reaction does not appear to be a significant problem. On the other hand, a more severe problem is encountered in equipment design due to the relative inability to control the reaction; however, for several experiments with pure nitrous oxide, a completely self-sustaining reaction was obtained without the use of any type of auxiliary reactor.

Experiments with $N_2O + .88N_2$ indicate that the amount of nitrogen dioxide formation may not be significantly great to prevent further consideration for use in a wind tunnel. Further experiments should be conducted for cases of more nearly adiabatic conditions to maximize the reaction temperature.

The observed spectra from the decomposition reaction show the presence of a continuum background, with the presence of absorption bands. The absorption bands correspond to nitrogen dioxide absorption, while the continuum is due either in total to the hot nitrogen dioxide radiation or a combination of hot nitrogen dioxide radiation and nitrogen dioxide fluorescence.

The reaction rates for nitrous oxide, $N_2O + .88N_2$, based $N_2O + AIR$ appear to follow the following scheme

$$k_{N_2O} > k_{N_2O + .88N_2} > k_{N_2O + AIR}$$

based on indirect observations of the temperature rise during the reactions.

REFERENCES

1. Sabol, A. D., and Evans, J. S., Investigation of the Use of the Thermal Decomposition of Nitrous Oxide to Produce Hypersonic Flow of a Gas Closely Resembling Air, NACA TN 3624, March 1956.
2. Thomas, R. E., Feasibility Study of the Use of Decomposed Nitrous Oxide in a Hypersonic Wind Tunnel, Wright Air Development Center Technical Note 59-377, September 1959.
3. Thomas, R. E., Experimental Study of the Use of Nitrous Oxide in a Hypersonic Wind Tunnel, Aeronautical Research Laboratories Technical Report 63-420, 1962.
4. Hunter, E., "The Thermal Decomposition of Nitrous Oxide to Forty Atmospheres", Proceedings of the Royal Society of London, Series A, 144, 386-412, 1934.
5. Krisjansons, J. O., Bollinger, L. E., and Edse, R., Explosion Limit Studies of Nitrous Oxide and Nitrous Oxide - Nitrogen-Air Mixtures to 200 Atm. and 1800°R, Aeronautical Research Laboratories Technical Report 62-431, September 1962.
6. Laughrey, J. A., Bollinger, L. E., and Edse, R., Detonability of Nitrous Oxide at Elevated Pressures and Temperatures, Aeronautical Research Laboratories Technical Report 62-432, September 1962.
7. Graven, W. M., "Kinetics of the Decomposition of N_2O at High Temperatures", J. Am. Chem. Soc., 81, 6190-2, 1959.
8. Fishburne, E. S., Nicholson, J. R., and Edse, R., Studies on the Decomposition of Nitrous Oxide, Aeronautical Research Laboratories Technical Report 63-134, August 1963.
9. Reuben, B. G., and Linnett, J. W., "Thermal Decomposition of Nitrous Oxide", Trans. Faraday Soc., 55, 1543-1553, 1959.
10. Kaufman, F., Gerri, N. J., and Bowman, R. E., "Role of Nitric Oxide in the Thermal Decomposition of Nitrous Oxide", J. Chem. Physics, 25, 106-115, 1956.
11. Johnston, H. S., "Interpretation of the Data on the Thermal Decomposition of Nitrous Oxide", J. Chem. Physics, 663-67, 19, 1951.
12. Briner, E., Meiner, C., and Rothen, A., "Researches Sur La Decomposition Thermique Du Protoxyde Et De L' Oxyde D' Azote", J. Chem. Physics, 23, 609-20, 1926.
13. Smith, D. H., and Clark, F. E., "Some Useful Techniques and Accessories for Adaption of the Gas Chromatograph to Soil Nitrogen Studies", Soil Science Society Proceedings, 111-115, 1960.

14. Smith, D. H., Nakayama, F. S., and Clark, F. E., "Gas-Solid Chromatographic Determination of Nitrogen Dioxide in the Presence of Oxygen", *Soil Science Society Proceedings*, 145-146, 1960.
15. Marvillet, L., and Transchant, J., "Qualitative and Quantitative Analysis of Gas-Solid Chromatography of Mixtures Containing Nitrogen Oxides", *Gas Chromatography*, 321-332, Butterworth Publications, London, 1960.
16. Lefort, M., and Tarrago, X., "Separation and Microanalysis of N_2 and NO in Mixtures of N_2 and its Oxides by Chromatography on an Absorbent Column", *J. Chromatography*, 2, No. 2, 218-220, 1959.
17. Blend, H., An Ultrasonic Investigation of the Dissociation Kinetics of Nitrogen Tetroxide, Dept. of Physics, University of California, Technical Report XIX, Office of Naval Research Contract NONR 233 (48), August 1962.
18. Fishburne, E. S., Bergbauer, D. M., and Edse, R., Shock Tube Decomposition of Nitrous Oxide, Aeronautical Research Laboratories Technical Report (in press).
19. Clyne, M. A. A., and Thrush, B. A., "Mechanism of Chemiluminiscent Combination Reactions Involving Oxygen Atoms", *Proc. Roy. Soc. (London)*, Series A, 269, 404-418.
20. Hall, T. C., and Blacet, F. E., "Separation of the Absorption Spectra of NO_2 and N_2O_4 in the Range of 2400 - 5200 A", *J. Chem. Phys.*, 20, 1745-49, 1952.
21. Neuberger, D., and Duncan, A. B. F., "Fluorescence of Nitrogen Dioxide", *J. Chem. Phys.*, 22, 1693-96, 1954.
22. Gordon, J. S., Thermodynamic of High-Temperature Gas Mixtures and Application to Combustion Problems, Wright Air Development Center Technical Report 57-33, January 1957.
23. JANAF Interim Thermal Chemical Tables, Thermal Laboratory, The Dow Chemical Company, December 1960.

APPENDIX I

The adiabatic flame temperature for the equilibrium reaction



was calculated for pressures of 1, 10, 100 atmospheres and for the case $b = 0$, $a = \frac{1}{2}$. For an adiabatic system, we have

$$n_{\text{N}_2\text{O}}^b \Delta H_f^{T_1, \text{N}_2\text{O}} + \sum_i n_i^a \Delta H_f^{T, i} = 0$$

$$\frac{T/T_b}{\eta_N^t} \sum \eta_i \left(\frac{\Delta H_f}{R T} \right)^{i, T} - \frac{1}{2} \left(\frac{\Delta H_f}{R T} \right)^{\text{N}_2\text{O}, T_b} = 0$$

$$\eta_N^t = 2 \frac{n_{\text{N}_2\text{O}}^b}{n^a}$$

where

η is the mole fraction

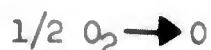
n_i is the specific molality of species i $\left(\frac{\text{moles of } i}{\text{gram of mixture}} \right)$

T_b is the temperature before reaction ($^{\circ}\text{K}$)

T_a is the temperature after reaction ($^{\circ}\text{K}$)

$\Delta H_f^{T, i}$ is the heat of formation of species i at the indicated temperature $\left(\frac{\text{calories}}{\text{gram of mixture}} \right)$

The equilibrium reaction for the dissociation of O_2 is

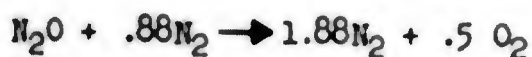


and the equilibrium constant can be given as

$$K_o = \frac{P_o}{\sqrt{P_{o_2}}}$$

The values for the thermodynamic function used in these calculations were obtained from Refs. 22 and 23. This method leads to an iterative or graphical type solution for the temperature, based on the equilibrium products at the various pressures and temperatures.

The adiabatic decomposition temperature was calculated also for the reaction



by evaluating the equation

$$\frac{T}{T_b} \left\{ 1.88 \left(\frac{\Delta H_f}{RT} \right)^{N_2, T} + 0.5 \left(\frac{\Delta H_f}{RT} \right)^{O_2, T} \right\} - \left\{ \left(\frac{\Delta H_f}{RT} \right)^{N_2O, T_b} + 0.88 \left(\frac{\Delta H_f}{RT} \right)^{N_2, T_b} \right\} = 0$$

The results of these calculations are presented in Fig. 6. It can be seen that the theoretical temperature rise for the case of no dissociation for the pure N_2O decomposition is approximately $1600^\circ K$, while for the reaction, $N_2O + .88N_2$, the temperature rise is approximately $1000^\circ K$.

APPENDIX II

CALCULATION OF RESIDENCE TIME AND RATE CONSTANT

The approximate residence time of the gas in the heater can be calculated as shown below

$$\tau_R = \frac{L}{U} \quad (\text{sec}) \quad (1)$$

where

τ_R is the residence time

L is the length of the heater

U is the average linear gas velocity

By continuity,

$$\bar{u} = \frac{\dot{m}}{\bar{\rho} A} \quad \left(\frac{\text{cm}}{\text{sec}}\right) \quad (2)$$

where

\dot{m} is the mass flow rate (gm/sec)

$\bar{\rho}$ is the average density (gm/cm^3)

A is the cross-sectional area (cm^2)

$$\dot{m} = m \left(\frac{\dot{V}}{22.4}\right) \quad \left(\frac{\text{gm}}{\text{sec}}\right) \quad (3)$$

and

$$\bar{\rho} = \frac{p}{\left(\frac{R}{m}\right) \bar{T}} \quad \left(\frac{\text{gm}}{\text{cm}^3}\right) \quad (4)$$

or

$$\bar{u} = \frac{R \dot{V} T}{22.4 p A} \quad \left(\frac{\text{cm}}{\text{sec}}\right) \quad (5)$$

where

\dot{V} is the volume flow rate at standard conditions (liters/sec)

\bar{T} is the average temperature $(^{\circ}\text{K})$

R is the Universal gas constant - 82.06 $\left(\frac{(\text{atm}) (\text{cm}^3)}{(\text{gm mole}) (^{\circ}\text{K})}\right)$

p is the pressure (atm)

For a pressure level of 11.2 atmospheres and a tube diameter of 2.5 cm, the expression for the average velocity is

$$\bar{u} = .0655 \dot{V} \bar{T} \left(\frac{\text{cm}}{\text{sec}}\right) \quad (6)$$

A flow rate of 3.76 liters/second, tube length of 91.5 cm, and temperatures of 1089 and 1158°K leads to residence times of .34 and .32 seconds, respectively. The corresponding concentration ratios

$\frac{(N_2O)_a}{(N_2O)_b}$ of N_2O after and before the reaction for the above conditions

is .289 and .0342, respectively.

Assuming a first order reaction, the decomposition of N_2O is given by

$$\frac{d(N_2O)}{dt} = -k(N_2O)$$

or

$$\frac{d(N_2O)}{(N_2O)} = -k dt$$

Integration leads to

$$\ln \frac{(N_2O)_a}{(N_2O)_b} = -k \tau_R$$

where a, b refer to after and before, respectively.

At $T_1 = 1089^\circ K$,

$$k_1 = 2.65 \quad (\text{sec}^{-1})$$

At $T_2 = 1158^\circ K$,

$$k_2 = 10.8 \quad (\text{sec}^{-1})$$

The reaction rate constant is given by the expression

$$k = ce^{-Ea/RT} \quad (7)$$

or

$$\frac{k_1}{k_2} = \exp\left\{\frac{Ea}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)\right\} = \exp\left\{\frac{Ea}{R}\left(\frac{1}{1158} - \frac{1}{1089}\right)\right\} \quad (8)$$

Evaluation of (8) gives

$$E_a = 51,000 \text{ cal/mole}$$

Substituting back into (7) and solving for c yields

$$c = 4.15 \times 10^{10}$$

and the final result is

$$k = 4.15 \times 10^{10} \exp \left\{ - \frac{51,000}{R T} \right\}$$

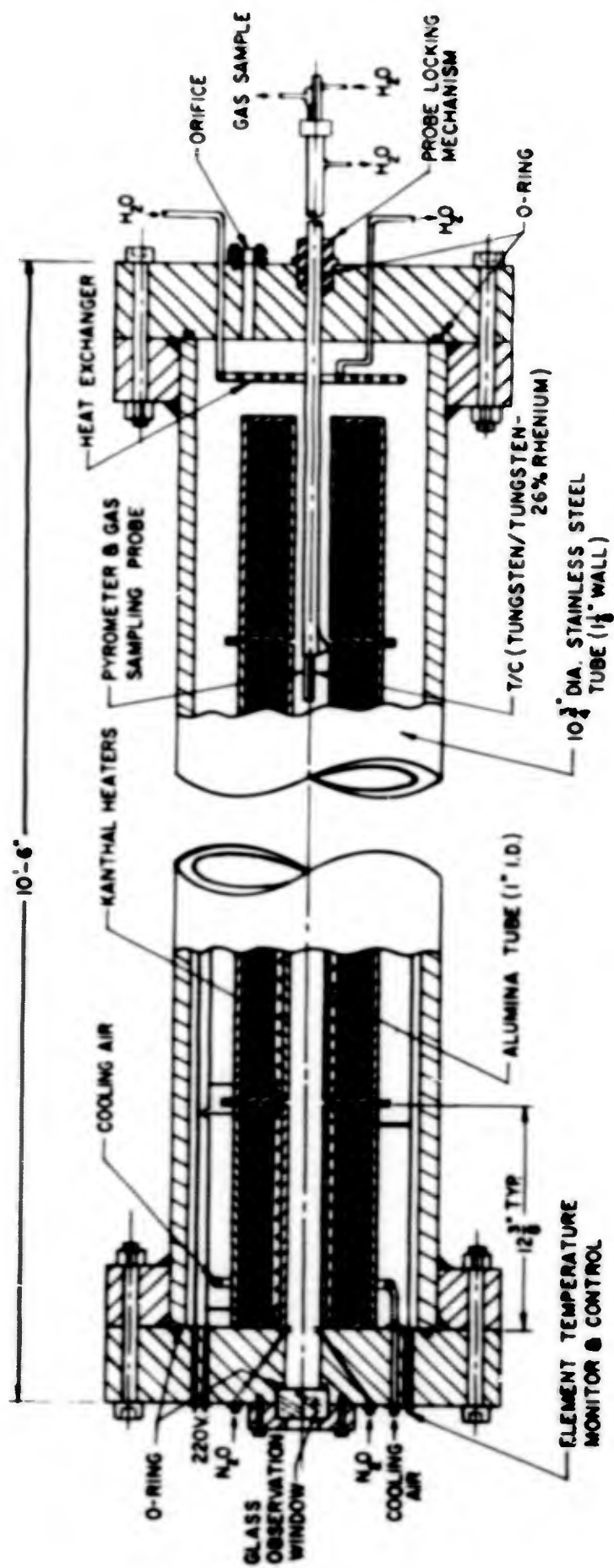
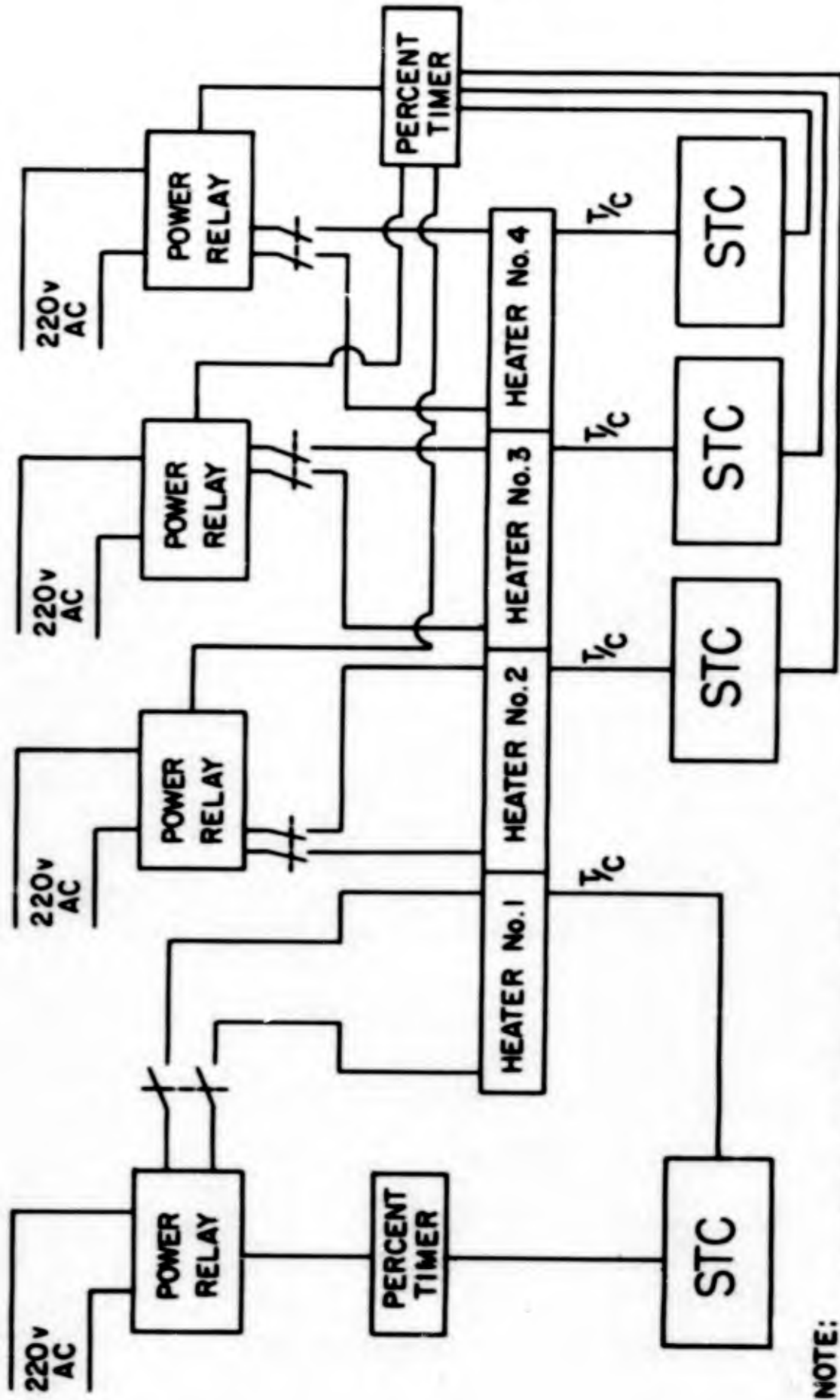


FIGURE 1. REACTION VESSEL

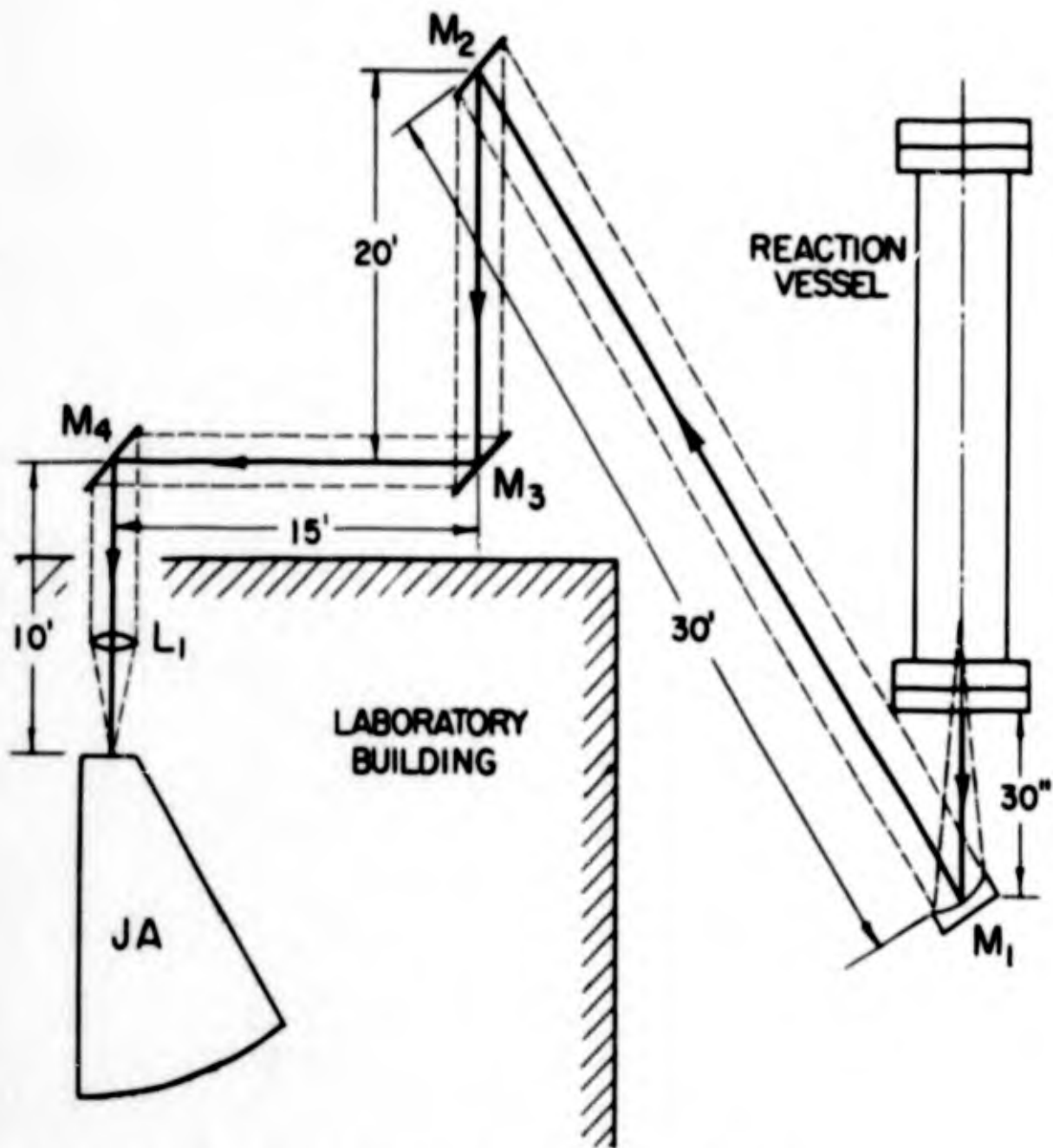


NOTE:

T/C — CHROMEL/ALUMEL THERMOCOUPLE

STC — SIMPLYTROL TEMPERATURE CONTROLLER

FIGURE 2. SYMBOLIC DIAGRAM OF TEMPERATURE CONTROL SYSTEM



M₁ - 6" DIA., 48" FOCAL LENGTH FRONT SURFACE PARABOLIC MIRROR

M₂, M₃, M₄ PLANE FRONT SURFACE MIRRORS

L₁ - 24" FOCAL LENGTH LENS

JA - JARRELL-ASH 21' GRATING SPECTROGRAPH

FIGURE 3. SPECTROGRAPHIC DIAGRAM

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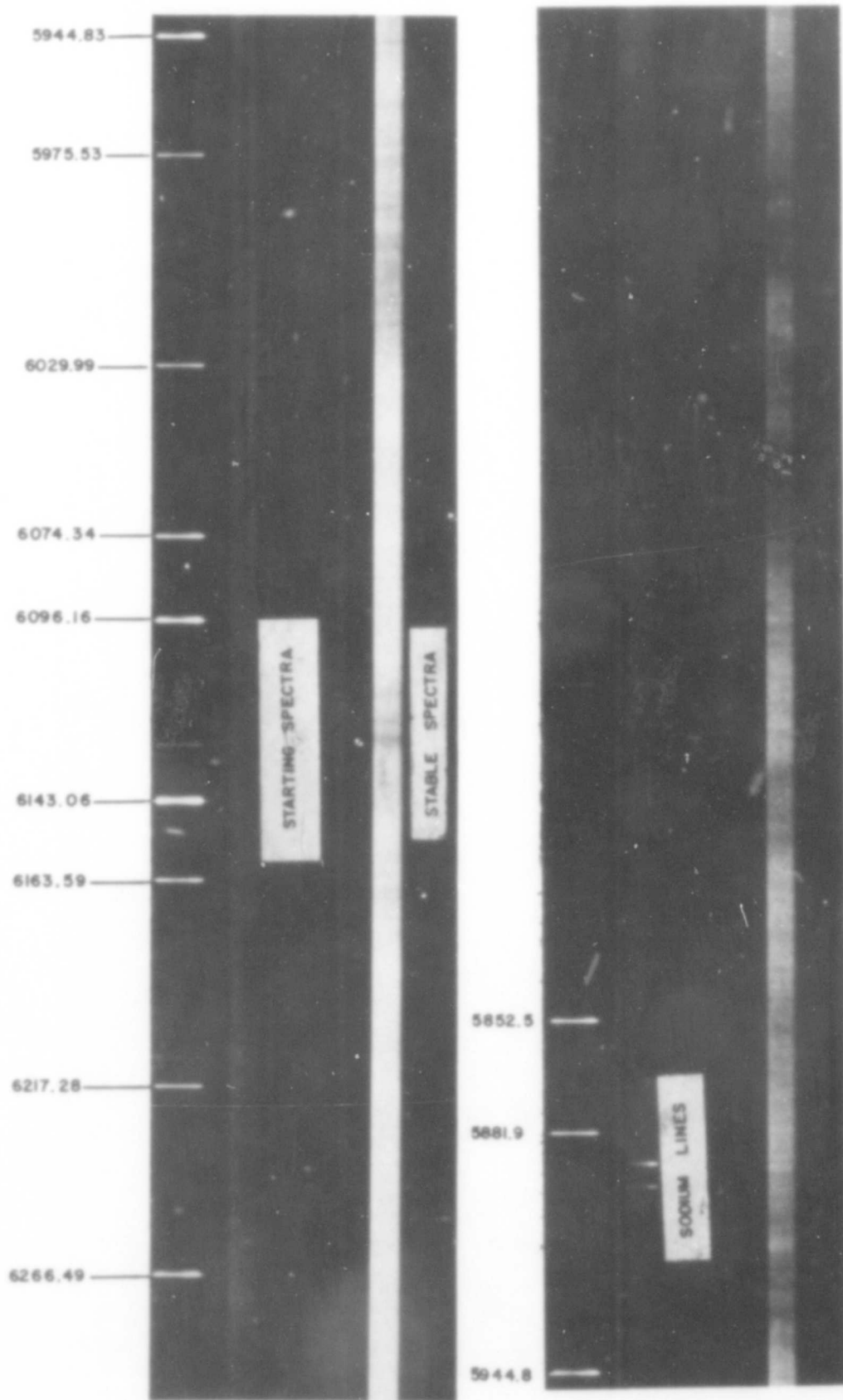


FIG. 4 SPECTRA OF STARTING AND STABLE DECOMPOSITION REACTION
JARRELL - ASH SPECTROGRAPH

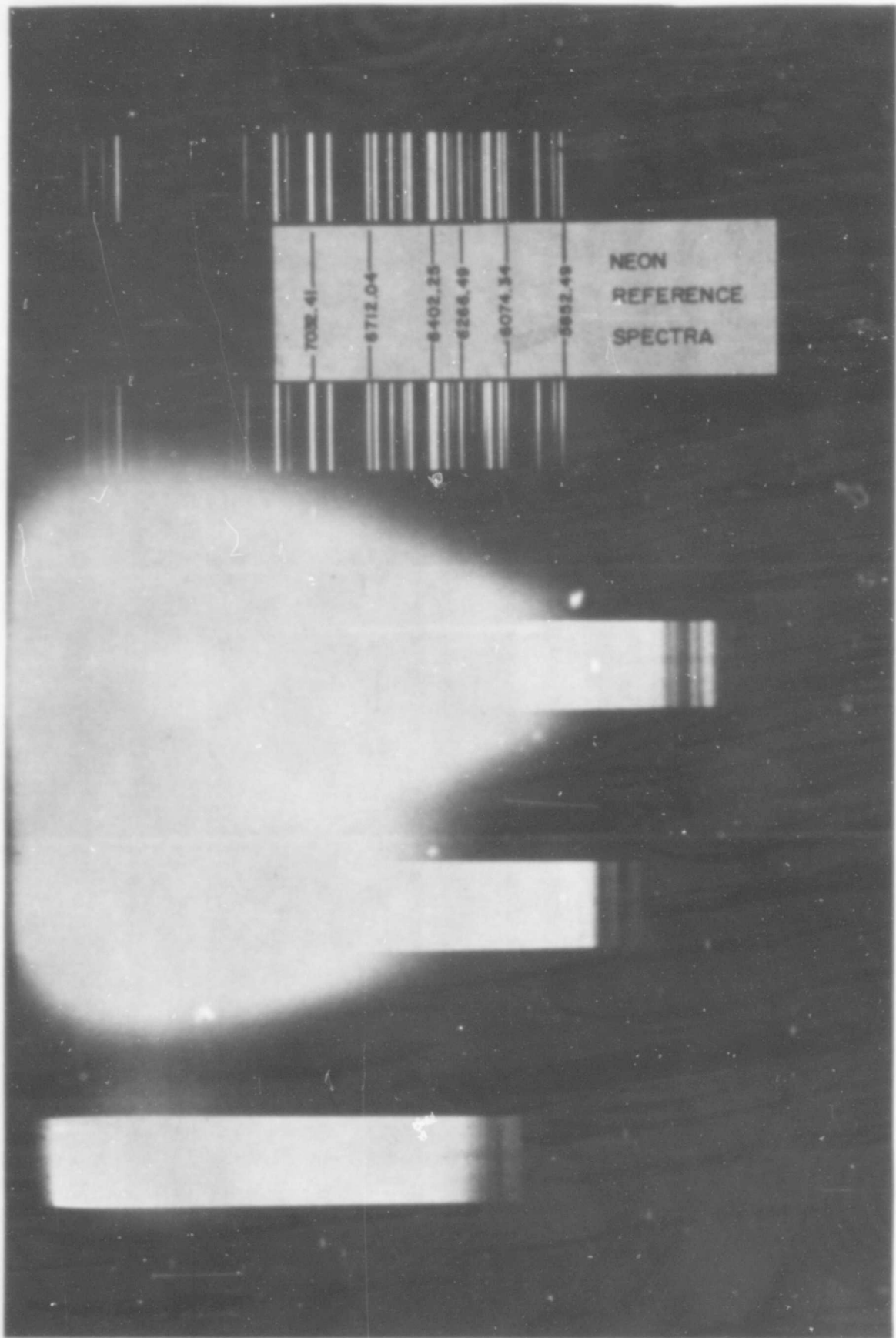


FIG. 5 SPECTRA OF STABLE DECOMPOSITION REACTION
BAUSCH & LOMB SPECTROGRAPH

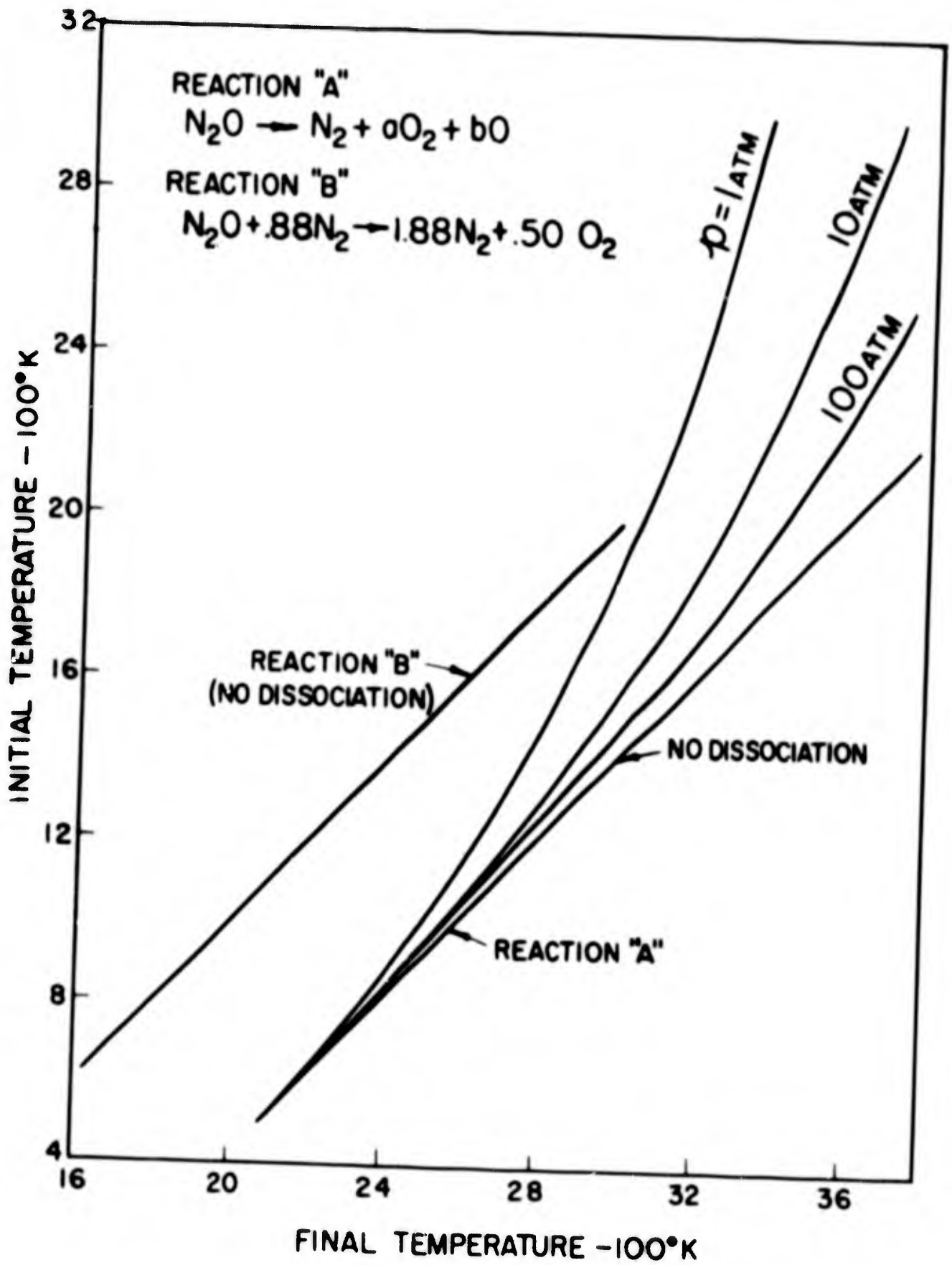


FIGURE 6. INITIAL vs FINAL TEMPERATURE

TABLE I

 PURE NITROUS OXIDE DECOMPOSITION
 FLOW RATE - 1.0 LITERS/SEC

Probe ¹ Location	Temperature Before (°K)	Temperature After (°K)	Temperature Rise (°K)	% N ₂ (Equilibrium Mixture at Room Temperature)	% O ₂	% NO ₂	% N ₂ O
4	878			NO DECOMPOSITION			
4	936	1117	181	67.41	28.31	4.28	-0-
4	950	1100	150	66.44	27.48	6.08	-0-
4	978	1125	147	69.44	27.86	2.70	-0-
4	1053	1163	110	66.03	27.15	6.82	-0-
4	1033	1156	123	66.92	27.27	5.85	-0-
4	1068	1177	109				
3	922			NO DECOMPOSITION			
3	958			NO DECOMPOSITION			
3	1019			NO DECOMPOSITION			
3	1072	1144	125	66.60	27.48	5.37	.55
3	1117	1186	114	67.72	27.65	4.63	-0-
2	858	1228	111	67.17	27.41	5.42	-0-
2	914			NO DECOMPOSITION			
2	967			NO DECOMPOSITION			
2	1039	1233	266	67.45	28.60	3.70	.25
2	1092	1278	239	66.93	27.91	5.15	.01
1	783	1297	205	66.59	28.03	5.38	-0-
1	772	1311	528	64.31	28.30	7.24	.15
1	838	1172	400	65.77	28.46	5.44	.35
1	866			NO DECOMPOSITION			
1	916	1461	595	66.57	28.97	4.38	.08
		1440	534	66.96	28.31	4.73	-0-

¹Probe location refers to position of probe at exit of heater sections numbered downstream from inlet

TABLE II

PURE NITROUS OXIDE DECOMPOSITION
FLOW RATE - 1.5 LITERS/SEC

Probe ¹ Location	Temperature Before (°K)	Temperature After (°K)	Temperature Rise (°K)	Products of Decomposition (Equilibrium Mixture at Room Temperature)			
				% N ₂	% O ₂	% NO ₂	% N ₂ O
4	883			NO DECOMPOSITION			
4	934		163	67.31	28.64	4.05	-0-
4	941			NO DECOMPOSITION			
4	986		164	67.69	28.05	4.26	-0-
4	1025		155	67.02	27.32	5.66	-0-
4	1075		158	65.40	28.94	5.66	-0-
3	922			NO DECOMPOSITION			
3	955			NO DECOMPOSITION			
3	1013		159	65.47	27.02	7.49	.02
3	1072		178	67.26	27.71	5.03	-0-
3	1138		139	66.40	26.94	6.66	-0-
2	855			NO DECOMPOSITION			
2	911			NO DECOMPOSITION			
2	977			NO DECOMPOSITION			
2	1036		361	65.98	27.90	6.06	.06
2	1077		330	65.55	27.36	7.09	-0-
1	794		295	65.50	27.32	7.18	-0-
1	783			NO DECOMPOSITION			
1	838		569	66.33	28.72	4.68	.27
1	861			NO DECOMPOSITION			
1	916		666	66.71	28.17	4.86	.26
			650	65.96	27.78	6.26	-0-

¹Probe location refers to position of probe at exit of heater sections numbered downstream from inlet

TABLE III

PURE NITROUS OXIDE DECOMPOSITION
FLOW RATE - 2.0 LITERS/SEC

Probe ¹ Location	Temperature Before (°K)	Temperature After (°K)	Temperature Rise (°K)	% N ₂	% O ₂	% NO ₂	% N ₂ O
				(Equilibrium Mixture at Room Temperature)			
4	886	-	-	NO DECOMPOSITION	-	-	-
4	938	-	-	NO DECOMPOSITION	-	-	-
4	933	-	-	NO DECOMPOSITION	-	-	-
4	988	1200	212	68.73	27.65	3.62	-0-
4	1050	1233	183	66.23	26.77	7.00	-0-
4	1079	1277	198	67.13	25.47	7.40	-0-
3	922	-	-	NO DECOMPOSITION	-	-	-
3	952	-	-	NO DECOMPOSITION	-	-	-
3	1019	1213	194	66.38	27.86	5.75	.01
3	1072	1175	103	66.15	27.34	6.51	-0-
3	1130	1311	181	66.04	26.81	7.15	-0-
2	850	-	-	NO DECOMPOSITION	-	-	-
2	900	-	-	NO DECOMPOSITION	-	-	-
2	977	1422	445	66.65	28.27	6.08	-0-
2	1027	1394	367	65.37	27.25	7.38	-0-
2	1088	1433	345	65.36	27.09	7.55	-0-
1	772	-	-	NO DECOMPOSITION	-	-	-
1	783	-	-	NO DECOMPOSITION	-	-	-
1	838	-	-	NO DECOMPOSITION	-	-	-
1	877	-	-	NO DECOMPOSITION	-	-	-
1	900	1588	688	65.95	27.45	6.60	-0-

¹Probe location refers to position of probe at exit of heater sections numbered downstream from inlet

TABLE IV

$N_2O + .88N_2$ DECOMPOSITION
FLOW RATE - 1.88 LITERS/SEC

Probe ¹ Location	Temperature Before (°K)	Temperature After (°K)	Temperature Rise (°K)	% N_2 (Equilibrium Mixture at Room Temperature)	% O_2	% NO_2	% N_2O
4	950	-	-	NO DECOMPOSITION	-	-	-
4	994	1200	206	79.60	18.41	1.79	.20
4	1056	1367	311	80.41	16.32	3.09	.18
4	1103	1342	239	77.40	18.40	3.85	.35
4	1128	1269	141	77.11	19.65	3.24	.0-
3	950	-	-	NO DECOMPOSITION	-	-	-
3	981	-	-	NO DECOMPOSITION	-	-	-
3	1005	1269	263	80.02	18.01	1.82	.15
3	1067	1269	202	77.41	18.40	3.99	.20
3	1158	1350	192	77.77	18.00	4.19	.04
2	958	-	-	NO DECOMPOSITION	-	-	-
2	958	-	-	NO DECOMPOSITION	-	-	-
2	1050	1419	369	75.61	20.32	3.84	.23
2	1090	1445	355	78.21	17.92	3.70	.12
2	1172	1509	337	78.21	18.25	3.52	.02
2	1230	1440	210	79.30	18.53	2.17	.0-
1	803	-	-	NO DECOMPOSITION	-	-	-
1	833	-	-	NO DECOMPOSITION	-	-	-
1	895	-	-	NO DECOMPOSITION	-	-	-
1	943	-	-	NO DECOMPOSITION	-	-	-
1	1005	-	-	NO DECOMPOSITION	-	-	-
1	1060	-	-	NO DECOMPOSITION	-	-	-

¹Probe location refers to position of probe at exit of heater sections numbered downstream from inlet

TABLE V

N₂O + .88N₂ DECOMPOSITION
FLOW RATE - 2.82 LITERS/SEC

Probe ¹ Location	Temperature Before (°K)	Temperature After (°K)	Temperature Rise (°K)	Products of Decomposition (Equilibrium Mixture at Room Temperature)	% N ₂	% O ₂	% NO ₂	% N ₂ O
4	950	-	-	NO DECOMPOSITION	-	-	-	-
4	1000	-	-	NO DECOMPOSITION	-	-	-	-
4	1050	1375	325	79.39	16.67	3.91	.03	
4	1111	1297	186	79.82	18.01	2.17	-0-	
4	1125	1450	325	78.31	16.77	4.92	-0-	
3	933	-	-	NO DECOMPOSITION	-	-	-	-
3	978	-	-	NO DECOMPOSITION	-	-	-	-
3	1042	-	-	NO DECOMPOSITION	-	-	-	-
3	1100	1394	294	76.58	17.64	3.06	.04	
3	1158	1438	250	78.61	17.61	4.25	-0-	
2	922	-	-	NO DECOMPOSITION	-	-	-	-
2	967	-	-	NO DECOMPOSITION	-	-	-	-
2	1058	-	-	NO DECOMPOSITION	-	-	-	-
2	1075	-	-	NO DECOMPOSITION	-	-	-	-
2	1172	1499	327	78.05	17.64	3.93	.38	
2	1222	1562	341	79.31	17.87	2.80	.02	
1	825	-	-	NO DECOMPOSITION	-	-	-	-
1	833	-	-	NO DECOMPOSITION	-	-	-	-
1	884	-	-	NO DECOMPOSITION	-	-	-	-
1	922	-	-	NO DECOMPOSITION	-	-	-	-
1	1000	-	-	NO DECOMPOSITION	-	-	-	-
1	1072	-	-	NO DECOMPOSITION	-	-	-	-

¹Probe location refers to position of probe at exit of heater sections numbered downstream from inlet

TABLE VI

$N_2O + .88N_2$ DECOMPOSITION
FLOW RATE - 3.76 LITERS/SEC

Probe ¹ Location	Temperature Before (°K)	Temperature After (°K)	Temperature Rise (°K)	Products of Decomposition (Equilibrium Mixture at Room Temperature)	% N_2	% O_2	% NO_2	% N_2O
4	942	-	-	NO DECOMPOSITION	-	-	-	-
4	947	-	-	NO DECOMPOSITION	-	-	-	-
4	1056	-	-	NO DECOMPOSITION	-	-	-	-
4	1111	1428	317	79.17	17.13	3.70	-0-	
4	1150	1464	314	79.25	16.06	4.69	-0-	
3	931	-	-	NO DECOMPOSITION	-	-	-	-
3	975	-	-	NO DECOMPOSITION	-	-	-	-
3	1033	-	-	NO DECOMPOSITION	-	-	-	-
3	1089	1100	11	69.51	12.41	4.44	13.64	
3	1158	1183	25	78.55	14.93	5.09	1.43	
2	886	-	-	NO DECOMPOSITION	-	-	-	-
2	942	-	-	NO DECOMPOSITION	-	-	-	-
2	1048	-	-	NO DECOMPOSITION	-	-	-	-
2	1184	-	-	NO DECOMPOSITION	-	-	-	-
2	1233	1510	323	78.64	17.52	2.77	1.07	
1	816	-	-	NO DECOMPOSITION	-	-	-	-
1	825	-	-	NO DECOMPOSITION	-	-	-	-
1	878	-	-	NO DECOMPOSITION	-	-	-	-
1	945	-	-	NO DECOMPOSITION	-	-	-	-
1	1003	-	-	NO DECOMPOSITION	-	-	-	-

¹Probe location refers to position of probe at exit of heater sections numbered downstream from inlet

TABLE VII

N₂O + AIR DECOMPOSITION

Probe ¹ Location	Temperature Before (°K)	Temperature After (°K)	Temperature Rise (°K)	Products of Decomposition (Equilibrium Mixture at Room Temperature)			
				% N ₂	% O ₂	% NO ₂	% N ₂ O
Total Flow Rate - 2.0 Liters/Sec							
4	962	1370	408	71.02	26.24	2.58	.16
4	1005	1311	306	70.46	25.07	4.44	.03
4	1078	1286	208	70.33	25.45	3.34	.88
4	1148	1293	145	70.94	25.56	3.38	.12
Total Flow Rate - 3.0 Liters/Sec							
4	950	-	-	-	-	-	-
4	1014	-	-	-	-	-	-
4	1072	-	-	-	-	-	-

¹Probe location refers to position of probe at exit of heater sections numbered downstream from inlet