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AEROTHERM
FINAL REPORT NO. 69-51

A STUDY OF THE BOUNDARY FLOW IN A ROCKET COMBUSTION CHAMBER

PART I

SUMMARY

by

Ronald D. Grose

AEROTHERM CORPORATION

ADVANCES IN AEROTHERMOCHEMISTRY

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September 22, 1969

Aerotherm Project 7009

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PART I

SUMMARY

by

Ronald D. Grose

Prepared for

Jet Propulsion Laboratory
Pasadena, California

Contract No. NAS7-463

JPL Technical Monitor — D. L. Bond

ABSTRACT

Boundary flow chemical composition and heat flux data from a hydrazine-nitrogen tetroxide rocket motor are presented. The spatial distribution of these data is related to certain injector design characteristics and to the ablation response produced by the injector in a Refrasil-phenolic chamber. Theoretical confirmation of the composition, heat flux and ablation data are made. Sampling system, experimental technique, and sample chemical analysis technique developments are also presented.

FOREWORD

This report, which is one of a four-part final report, summarizes the results of experimental and analytical research into the chemical composition and heat transfer characteristics of a hydrazine-nitrogen tetroxide liquid rocket motor. The reports in the series are:

Part I - Summary

Part II - Data Analysis, Correlation and Theoretical Predictions

Part III - Data Report

Part IV - Development of Experimental Hardware and Technique

This effort was conducted for the Jet Propulsion Laboratories of the National Aeronautics and Space Administration under Contract No. NAS7-463. Mr. Donald L. Bond and William H. Tyler were the technical monitors.

The Jet Propulsion Laboratory furnished the rocket motor for the test program. Firings of the developed equipment were conducted under subcontract to the United Technology Laboratory in Sunnyvale. Chemical analyses of the collected samples were performed by the West Coast Technical Company in San Gabriel, California.

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SECTION 1

INTRODUCTION

The design of rocket motor injectors is a complex science approaching that of an art especially when both the performance and survivability of materials forming the rocket motor are to be optimized. Many of the parameters which the injector designer must consider have little or no quantification and the designer must rely on experience and expensive experimentation, usually with full scale flight weight equipment. The study program reported here addresses itself to two of the many parameters that are of importance to the designer – chemical composition in the boundary flow and heat transfer to the chamber walls. Both of these parameters are important to the understanding of how injectors effect not only motor performance but the survival of the materials forming the motor. Also important are the experimental technique and apparatus developed in the program with which such data can be rapidly and inexpensively obtained.

The material presented here summarizes the work conducted by the Aerotherm Corporation for the Jet Propulsion Laboratory in the study of the boundary flow in a liquid rocket motor. This work entailed the development of the boundary flow gas sampling system and heat flux gages, the experimental technique, chemical analysis technique, and data reduction, analysis and prediction. Data analysis, correlation and prediction are reported in Part II; testing and data reduction are reported in Part III; and the development activity in Part IV. In this report attention is also given to the conclusions drawn from this work and to the recommendations for future efforts suggested by the difficulties and anomalies which were encountered.

SECTION 2

BACKGROUND

The study of boundary flow composition in a rocket motor combustion chamber appears to be a subject not too extensively investigated although exhaust stream sampling is performed on a relatively routine basis. A major problem is the severe environment in which the system for obtaining the boundary flow gas samples must operate. Because there existed a lack of suitable equipment with which the problem could be investigated, the Jet Propulsion Laboratory undertook the development of such equipment with the view of generating valuable data for injector designers confronted with providing high performance injectors for both ablative and nonablative rocket motor chambers.

In the mid-1960's a sampling scheme was conceived which employed a unique-zero-leakage, minimal-dead-volume, valve which had been developed for propellant flow control on the Mariner Program. Using this valve as a basis for the research equipment concept, the Jet Propulsion Laboratory proceeded to have constructed a copper heat sink combustion chamber and suitable injector, the latter embodying certain design features established in the ALPS program which provide exceptionally good stability, repeatability and ruggedness — all highly useful features for a research program.

The injector is designed to combust hydrazine and nitrogen-tetroxide at a chamber pressure of 150 psi and at a mixture ratio of about 1.3. The injector is constructed out of stainless steel and has ten doublets of conventional design positioned in a symmetric pattern. View of the chamber and injector are presented in Figures 1 and 2. Two identical injectors of this design were constructed by JPL, the first of which demonstrated the best c* and ablation performance of the series of N_2O_4/N_2H_4 injectors developed in the ALPS program. The second injector, and the one used in the subject program, also demonstrated good performance but in the JPL-Edwards

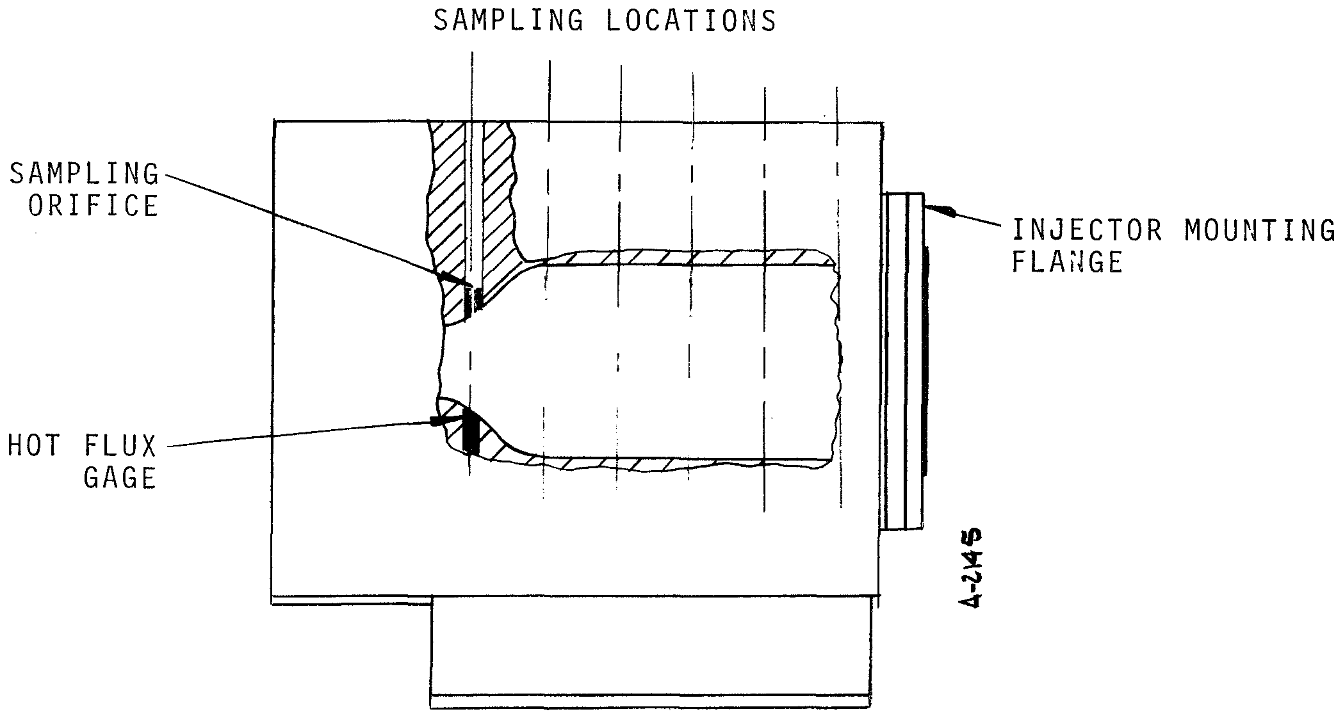


Figure 1. Combustion Chamber

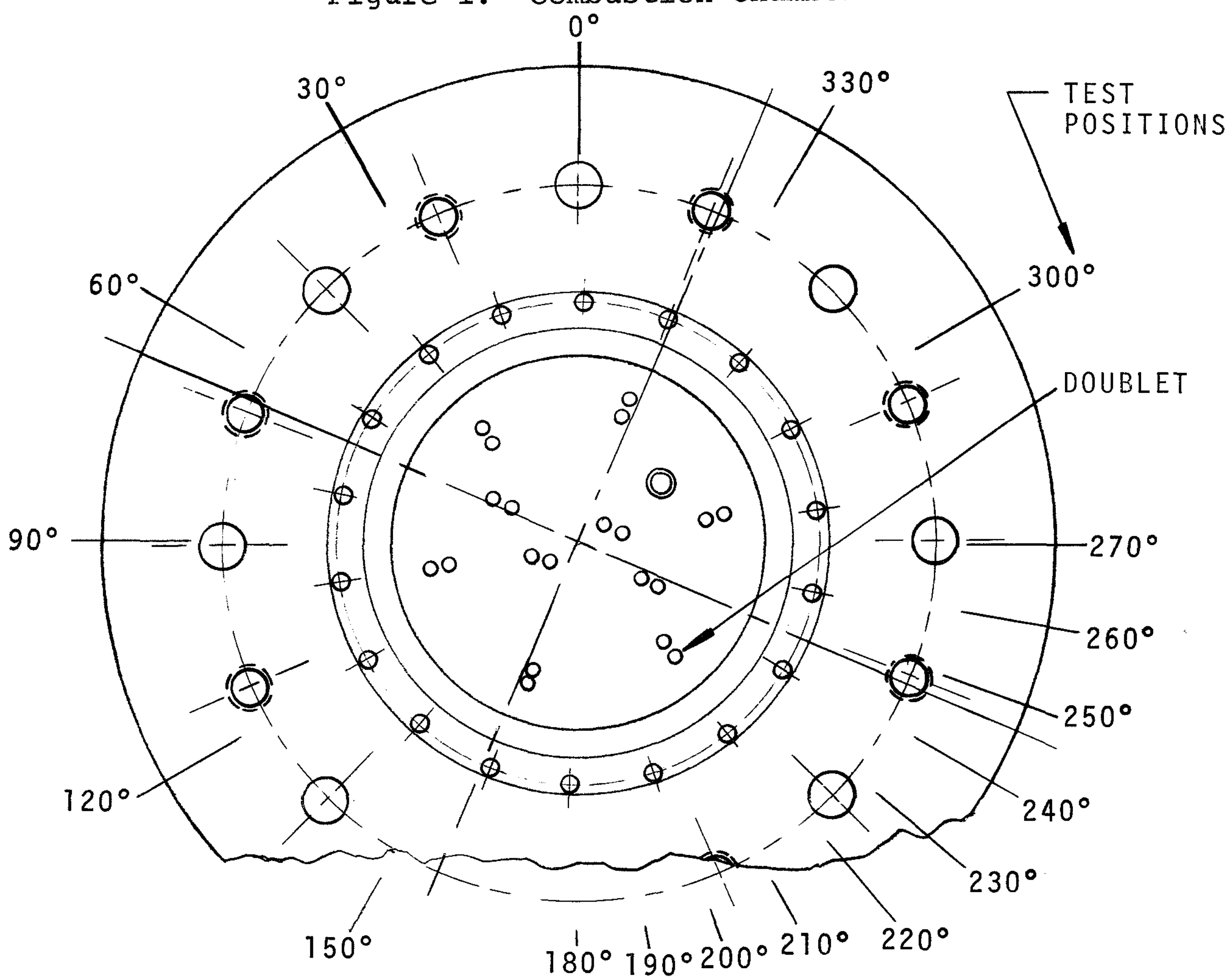


Figure 2. Injector

Facility tests of this injector, the ablation of a Refrasil-phenolic nozzle was severe.

The rocket motor was so designed that heat flux and gas samples could be obtained at six evenly spaced axial stations between the injector face and the nozzle throat. Because the injector is attached to the chamber by a clamp ring, the injector is free to rotate to any position relative to the chamber so that it is possible to obtain data corresponding to any desired injector azimuth. The positions chosen for the program are shown in Figure 2.

SECTION 3

OBJECTIVES OF THE PROGRAM

The principal objectives of the program are: (1) to demonstrate that meaningful gas composition data from a rocket chamber boundary flow can be obtained, (2) to correlate this data (along with heat flux determinations) with injector design details. Secondary objectives include the demonstration of chemical composition, heat flux and ablation state-of-the-art predictions. These predictions serve not only to verify the experimental results but to point out deficiencies in current understanding of the physics involved and thereby give direction to future research efforts.

SECTION 4

APPARATUS DEVELOPMENT

In the following paragraphs the description of the research apparatus development is presented. This includes the sampling system, heat flux gages and the special sample equipment developed for use with the mass spectrometer.

4.1 SAMPLING SYSTEM

From the experimental and analytical studies conducted early in the program, a sampling system was developed in which stainless steel lecture bottles are individually connected to each of the six sampling ports through a rather complex manifold/valve arrangement. In this sampling system, termed the bleed sampling method, a small flow rate of inert gas is passed through the system into the chamber prior to the sampling event to prevent non-representative sample gases from collecting in the sampling circuit and impairing the accuracy of the determination. To prevent a surge of such gases from entering the sampling circuit during the ignition transient (which was of concern because of the short time intervals involved), a two-stage bleed is employed so that during the ignition transient a relatively high bleed rate exists which is reduced prior to sampling to prevent the boundary layer from being overly disturbed. This bleed flow and the flow of the sample gas itself is controlled by a series of recently developed — commercially available — small-pneumatically operated — valves. These valves have an envelope so small that twelve of these valves (and twelve manually operated valves) are contained in the portable case enveloping not only the valves, but the motor, sampling system, and bottles as well. This case contains the hot gases used to heat the apparatus to a nominal operating temperature of about 300°F. An elevated temperature is required to prevent condensation of water from occurring in the sampling system and on the chamber walls.

Figure 3 shows the schematic of the sampling system circuit and valving arrangement for one of the six bottles and Figure 4, the schematic for the complete system. The pneumatic valves are controlled by a separate inert gas circuit which is, in turn, controlled by electric solenoid valves operated by automatic sequencing apparatus in the control room. Figure 5 shows the sampling system as installed on the motor within the case on the test stand at UTC.

The sequence of operations followed in each test using this sampling system is shown in Table 1 (page 13). The purpose of the pre-firing sequence of operations is to assure that the sampling system does not contain any contaminents. In the firing sequence, only the details pertinent to the sampling events are shown.

4.2 HEAT FLUX DETERMINATION

Heat flux to the chamber wall is measured by the use of null point heat flux gages inserted into holes drilled in the chamber wall. The gages were made by brazing chromel alumel thermocouple wire into blind holes drilled into copper slugs which were contour milled to conform to the chamber geometry (after assembly) by the use of a molded chamber template. One dimensional flow of heat through the calorimeter was assured by the creation of an air gap between the calorimeter and the chamber wall material. Figure 6 shows the construction details of the gage. Since the null point gage, in theory, determines the surface temperature, the heat flux at the surface is computed from the surface temperature history using a LaPlace transform of the Fourier one-dimensional heat flux equation.

4.3 SAMPLE CHEMISTRY DETERMINATION

A special procedure was developed for the determination of the collected sample. This development was necessitated

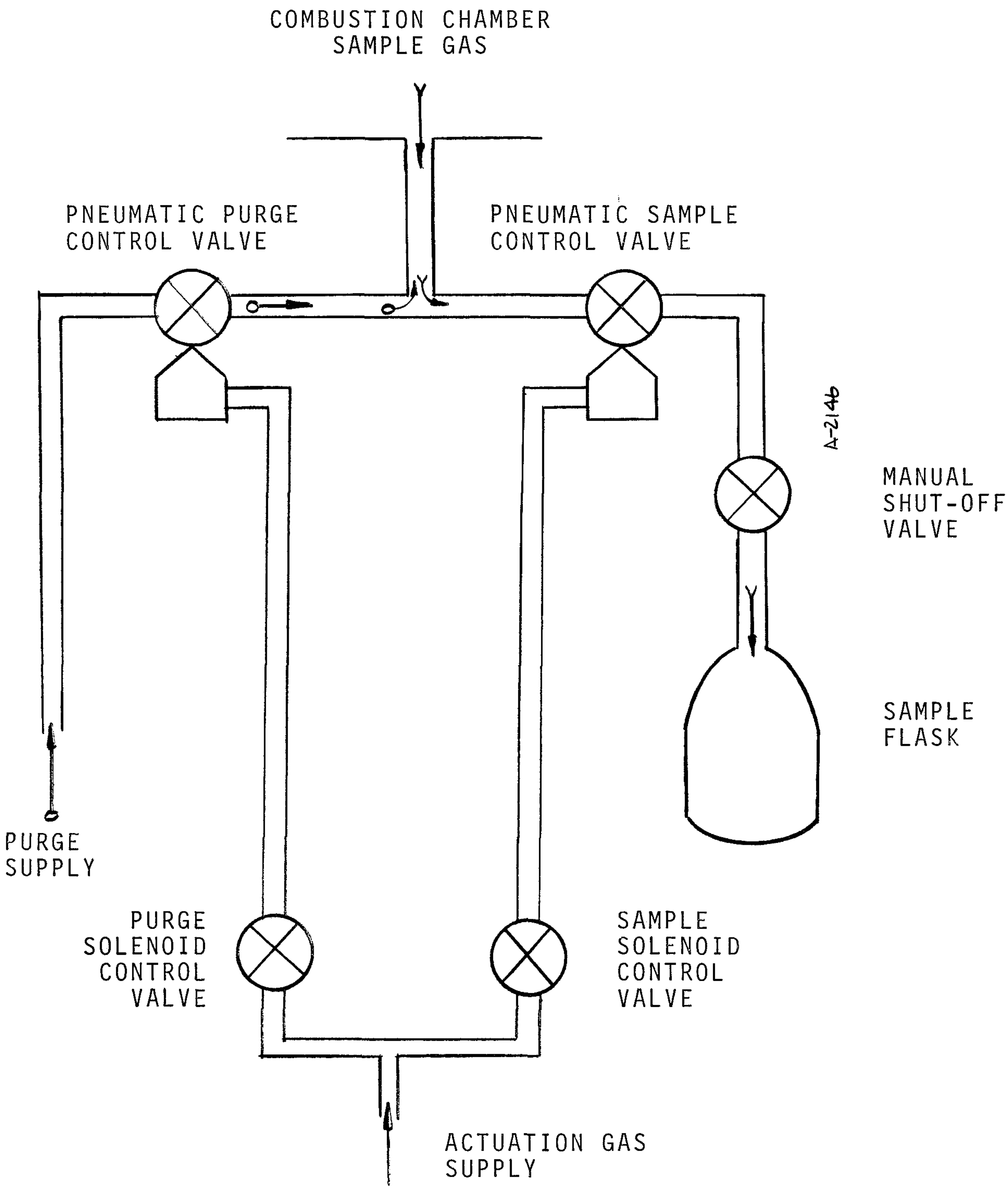


Figure 3. Purge System Schematic

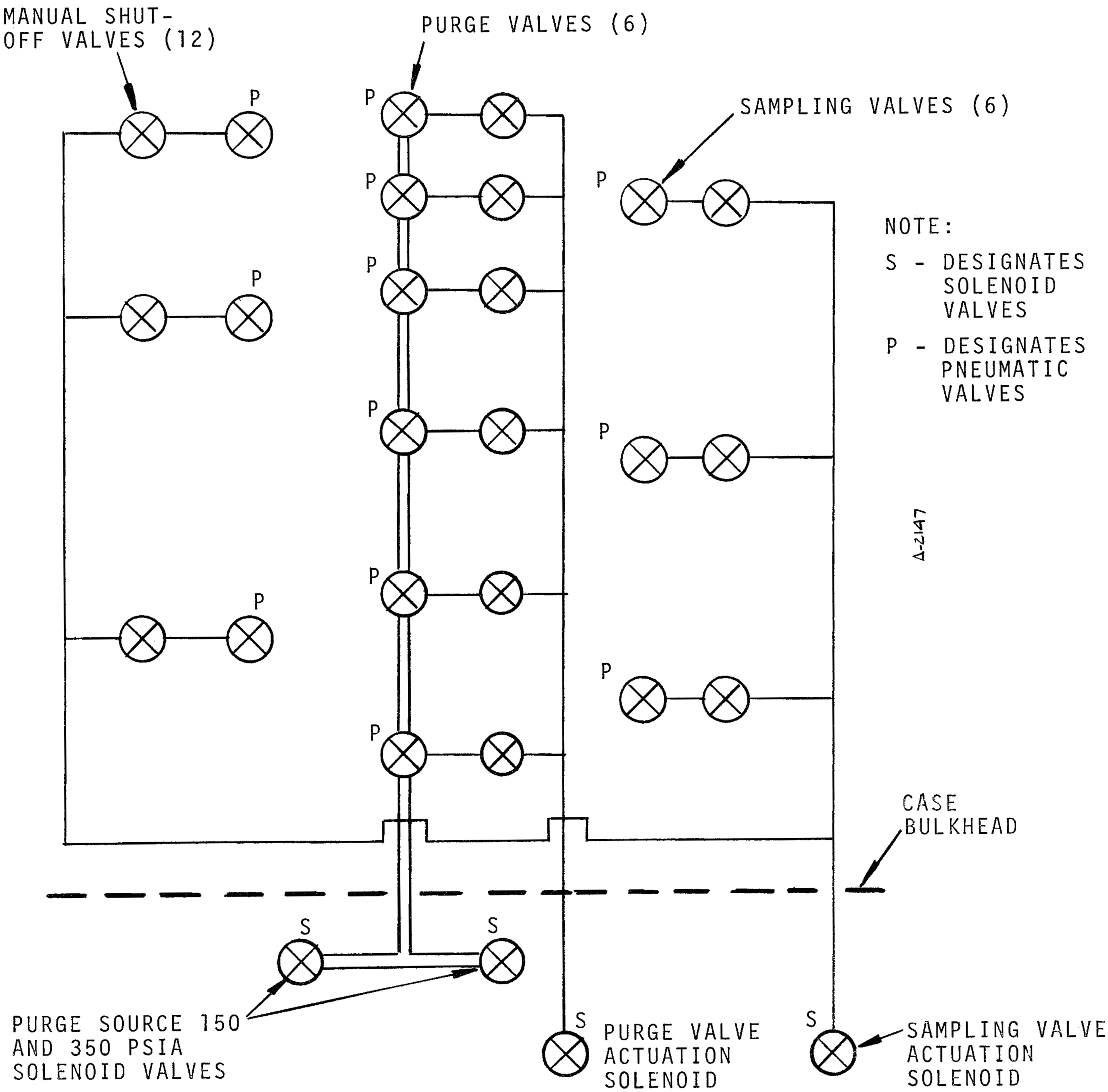


Figure 4. Pneumatic Circuit Schematic

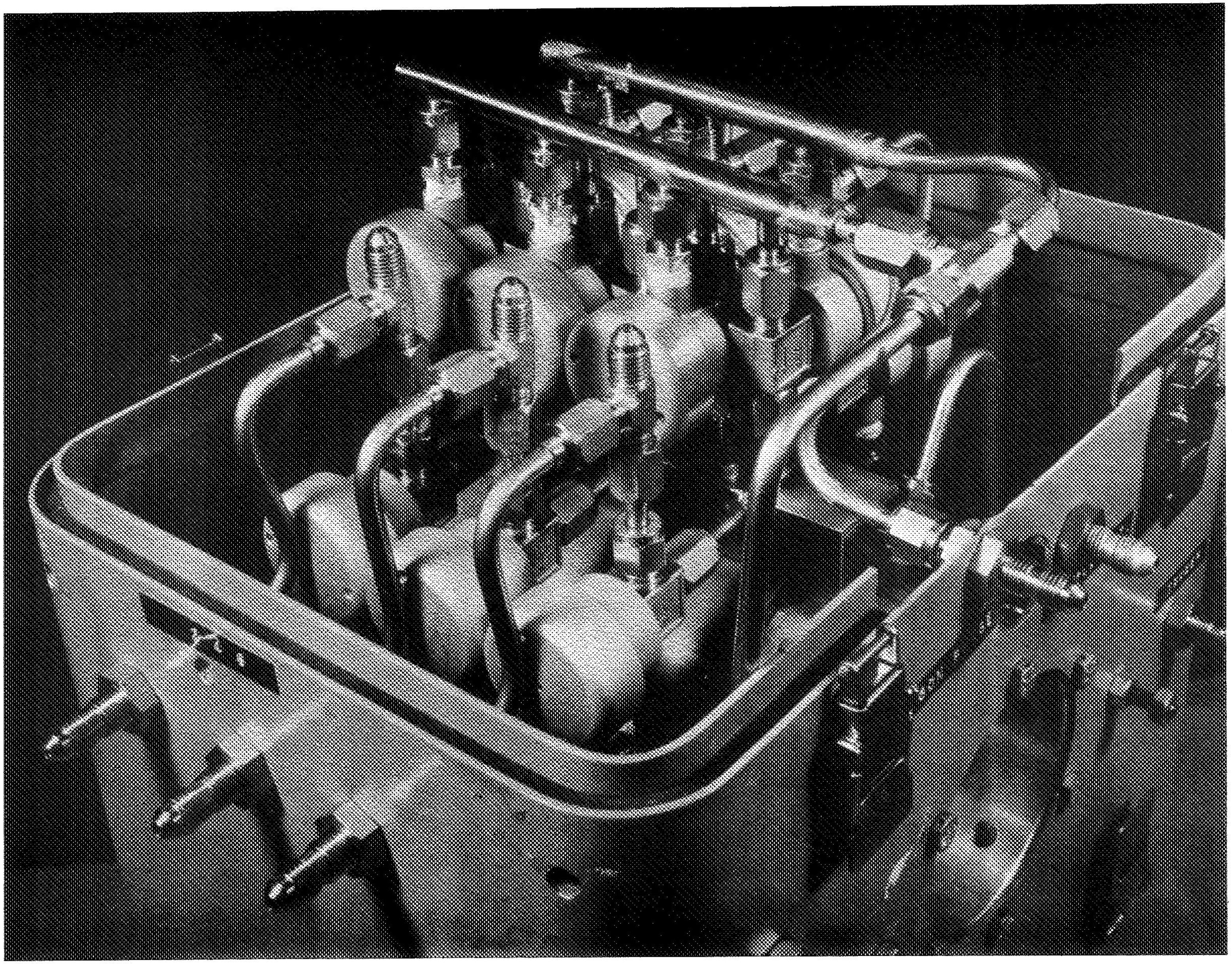


Figure 5. Sampling System Hardware Views
a. Close-up Showing Remote Valves

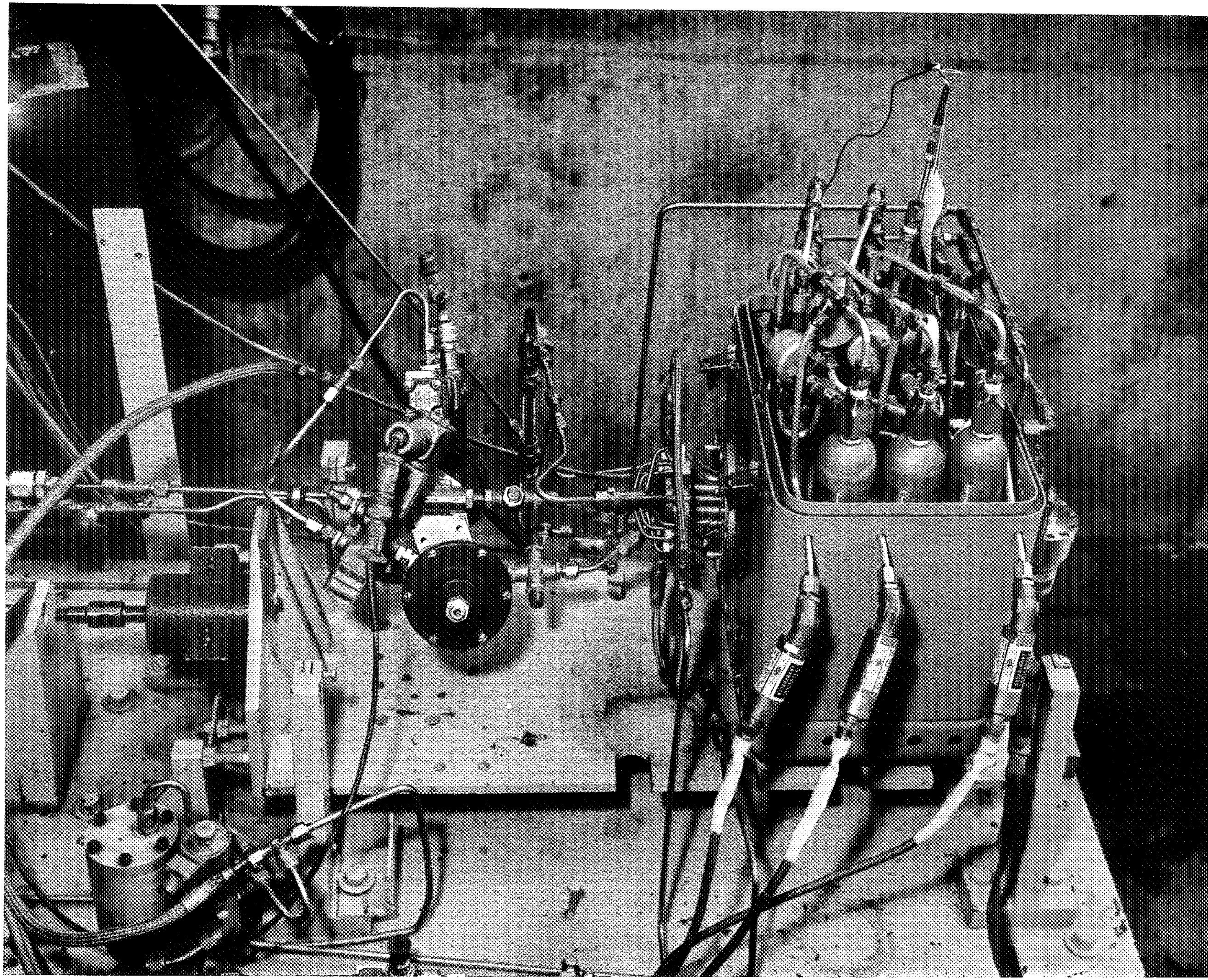


Figure 5. Concluded
b. Overall View of Apparatus on Test Stand

GAGES

	1-5	6
A	.89	1.402
B	1.37	1.902
C	.05	.100

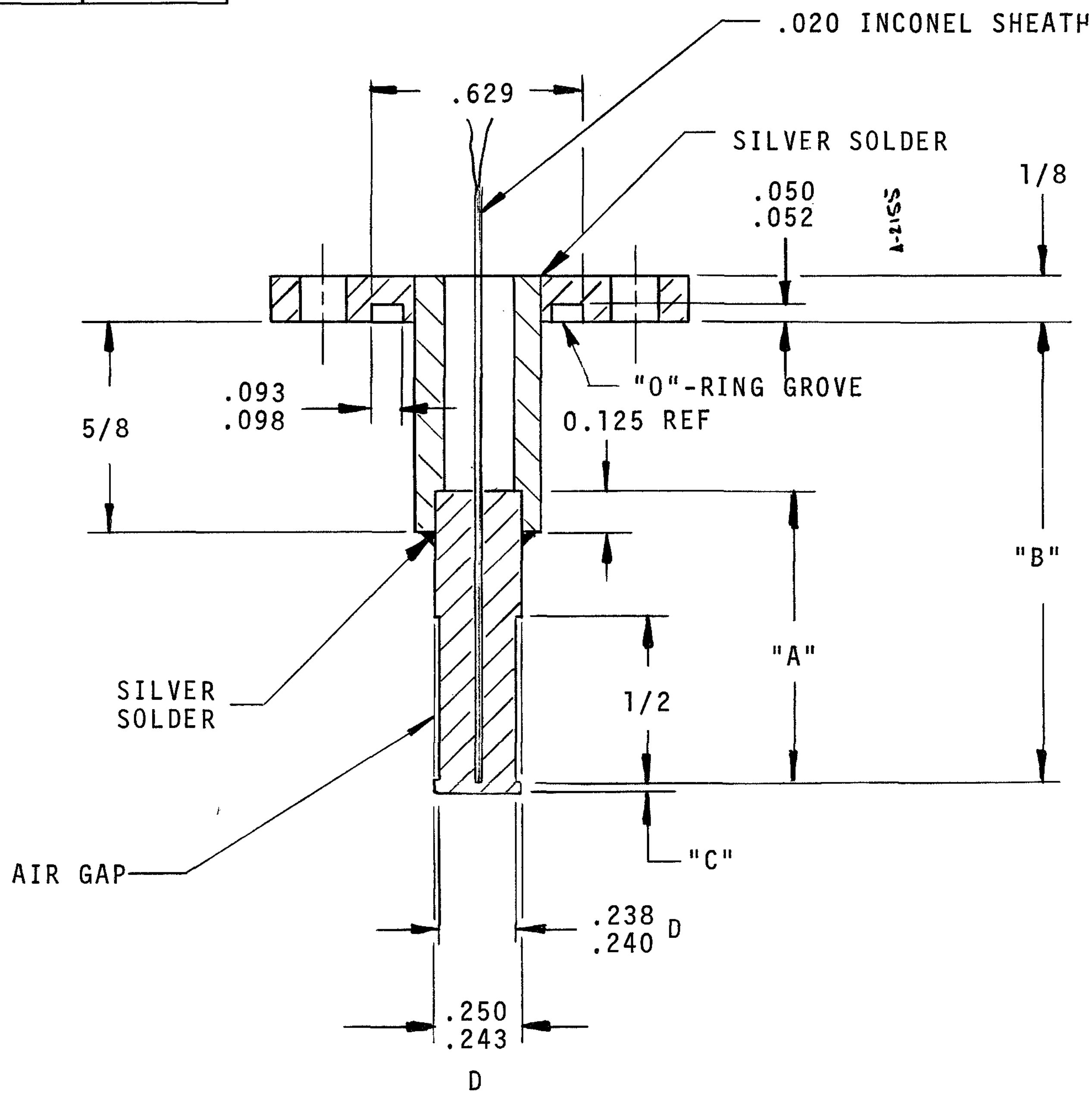


Figure 6. Heat Flux Gage Manufacturing Details

TABLE 1

PRE-FIRING SEQUENCE

Seq. No.	Operation
1	Rotate injector to proper position
2	Circuit and sequencer check
2.1	Verify 150 and 350 psia solenoid valve actuation
2.2	Connect 150 and 350 psia purge lines to case, verify 80-psi-purge-actuation; circuit solenoid valve actuation; connect line to case and with 150 psia purge on, verify flow in chamber
2.3	Verify 80 psi-sampling-valve-circuit solenoid valve actuation
2.4	Complete and check all connections necessary for the foregoing procedure
3	Open sampling cylinder toggle valves
4	Secure case - begin heating to 300°F
5	Install nozzle plug, begin vacuum pump down, open sampling valves
6	When chamber temperature (T_b) = 300°F, close pneumatic sampling valve, bring chamber to atmospheric pressure, verify no rise in pressure in sampling cylinders
7	Pump chamber down (vacuum), release (2) nuts on pump down fixture, open helium purge valves with 150 psia supply circuit open; maintain 150 psia purge until firing sequence

FIRING SEQUENCE

Seq. No.	Operation	Time
1	Actuate 350 psia helium-purge-supply-circuit with 80 psi purge-valve-actuation-curcuit open	-10 (1)
2	Begin firing sequence	0
3	Close 350 psi helium purge supply, open 150 psi helium purge supply	0.5
4	Close 80 psi helium purge actuation circuit	1.4
5	Open pneumatic sampling valves	1.5
6	Close pneumatic sampling valves	2.5
7	Open 80 psi helium purge actuation circuit	2.6
8 (2)	Terminate firing	4

(1) Approximate time (seconds)

(2) 150 psi helium purge still operating

POST-FIRING SEQUENCE

1	Close toggle valves, remove sampling cylinders
2	Install nozzle test plug fixture with fitting open
3	Open sampling valves, purge lines to cylinders by capping nozzle plug fixture (2)
4	Remove cylinder pressure transducers
5	Cycle 350 psi helium purge to purge all lines
6	Close helium purge, close sampling valve

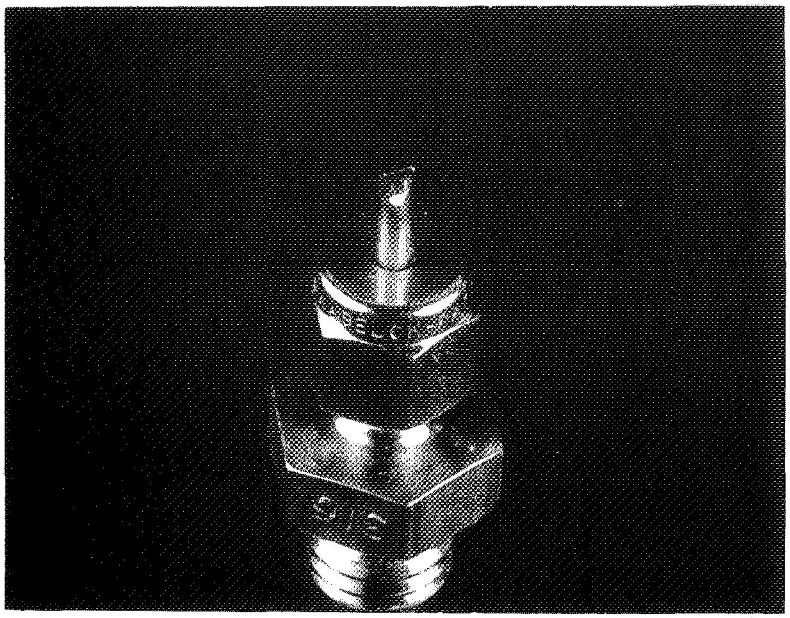
(2) 150 psi helium purge still operating

POST-FIRING SEQUENCE (Concluded)

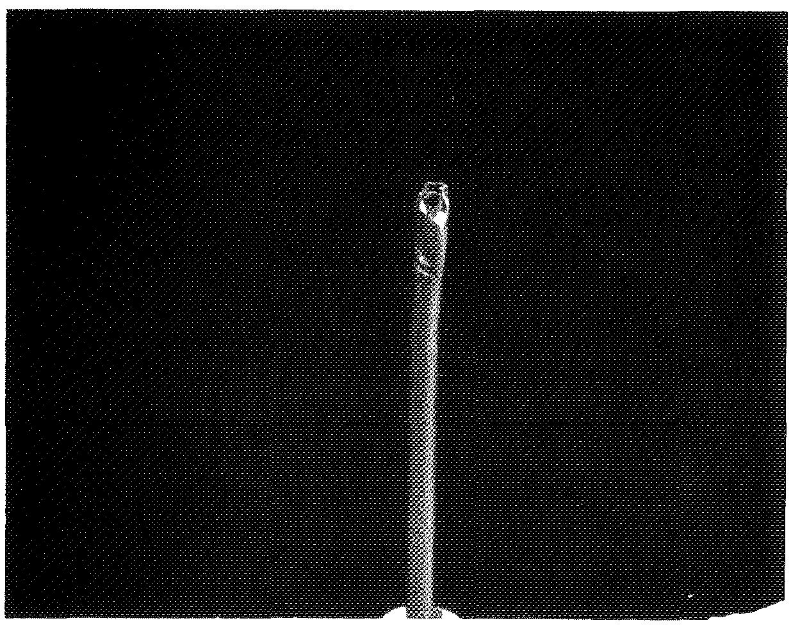
Seq. No.	Operation
7	Install (6) sampling cylinders with toggle valves closed
8	Open 350 psi helium purge, open sampling valve; verify no leakage at cylinder inlets
9	Close 350 psi helium purge, release pressure from chamber
10	Close sampling valves

because of the difficulties associated with accurately measuring the composition of samples containing large quantities of highly polar molecular species such as water and ammonia found in the N_2O_4/N_2H_4 boundary flow. The procedure essentially consists of transferring the collected samples from the lecture bottles to small tubes, called microtubes, under equilibrium thermodynamic conditions (i.e., lecture bottle pressure and elevated temperature) and analyzing the entire contents of the microtube in a mass spectrometer. By avoiding the standard inlet system on the mass spectrometer, problems believed to be associated with surface adsorption of polar species on the room temperature inlet system walls were circumvented. Conventional valves were avoided to eliminate problems with trapped nonrepresentative species or contaminents in the seat region. In the place of a valve, the stainless steel microtubes were opened and closed by a specially developed crimping and decrimping process.

Figure 7 shows several views of a typical microtube. These tubes were filled from the lecture bottles in an oven after temperature and pressure stabilization were achieved. The tubes were then crimped off (two for each sample bottle) by a standard crimping tool. With a careful crimping technique, it was found that such crimped seals would maintain helium leak tightness up to several atmospheres of pressure. A special decrimping tool was developed which could be coupled directly to the leak chamber of the mass spectrometer. Figure 8 shows the construction details of the decrimper and Figure 9, an overall view of the completed decrimper. The unit was constructed entirely of stainless steel in which the actuating mechanism from a bellows valve was used to avoid contamination of the small sample mass by chemical activity with O-ring material. A stainless-steel-glass-bellows-adaptor was heliarc welded to the housing to provide a connection between the decrimper and the glass leak chamber on the mass spectrometer and to allow for thermal expansion between the two.



MICROTUBE SHOWING CRIMPED SEAL



MICROTUBE SHOWING OPENED SEAL

Figure 7. Microtube Details

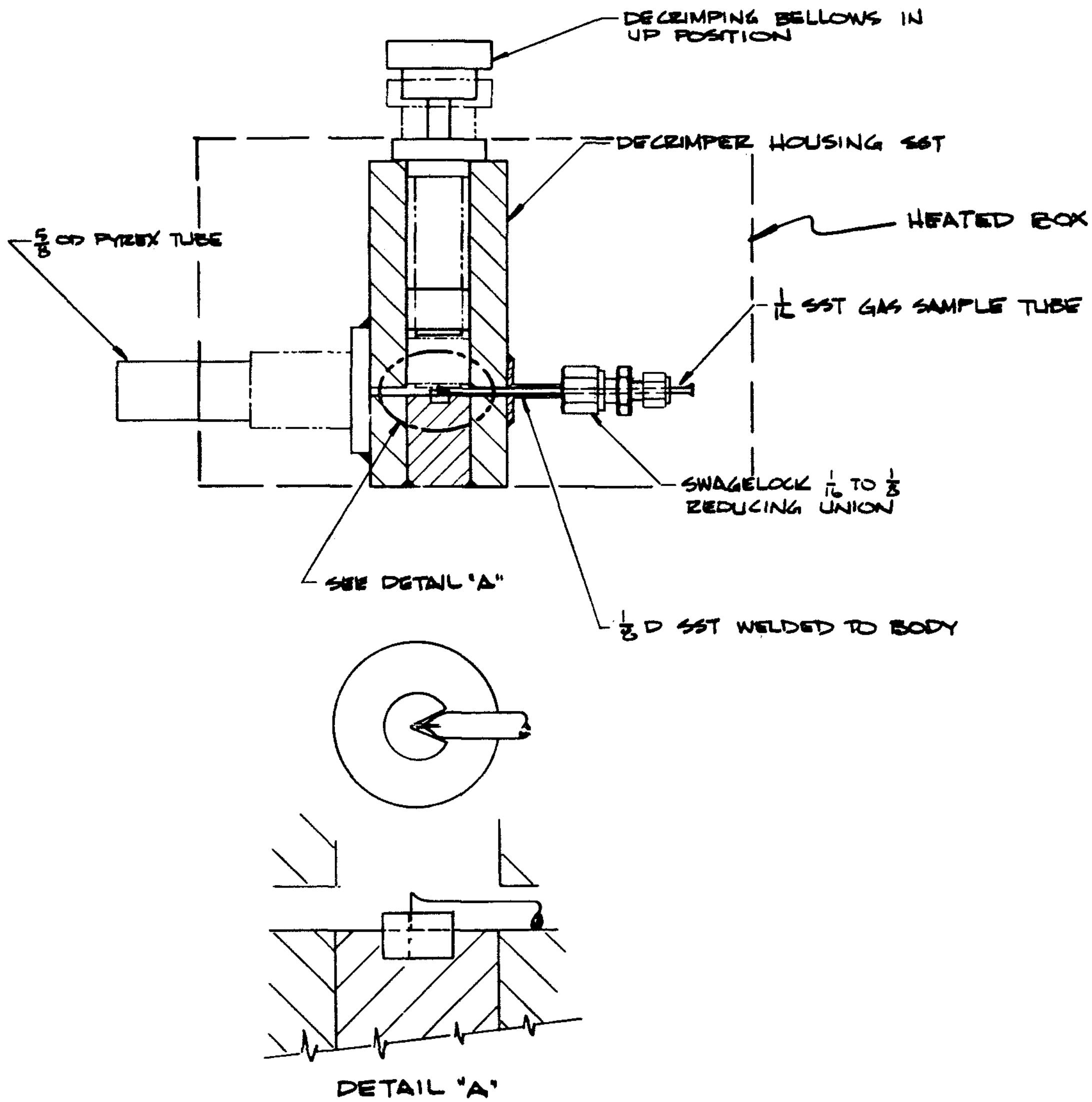


Figure 8. De-Crimper Design Details

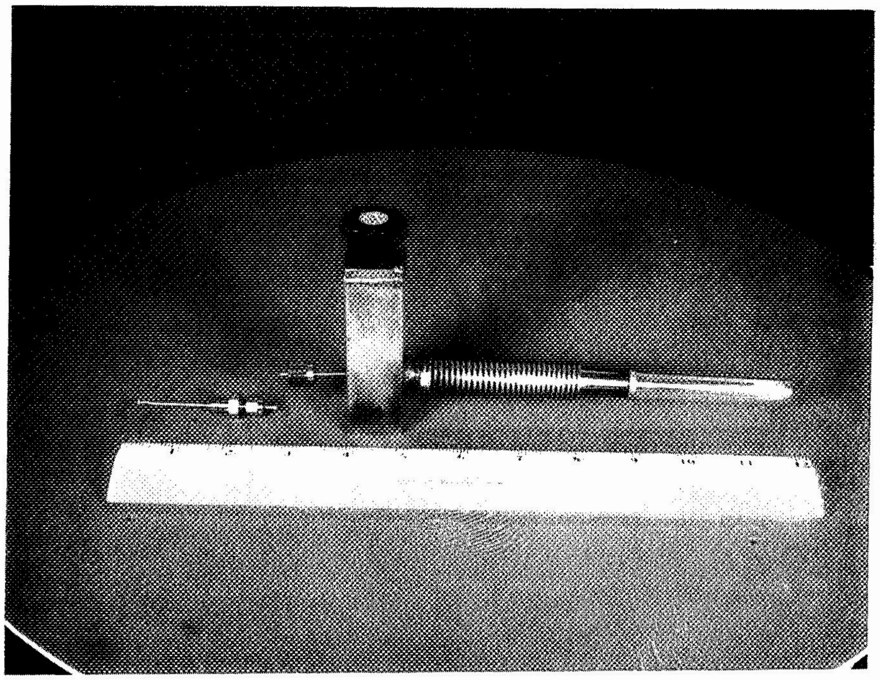


Figure 9. De-Crimper and Microtube Assembly

4.4 TIMING AND COST

The apparatus was found to be quite reliable although some difficulty with seat contamination of the sampling control valves was experienced. It was found possible to obtain firing rates as high as five or six per day. One limitation was the number of lecture bottles available, in that bottles could not be turned around rapidly enough due to the construction of microtubes. With more than one oven and several technicians, the firing rate could have been increased. With an analysis cost of about $20 per microtube the cost per sample was found to be about $200 not including data reduction or analysis. For a large number of firings, digital recording equipment for both the engine data and heat flux instrumentation and digital output from the mass spectrometer (if a large number of species are involved) is highly desirable to reduce data reduction time and cost and to eliminate data reduction errors.

SECTION 5

CORRELATION OF BOUNDARY FLOW CHEMISTRY AND HEAT FLUX WITH INJECTOR PARAMETERS

The quantitative relationship between the large number of injector design parameters and events which occur in the combustion chamber are to this day largely a mystery even though these events are vital to the satisfactory performance of the rocket motor. This lack of understanding is a measure not so much of a lack of analytical effort but of the complexity of the subject. It was hoped at the outset of this program that a detailed experimental study of some of the boundary flow parameters in the chamber would be helpful to the understanding of these relationships. As will be seen in the following data correlation, the experimental data show very significant trends (although unexpected) which should not be characteristic of a properly functioning injector. Relative to these dramatic trends, the correlation of boundary flow composition and heat flux is found to bear only a weak relationship to the injector spray pattern.

Preliminary predictions of composition by Aerotherm, unreported in the literature, demonstrate that the interplay between the injector elements is very significant so that an accurate description of the dependence of the boundary flow parameters probably requires a more closely spaced data acquisition than that used in this program.

5.1 DOUBLET SPRAY PATTERN

The spray pattern from impinging doublets has been found experimentally to be elliptical in cross section (for non-reacting fluids at least). Considerable work has been done at JPL in studying the impingement of both reacting and non-reacting jets. For the latter, a mass and mixture ratio variation has been measured using specially constructed spray booths. The mass distribution has been found to be elliptical with a hyperbolic decay dependence on radius while the centerline mass flux has a square power law decay from the point of impingement. The mixture ratio variation has a modified error function type of profile on the minor axis of the ellipse (which contains the orifices) and is relatively constant in planes parallel to the major axis. The O/F varies from about 4:1 to about 1:2 and shows significant penetration. That is, the spray is oxidizer-rich on the fuel orifice side of the doublet and vice-versa.

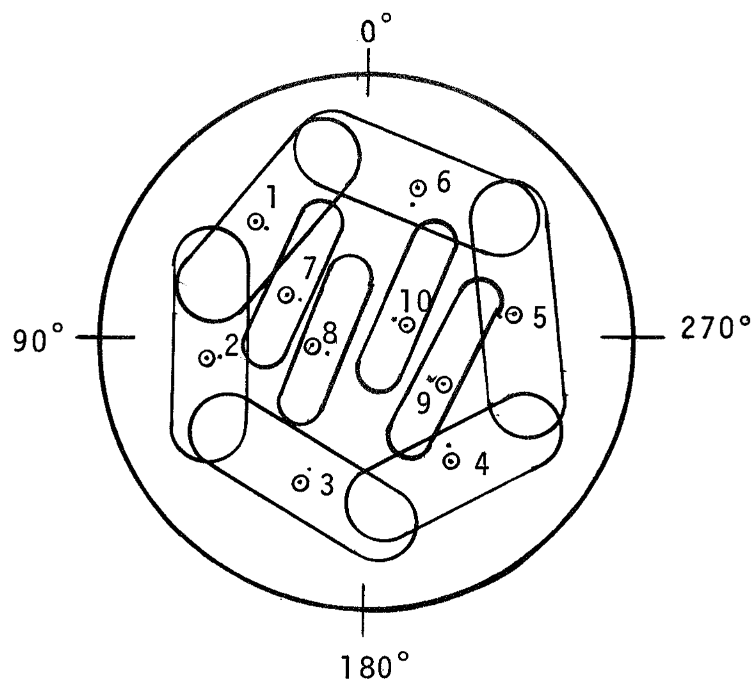
Some interesting recent studies at JPL show that the penetration phenomena demonstrated by non-reactive fluids may not model the reactive jet situation especially for hypergolic propellants such as N_2O_4 and N_2H_4. Such phenomena has been termed reactive flow separation (or blow apart) and results in a reversal of the mixture characteristice described above. For the present injector design, this means that the boundary flow would be oxidizer-rich instead of fuel rich, were the blow apart effect to prevail.

5.2 SPRAY BOOTH NON-REACTIVE DATA

Because the injector used in this program has ten doublets, the flow field in the chamber is necessarily a composite of the flow field produced by all of the doublets each of which have the characteristics described in the preceeding section. A representation of this superposition is shown in Figure 10a (reproduced from Reference 1)*. Even in this simple representation, it is evident that the composite flow field is a complex interaction of the ten element flow fields.

Currently the most frequently used method for obtaining a "feel" for the composite flow field is to gather non-reactive distribution data from a shower booth using simulated propellants.

*Figures 10a and b reproduced from Reference 1 have been modified slightly to account for the different angular relationship of the subject injector.



a. Doublet Non-Reactive Spray Pattern

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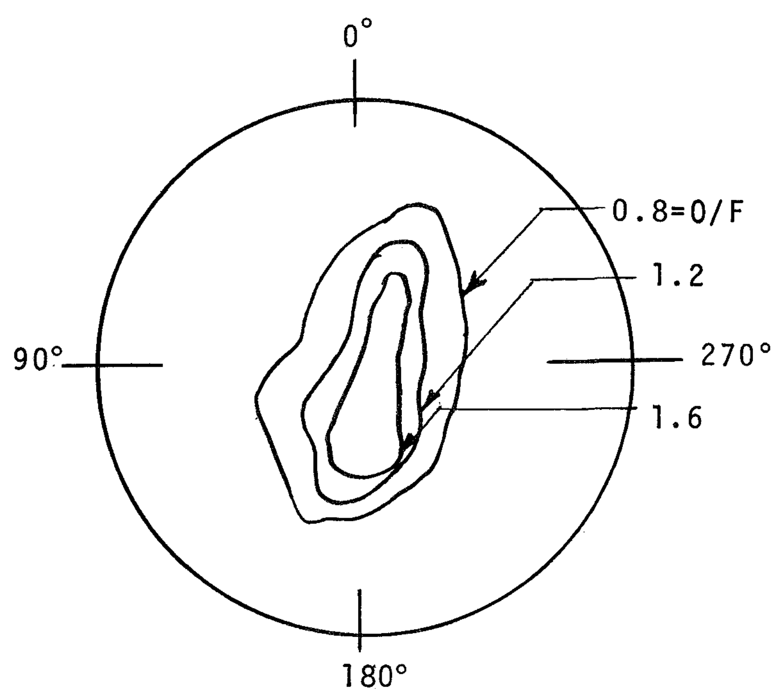
Part I



b. Mixture Ratio Distribution

Figure 10. Injector Non-Reactive Spray Pattern

Shower booth data taken from the twin of the injector used in this study is shown in Figure 10b. Such data can only show the most general features of the flow field. For example, the data in Figure 10b shows the injector does not produce the symmetrical flow field one might expect from the layout of the injector elements although a directional bias due to the orientation of the central elements is evident.*

5.3 CHEMISTRY CORRELATIONS

The correlation of the boundary flow chemical composition data with the injector angle orientation is presented in Figure 11. This data was obtained from the mass spectrometer determinations of the atomic composition in the sample bottles and has been cast in a mass frame of reference by multiplying the oxygen to hydrogen atomic ratio by the molecular weight ratio of the oxidizer and fuel respectively:

$$O/F = \left(\frac{O}{H}\right)\left(\frac{\mathcal{M}_o}{\mathcal{M}_f}\right)$$

This technique is based on the premise that each atom of oxygen represents one molecule of oxidizer and similarly for one atom of hydrogen. Multiplying by the molecular weight provides a convenient way of comparing non-reactive and reactive data on a mass flow basis.

The spatial variation of the boundary flow composition is presented in cartesian coordinates in a series of curves (one for each sampling station) in Figure 11; where number 1 is near the injector end of the chamber. While these figures do show the O/F dependence, O/F alone does not specify the boundary flow composition because unequal diffusion (and perhaps other events not understood at present) cause the flow to demonstrate nitrogen rich characteristics -- which dilution modifies the enthalpy

*Such irregularities are typically attributed to manufacturing tolerances which are very critical for small orifices.

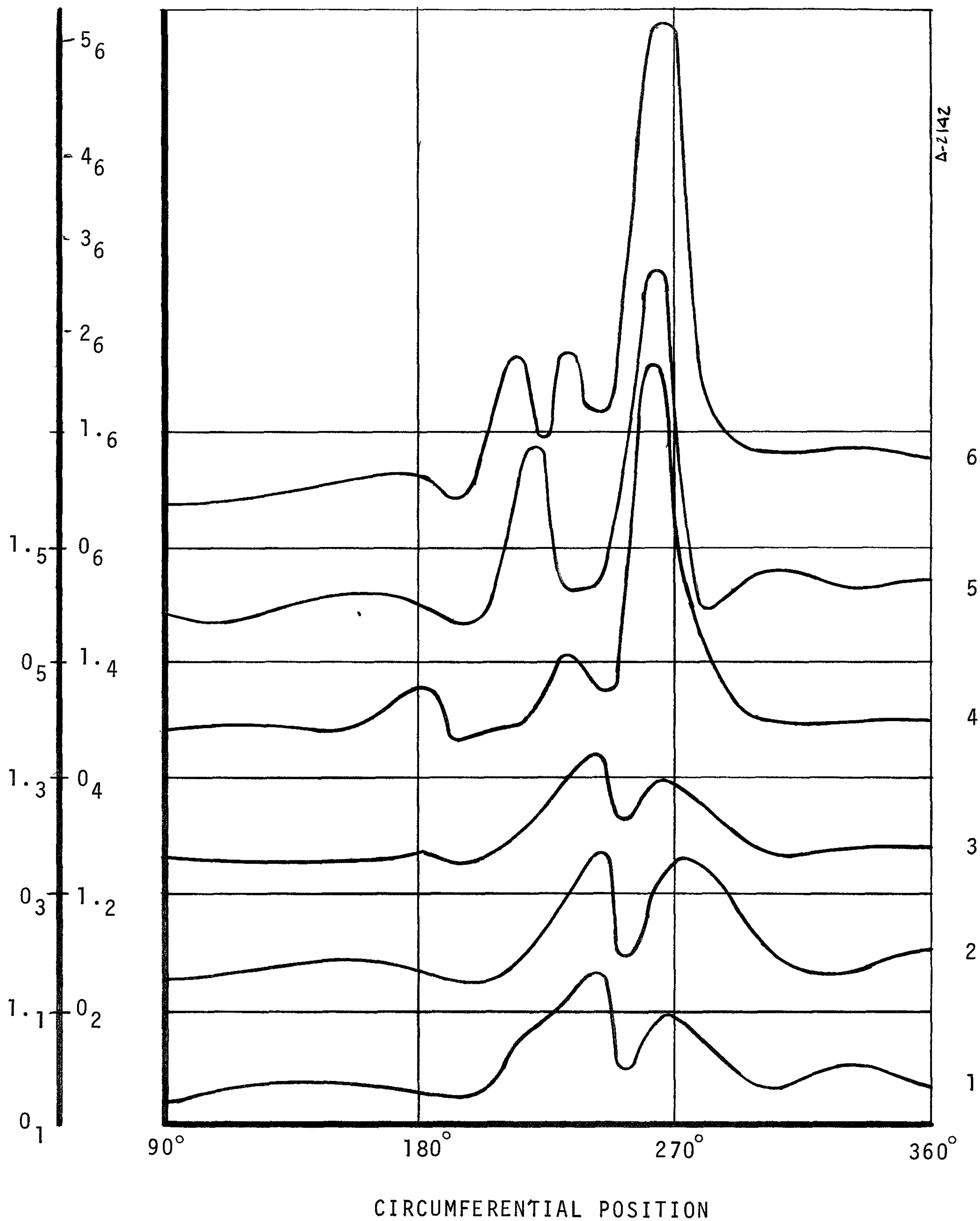


Figure 11. Local Mixture Ratio Variation in the Boundary Flow

potential of the boundary flow (and other parameters of significance). Such complications are not treated in the correlations presented here.

The figures in this set show that the boundary flow is predominantly fuel rich as desired – becoming less fuel rich as the flow proceeds down the chamber to the exit. However, in one region, specifically between 220 and 280 degrees, the boundary flow has a very high oxidizer to fuel ratio characteristic; which, for the last stations, is as high as the highest determined in the tests of the individual element non-reactive tests (i.e., O/F = 4:1) mentioned previously. Note also in the fuel rich regions, the O/F values are lower than the non-reactive data (O/F < .5) from the individual elements.

While the data does show higher O/F ratios in the 270° quadrant as expected from the shower booth data (though not to the extent displayed in the data here), the high ratios expected at the 75° sector do not appear although a slight rise is found for the 30° position for most of the stations (not shown).

5.4 SPRAY PATTERN CORRELATION

Although more difficult to assimilate, the most practical way to correlate the foregoing variations in boundary flow mixture ratio with the injection element orientation is to compare it with the doublet locations in polar coordinates. A typical plot is presented in Figure 12. The doublets are numbered from one to ten as they are encountered in rotating counter-clockwise (the outermost first). It is necessary to visualize the interaction of the spray patterns bearing in mind the elliptical pattern (probably oxidizer rich) on the fuel orifice side (denoted by the letter f) and vice-versa for the oxidizer side (denoted by the letter o). Also bear in mind the mixture ratio is probably relatively constant in planes parallel to the ellipse major axis (the long line) of the spray pattern.

In Figure 12 it is quite apparent that the boundary flow is oxidizer rich in the neighborhood of the number 4 and 5

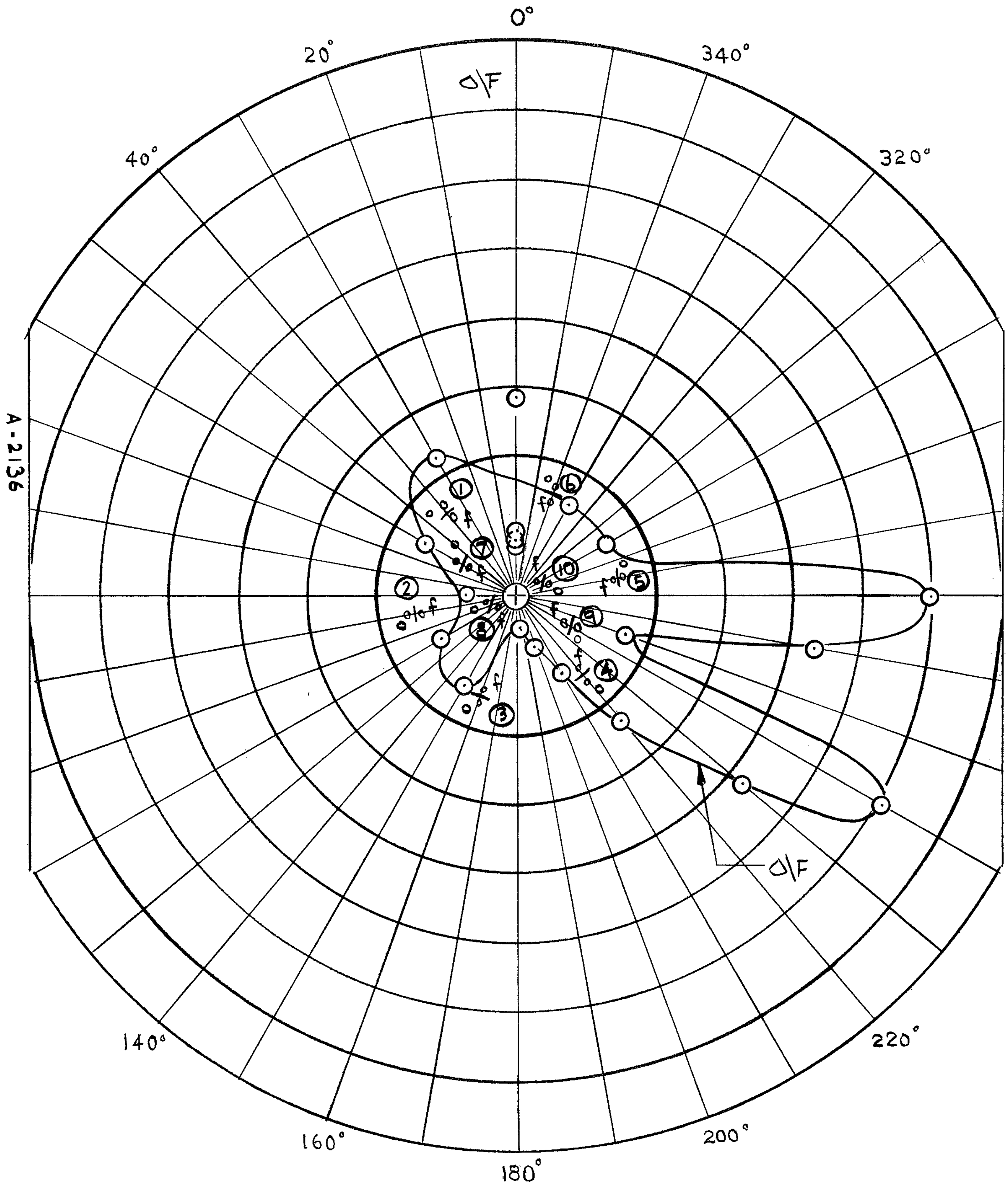


Figure 12. Correlation of O/F with Doublet Pattern

doublets. Doublets 2, 6, 7, and 8 appear to be producing a fuel rich mixture at the wall. Some preliminary insight into the complicated interaction of the spray can be inferred from these data. For example, note how the fuel rich spray from 3 penetrating the oxidizer rich spray from 4 produces low O/F at 180°. Conversely, the oxidizer rich side of doublet 2 could produce the slight hump in O/F at 30° as it penetrates the fuel rich spray from 1 at the wall. Similar interactions can be visualized for 2 and 3;1and 6, etc. One is tempted to conclude that except for 4 and 5, the variations noted in O/F distributions are due to these spary interactions.

Several typical examples of the many atomic and specie spatial profiles generated in this program are presented in Figures 13 and 14. For the most part, the boundary flow is characterized by excessive amounts of ammonia near the injector which decreases with axial distance down the chamber wall (presumably as the liquid ammonia vaporizes). There is a corresponding increase in nitrogen and water. For the high O/F chamber positions (typified by Figure 13b), little ammonia is found and free oxygen and much more nitrogen are present in its place. The atomic fraction plots show similar transitions -- from a hydrogen rich situation near the injector to nitrogen rich near the throat. In the high O/F region (Figure 14b) nitrogen is everywhere the predominant atom gram fraction.

Redundant test data showed that the sampling rates used in these experiments were low enough that upstream sampling did not effect downstream results. Data from tests in which sampling duration and mixture ratio were varied, showed some effect due to these parameters but so few tests were performed that positive conclusions could not be drawn because of certain inconsistancies evident in the data.

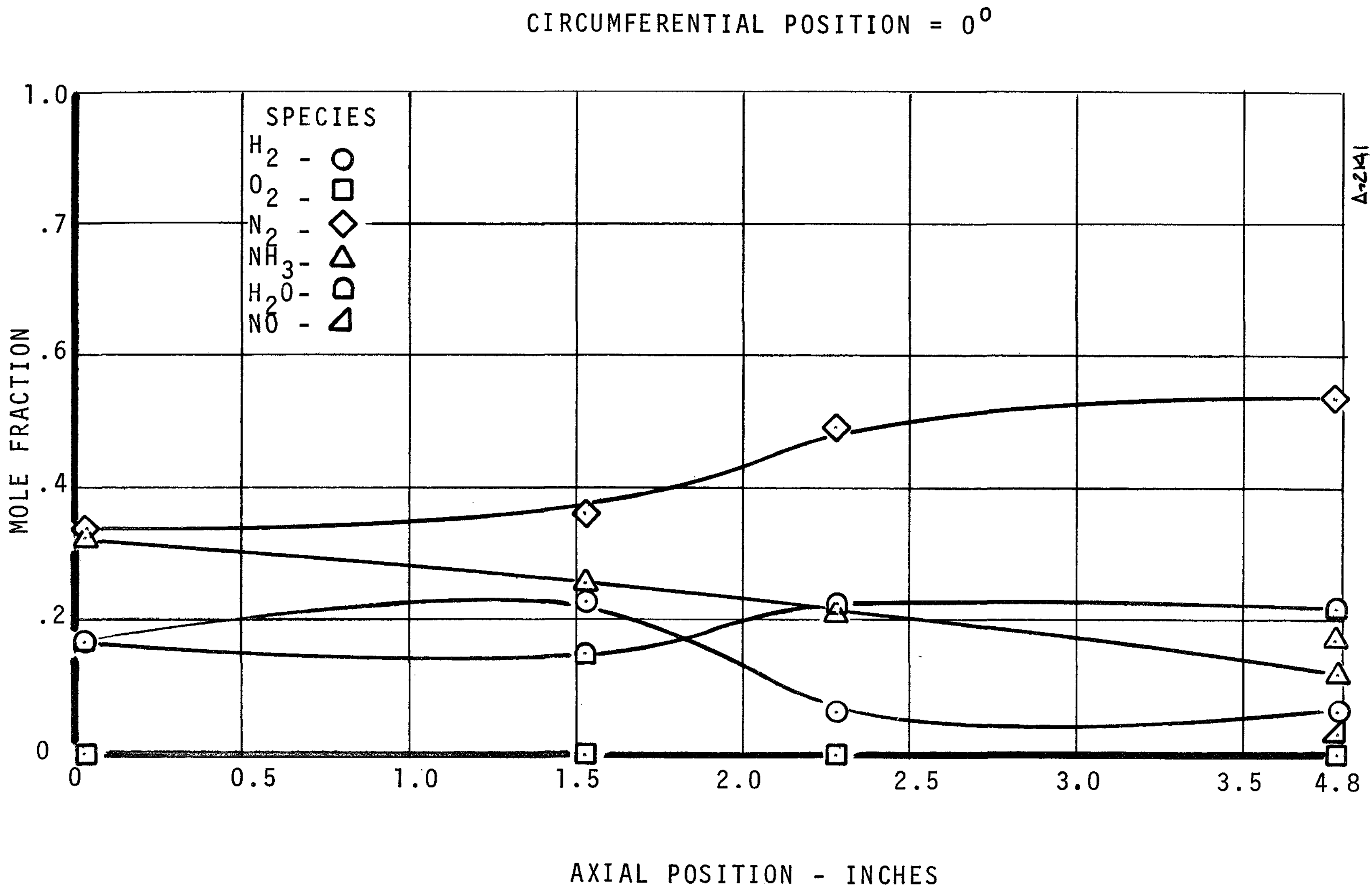


Figure 13. Species Axial Profile
a. Circumferential Position = 0°

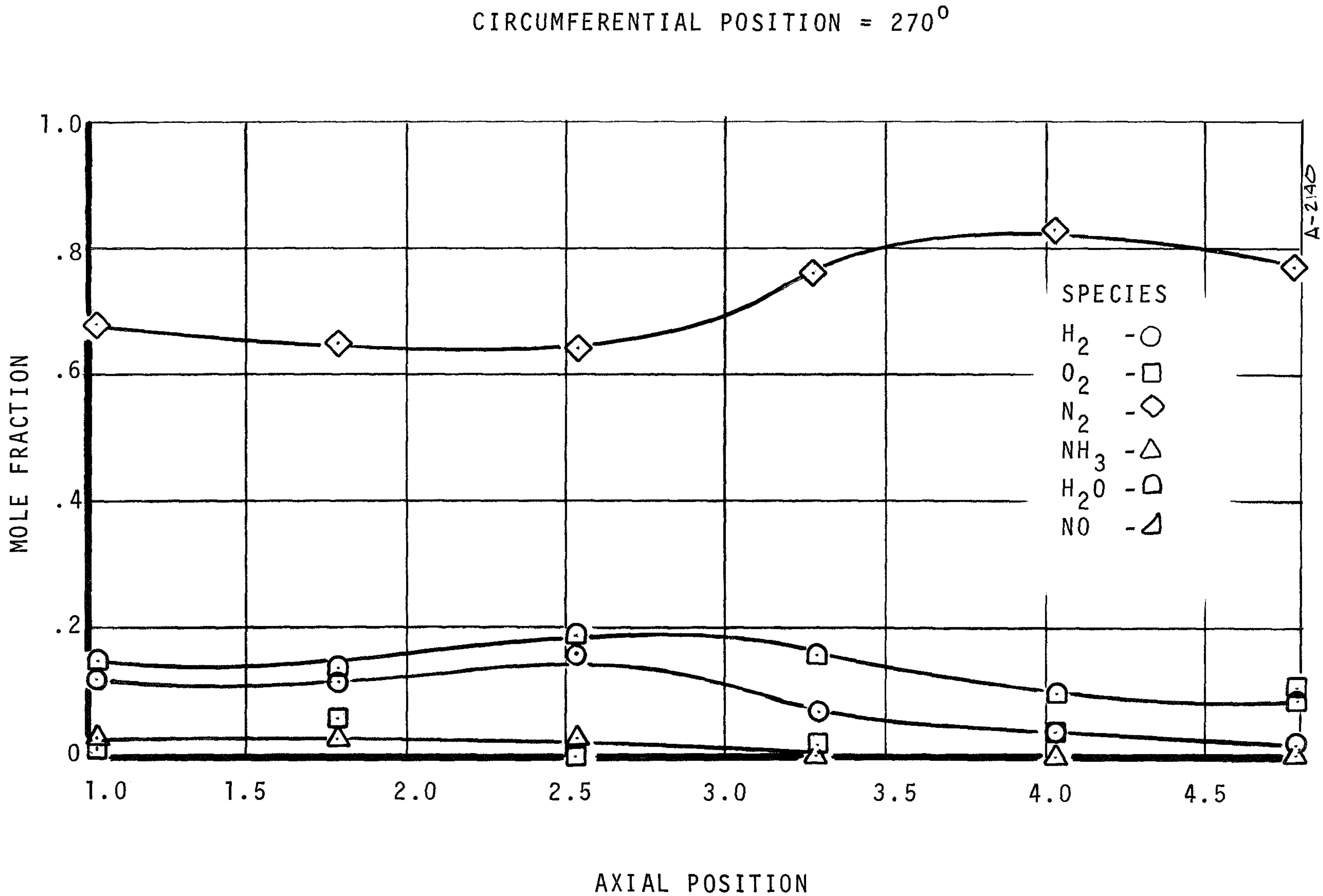


Figure 13. Concluded
b. Circumferential Position = 270°

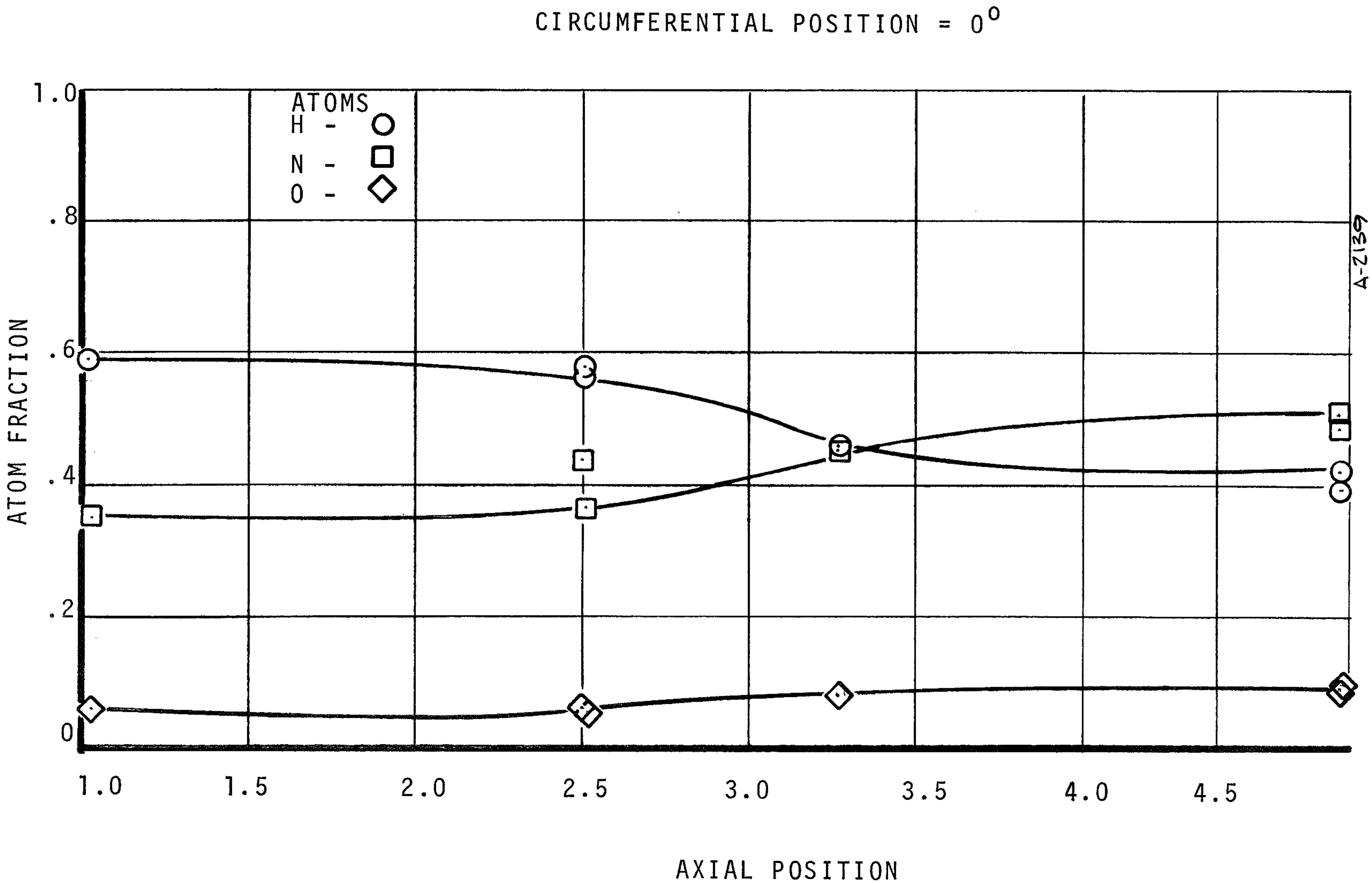


Figure 14. Gram-Atom Axial Profiles
a. Circumferential Position = 0°

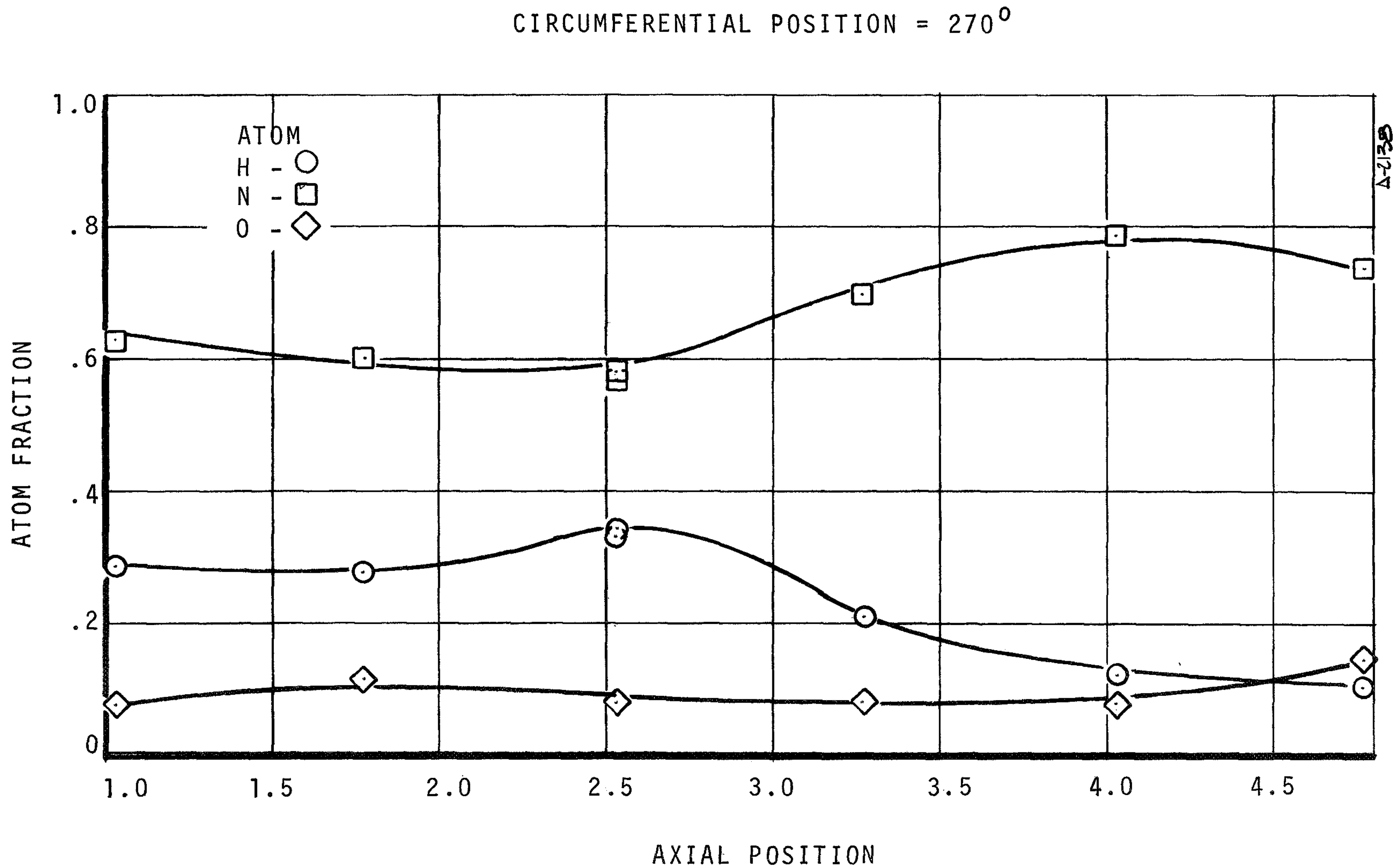


Figure 14. Concluded
b. Circumferential Position = 270°

5.5 HEAT FLUX DATA AND CORRELATION

A certain amount of difficulties due to both instrumentation failures and calorimeter contamination prevented the attainment of either a complete set of heat flux data or data of unquestionable quality. The best of the heat flux data obtained is presented in Figure 15 which both conveniently summarizes all the data and compares it with the spatial composition trends. It is seen for the positions near the injector that there is a fair degree of correlation between the change in heat flux magnitude and changes in oxidizer to fuel ratio, although the dramatic changes in the oxidizer rich region does not seem to have a heat flux counterpart. The relationship between the two becomes more tenuous for the other axial locations and near the throat there seems to be little if any relationship. It can be noted that the phenomenon causing the significant changes in heat flux appears to be represented in all three gage responses. In particular, attention is drawn to the rise in heat flux to the 60° position and the sudden drop at about 80°. A general rising trend to the oxidizer rich region followed by a drop back down to the 0° position values can be seen. The data from Reference 1 taken from an identical injector in a steel chamber at a slightly higher wall temperature displays a completely different spatial characteristic since the data are much more constant. The calorimeters of Reference 1 were constructed on a different principle and a different analytical technique for calculating heat flux was employed. These differences may or may not account for the different characteristics between the two data sets.

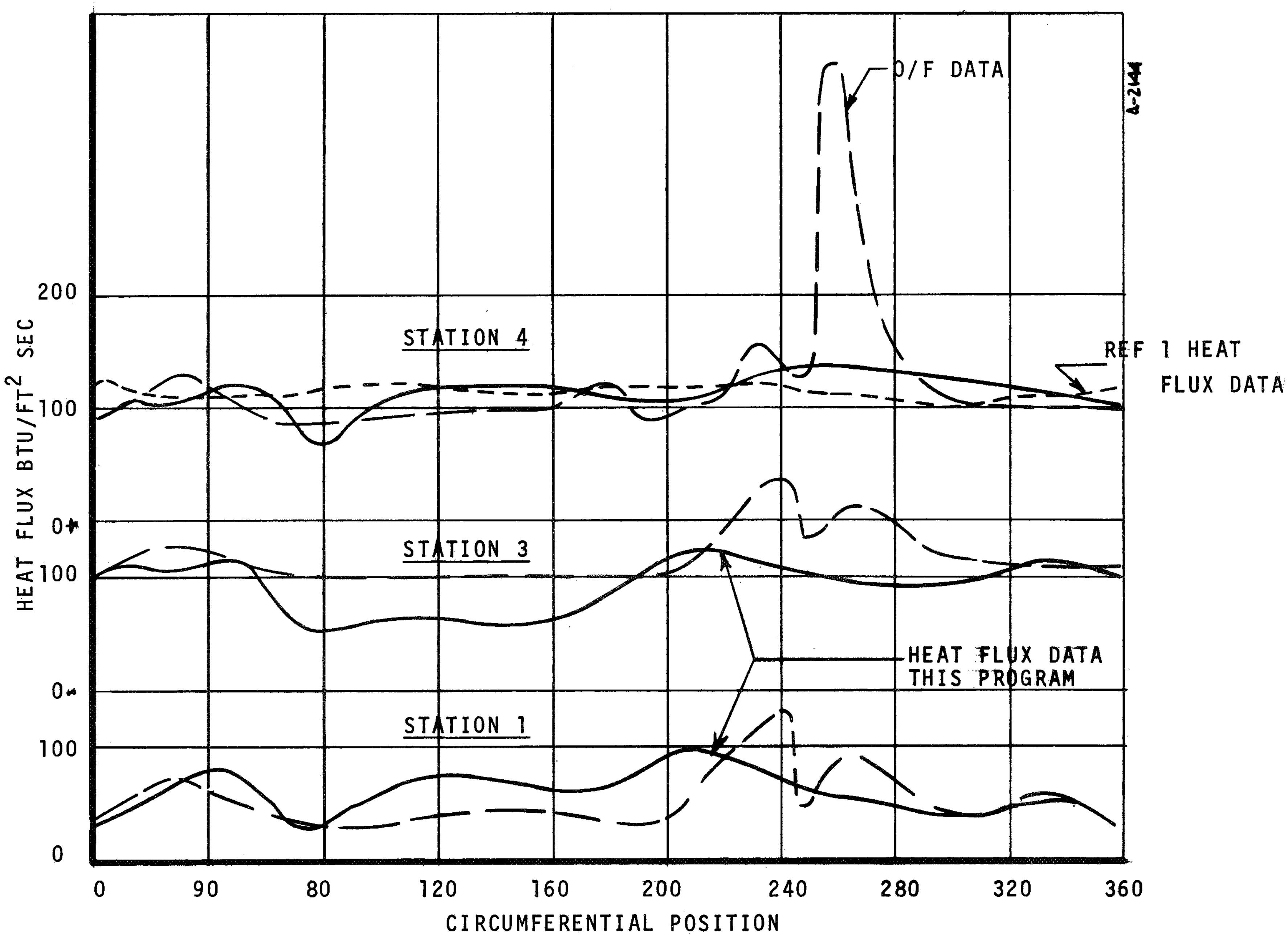


Figure 15. Comparison of Mixture Ratio and Heat Flux Dependence

SECTION 6

ANALYSIS AND PREDICTION

6.1 COMPOSITION ANALYSIS AND PREDICTION

Theoretical analysis were made on some of the experimental composition results. Equilibrium species predictions were made based on the calculated atom gram fractions from the mass spectrometer determinations. These predictions were performed for individual samples as a function of temperature. The predicted temperature dependent species composition were then compared with the spectrometer species determination. In most cases a theoretical temperature exists such that precise agreement with all pertinent species can be found and this temperature agrees quite closely with the measured wall temperature. An example of this agreement is presented in Figure 16. This figure shows a rapidly changing composition as a function of temperature (the cause of the composition change being the decomposition of ammonia at or about the chamber wall temperature). For the particular example chosen, agreement within a few percent for all species is found at a temperature of $472^{o}K$. The measured wall temperature (mean during the sampling event) was $453^{o}K$.

Other cases are found where a unique solution is obtained but for temperatures much higher than wall temperature and also a few cases are found where no temperature can be found such that agreement is obtained. The first situation can possibly be interpreted as a composition frozen near the chamber flame temperature and the second as a general nonequilibrium condition. More experimentation and documentation of these kinds of effects need to be performed to establish the plausibility of these interpretations.

Several predictions of bottle composition were attempted utilizing a more general constraint than bottle atomic composition. The chamber boundary layer flow was modeled by employing a recently developed Aerotherm turbulent boundary layer code in which equilibrium chemical reactions and unequal

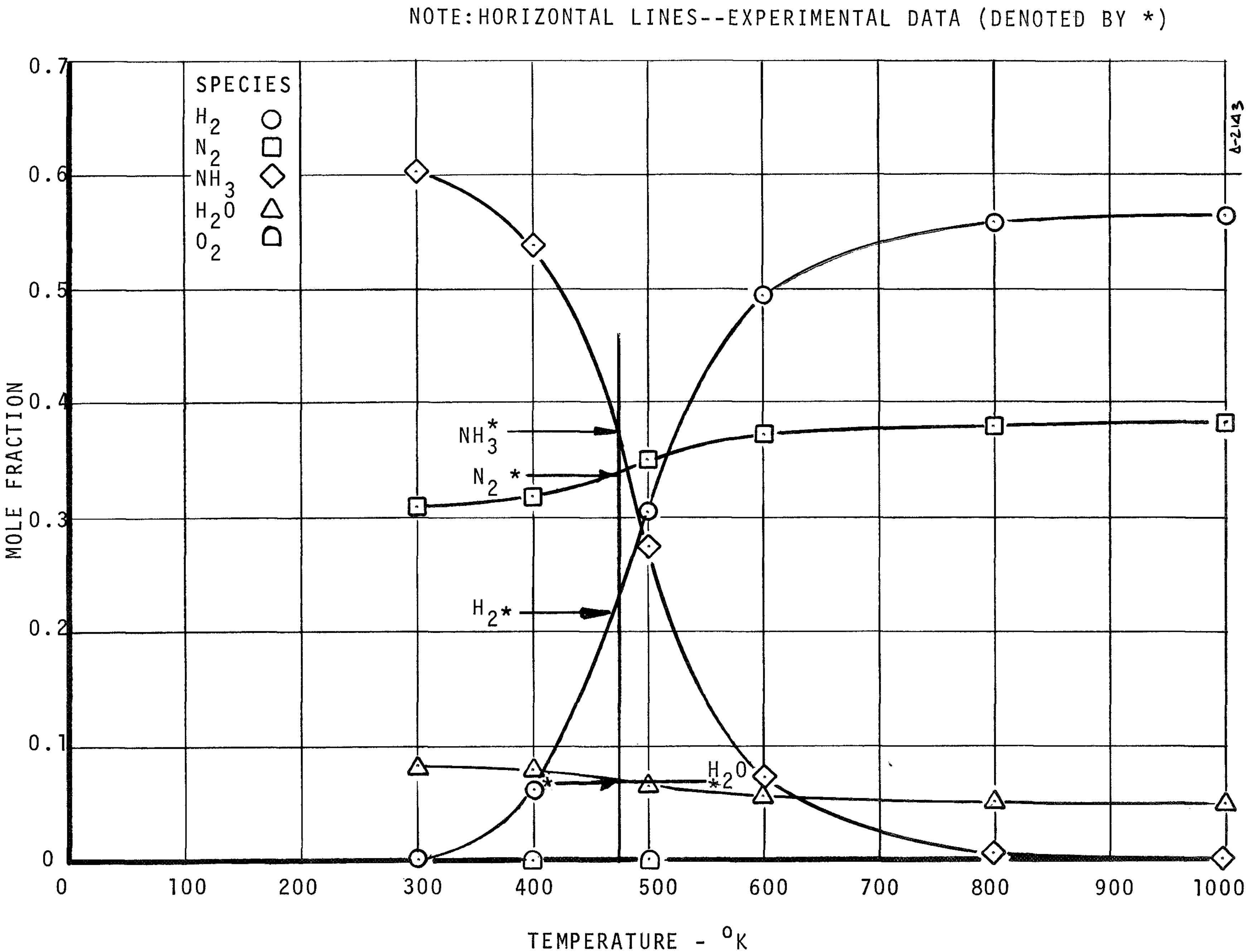


Figure 16. Equilibrium Composition Comparison with Data

species and thermal diffusion events can be treated. The edge composition was specified to be the mean chamber condition and an arbitrary composition profile was specified at the injector station which varied from this edge composition to either a) pure hydrazene at the wall, or b) a propellant mixture ratio of .5 at the wall. Starting with this initial condition the program generated nonsimilar composition profiles (and profiles of other properties as well). This theoretical boundary flow was then theoretically sampled using potential flow streamlines produced by a sink to represent the three dimensional flow situation. Choosing for comparison, one of the flasks which had a small amount of ammonia present, the theoretically produced sample results are found to be amazingly close to the experimentally measured composition as shown in Table 2 (page 39). When ammonia is present in large quantities, the predictions are in considerable error. This error is a consequence of the fact that unless a liquid layer of ammonia (or hydrazine) is presumed present on the wall, the temperature gradients in the laminar sublayer are so great that little mass of ammonia can theoretically be present.

6.2 HEAT FLUX DATA PREDICTION

Theoretical predictions were made of the measured heat flux at two azimuths; one corresponding to the high O/F region ($\emptyset \approx 270$) and one representative of the fuel rich region. These analyses provided an opportunity for assessing any benefits that may possibly accrue from a knowledge of the boundary flow composition in making predictions of this kind.

The predictions were made with a turbulent boundary layer code employing the integral energy thickness theory generalized to treat flows of arbitrary chemical composition. Measured wall temperature, boundary flow composition, and the theoretical enthalpy at the edge (for the mean chamber condition) were input to the program. Typical results are presented in Figure 17 where excellent agreement is apparent. In most problems to date, the results from the program have had to be factored by about .7 to obtain agreement with experimental heat flux. The agreement

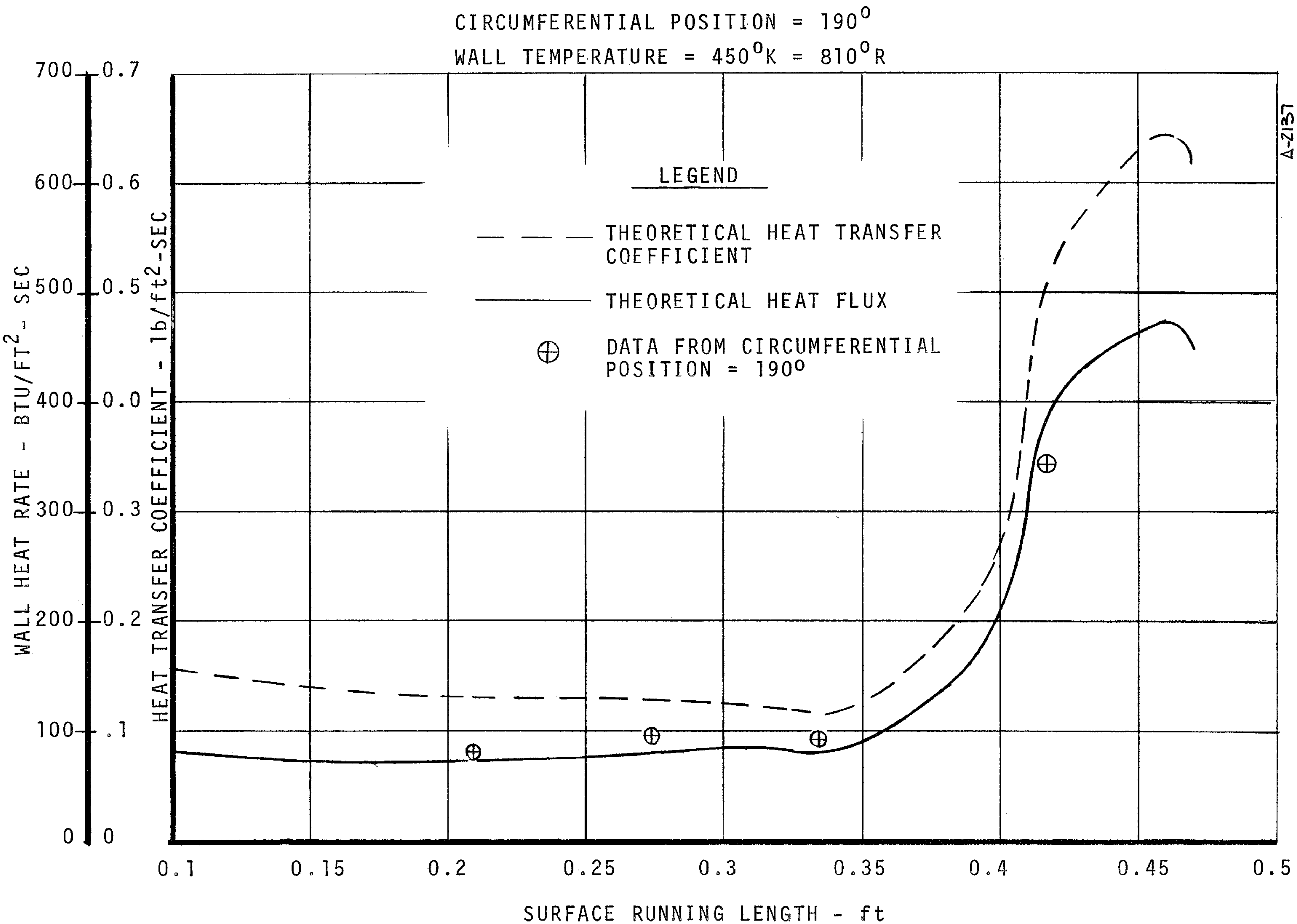


Figure 17. Comparison of Theoretical Heat Flux with Data

TABLE 2

COMPARISON OF PREDICTED AND MEASURED SAMPLE COMPOSITION

		H	N	O
Data	Run 11	0.50	0.45	0.04
Theory	O/F=0. at the wall	0.607	0.34	0.05
Theory	O/F=0.5 at the wall	0.54	0.34	0.12

TABLE 3

COMPARISON OF PREDICTED AND MEASURED ABLATION

Recession (Inches)		
Azimuth	Data	Predicted
270 *	0.4	0.44
160	~.0	0.24

Firing Time = 64 seconds

*Maximum ablation point

displayed in this figure was obtained without the application of any factor. This improvement in agreement is, at this time, attributed to the benefit of having composition data.

6.3 ABLATION RESPONSE PREDICTION

Preliminary attempts were made to predict the ablative response of a Refrasil-phenolic throat material which had been tested with this injector previous to the program. Two circumferential positions were chosen which correspond to the maximum and minimum recession points. While the ablation predictions were satisfying, several presumptions with regard to the edge thermodynamic state had to be made which were not totally consistent with what had been used for the prediction of heat transfer. In short, by assuming the edge thermodynamic state to be given by the theoretical flame temperature, the maximum ablation or recession rate was predicted nearly exactly, as shown in Table 3. However, the minimum point, which showed nearly zero ablation, was significantly over-predicted since the theoretical results showed only a factor of two reduction from the maximum recession rate. Predicting the response of a material like Refrasil-phenolic is approximate at best since there are a number of ill-defined phenomena poorly modeled at present which require further research even for situations in which the boundary conditions are well defined. Apparently there is a significant cut-off mechanism, such as fail temperature, which was not treated properly for the minimum recession point case. Theoretical explorations along these lines could not be performed in the current effort.

SECTION 7

SUMMARY AND CONCLUSIONS

Aerotherm Corporation in conjunction with the Jet Propulsion Laboratory has developed the apparatus and experimental technique with which the composition in the boundary flow of a rocket motor can be determined with reasonable accuracy. The specific propellant system used for this demonstration was hydrazine and nitrogen tetroxide, but the techniques should be applicable to any system producing gaseous or easily vaporized combustion products provided they can be analyzed on a mass spectrometer with the technique developed herein. The test data obtained with the apparatus showed that the injector used in the program although identical to a previous injector which gave good performance in ablative motors, nevertheless appears to have produced significantly different boundary flow composition than did the other injector. The mechanical reason for this different performance was not determined in the study. The high oxidizer to fuel ratio and significant free oxygen found in one chamber region (which produced severe ablation of a Refrasil-phenolic chamber) is possibly due to blow apart phenomena affecting just one or two doublets of the ten in the injector. Everywhere else, the boundary flow showed a relatively constant fuel rich composition and correlation with the doublet pattern was weak or nonexistent. The complex interaction of the spray patterns needs to be studied so that this important effect can be factored into such correlations. Likewise the heat flux measurements which accompanied the composition determination, showed little or no correspondance to either the injector doublet pattern or to the variation in boundary flow composition that does exist.

Predictions of the composition data were favorable considering their very preliminary nature. These predictions demonstrated conclusively that, theoretically at least, there is required to be a liquid layer of either hydrazine or ammonia present on the chamber surface to predict the ammonia concentrations measured in the collected samples. Equilibrium predictions of the composition using the atomic data from the sample showed good specie agreement for the majority of the cases studied with theoretical temperatures slightly in excess of the measured wall temperature. Evidence of what is interpreted to be high temperature kinetics were also found. Predictions of the measured heat transfer were quite successful although also quite limited. The theoretical ablation calculations predicted the correct level for the maximum ablation point and the correct trend, if not the level, for the low ablation region. The fact that mutually inconsistent presumptions regarding the boundary flow edge thermodynamic state between the heat transfer and the ablation predictions were required suggests that further research is required in this area.

SECTION 8

RECOMMENDATIONS

The recommendations given below generally follow along the lines of the principal questions and anomalies that were raised in the course of the program. Many of the recommendations are based on factors deemed to be inappropriate for discussion in a summary document so that little in the way of supporting discussion is presented here and reference is made to the pertinent main document. In this regard an attempt is made to reference the specific areas of the final report in which the problem areas is treated in detail.

8.1 EXPERIMENTAL RECOMMENDATIONS

Several types of experimental programs are seen to be needed which could employ the equipment in its current stage of development. It would, however, be advantageous to incorporate at least some of the improvements suggested in Section 8.2 which follows.

With a complete set of heat flux instrumentation, certain key injector positions should be retested to verify the findings of this program. In addition this redundant data could be used to verify the kinetically controlled composition hypothesis (Part II - Section 5). These tests would not only rectify the lack of detailed heat flux data in the throat region but could also be used to obtain pre-ignition heat flux gage response data (Part III - Section 4).

Experiments with various sampling flow rates and different wall temperatures could be conducted to correlate the theoretical boundary flow predictions (Part II - Section 4). Large sampling flow rates could be used to determine the local boundary layer edge composition (with moderate flow field disturbance).

Several tests should be conducted to make sure that the results currently attributed to unequal diffusion effects are not due to gravitational body forces, especially in the case of the condensible species (Part II - Section 4.3).

Additional tests should be made in which mixture ratio and sampling duration are varied over a large range so that conclusive data on these parameters can be obtained (Part III - Section 5).

It is recommended that a test program be conducted with a pyrolytic graphite or uncooled steel chamber to fully assess the effect of wall temperature on boundary flow composition and hence heat rate (Part II - Sections 4 and 5).

Shower booth tests of the injector should be conducted to uncover the cause of the composition distribution detected in this program.

8.2 EQUIPMENT DEVELOPMENT

Several modifications to the existing experimental apparatus are desirable to enhance its capabilities. These are:

a. Installation of heat flux gages and sampling ports in the throat and next to the injector face

b. Modification of the sampling system to provide thorough flow sampling with direct coupling of the microtubes

c. Modification of microtube hardware, especially the decrimper, to reduce the sample failure rate

d. Upgraded instrumentation (particularly the mass spectrometer) to full digital output so that a fully computerized data reduction can be implemented (Part III)

e. Construction of more rugged heat flux gages (null point). These gages should be fully calibrated in an arc tunnel or other suitable high heat flux facility in which known boundary conditions can be duplicated and precisely controlled.

f. If possible, install sampling ports and heat flux gages on the injector face

The following equipment developments require considerably greater investments than the foregoing and also provide far greater generality.

a. Development of a sampling system for advanced propellants--the system to combine flow through technique with micro-tubes, the JPL corrosion resistent valve, and a method for determining solid particles

b. A more elaborate and possibly more accurate and foolproof alternative system to (a) is the direct coupling of a laboratory grade magnetic mass spectrometer directly to the sampling port(s)

c. With either (a) or (b) the performance of such a system should be established with a suitable space storable propellant

d. Construction of sampling systems to be used for qualification testing of production injectors/motors

e. The construction of cooled probes inserted through the chamber walls (either fixed or movable during a test) which would produce very valuable data on overall composition in the chamber. These probes could be small enough such that little flow disturbance would be created

f. Along the same lines as (e), special calorimeters inserted through the wall could be used to obtain invaluable data on the energy content of regions within the flow field and boundary layer which could greatly assist correlation and prediction processes established in this program (Part II - Sections 4 and 5).

8.3 INJECTOR EXPERIMENTAL EQUIPMENT

There appears to be a significant lack of phenomenological information even for the simple doublet situation (which produces a complex spray pattern). A number of subtle physical processes which affect spray properties need to be thoroughly examined. It is recommended that a simple open combustion system be devised for this purpose along the lines of those used in the past at JPL in which injector design variables can be readily varied. It is envisioned that the apparatus would be constructed so that numerous propellants and nonreactants could be tested. Some of the factors which could be investigated include:

a. Effects of manufacturing tolerances (controlled variation)

b. Effect of entrained flow or external flow between unreacted jets

c. Effect of scale

d. Effect of multiple doublets

e. Orifice properties and design features such as injection angle.

The system could be contained in a large tank in which a high pressure inert atmosphere could be superimposed. Such an open system would permit flow visualization with either high speed movie or stop action photography or laser holography.

8.4 ABLATION MATERIAL TESTS

It has been found historically at Aerotherm that in the calculation of ablation response, the predictions are more limited by the lack of information concerning physical properties of the material being studied than by any other single factor. This study was no exception. In particular, data is needed for:

a. Fail temperatures

b. Shear strength, and thermal conductivity of the char

c. Off-gas composition

8.5 RECOMMENDATIONS FOR ANALYTICAL STUDIES

In conjunction with the testing of 8.1 the heat flux calculation procedure for the null-point calorimeters is in need of detailed thermal analysis as applied to the rocket chamber situation. It is recommended that existing 2 or 3-dimensional finite element computer programs be used in such studies. The effect of pre-ignition cooldown should be investigated as completely as possible with the hope that a more accurate re-reduction of the heat flux data of this program could be made (Part III - Section 4).

The types of data analysis and predictions begun in this program should be carried further as prudently as possible in the support of the foregoing experiments and in the hope of increasing the knowledge of what is happening within the chamber. At the minimum, these analyses should complete the equilibrium sample specie predictions for each sample already obtained in this program. The heat flux predictions should be carried forward to the point that the significant heat flux variations found in the experiments reported here can be understood.

Once the foregoing has been accomplished, analytical procedures would be in a position to be used for correlating the film transport coefficients which would be highly useful for the prediction of ablation and heat transfer in injector and motor design studies. Such correlation studies are already in progress for external heating situations.(2)

The turbulent boundary layer procedure used in the studies reported here, could be improved by the addition of a capability to handle situations when condensation of species occurs. Such a situation is thought to occur in combustion chambers operating with cool wall temperatures. Predictions with such a program using a liquid layer next to the wall would, it is felt, be highly useful in explaining and possibly correlating the type of data obtained here.

There seems to be a need for a major analytical program for predicting the boundary flow and three-dimensional chamber flow field characteristics. A mutual benefit would accrue if such studies were to be combined with the experiments recommended previously. Such a program would proceed along various stages of sophistication as follows:

a. Nonreactive spray data and dispersion formulas modified to account for wall accumulation effects could be developed to use as a tool for correlating the composition data with injector characteristics(3,4)

b. Using (a) as a basis and considering existing spray and jet impingement data and theory, a complete 3-dimensional spray analysis computer program could be developed. The ultimate program should have the capability for accounting for such subtle effects as differences in orifice tolerances, roughness, etc. Such a computer code would hopefully have the power to explain the phenomena found in the Mod IV injector.

c. Final developments are envisioned along the lines of completely coupling the foregoing with a three-dimensional viscous flow field capability complete with turbulent boundary layer. Such procedures would incorporate the foregoing with flow field and turbulent boundary layer codes already in existence. Consideration would have to be given to existing spray dispersion models of a statistical nature such as the the Rosin-Ramueler model; the stability and dynamics of fuel droplets in reacting flow fields; and including the impingement work with penetration and blow-off effects done at JPL. Viscous transport and recirculation modeling could be along the line of the Richardt and Korst theory, respectively.[5,6,7,8]

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