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PRINCETON UNIVERSITY

DEPARTMENT OF AERONAUTICAL ENGINEERING

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SECURITY INFORMATION

DEPARTMENT OF THE NAVY
BUREAU OF AERONAUTICS

Contract NOas 52-713-c

COMBUSTION INSTABILITY

IN

LIQUID PROPELLANT ROCKET MOTORS

First Quarterly Progress Report
For the Period 1 May to 31 July 1952

Aeronautical Engineering Report No. 216A

Guggenheim Jet Propulsion Center
Department of Aeronautical Engineering
PRINCETON UNIVERSITY

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SECURITY INFORMATION

"B" Building   "E" Building   Jet Propulsion Test Building

FRONTISPIECE - Jet Propulsion Research Facilities, The James Forrestal Research Center, PRINCETON UNIVERSITY
June 1952

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CONTENTS

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FIGURES

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Section I **SUMMARY**

Theoretical studies of the phenomena of combustion instability in liquid propellant rocket motors and experimental test thereof will be undertaken by the Guggenheim Jet Propulsion Center at Princeton as a part of its research program under this contract dated 30 April 1952.

During the first three months period, facilities at the University's new James Forrestal Research Center and personnel were assigned and the initial phases of experimental program were planned in some detail. The first phases of the experimental work will include the determination of overall combustion time lags for the monopropellant, low frequency case.

The basic analysis of Crocco was extended to cover the cases of concentrated combustion at various stations and distributed combustion along the chamber axis.

A constant rate monopropellant feed system was completely designed and preliminary designs of the ethylene oxide rocket motor and the instrumentation systems were worked out. Of particular interest was the specification and order of a special version of the MIT catenary-diaphragm, strain-gage pressure transducer having a water-cooled, double diaphragm and provision for applying a reference back pressure. This pickup should have wide application for combustion instability studies.

Searches have been made of the literature for sources of information on combustion instability and ethylene oxide.

Visits to a number of activities working on liquid propellant rocket combustion instability problems were made for purposes of familiarization with equipment and results. Combustion instability was generally agreed to be a major problem and interesting results of experimental work relating closed-pipe resonance, injector configuration, chemical kinetics and many other factors to the phenomena of combustion instability have been recorded. A non-linear shock wave form of combustion instability has been observed.

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Section II INTRODUCTION

A. Object

BuAer Contract NOas 52-713-c has been undertaken as a part of the research program of the Guggenheim Jet Propulsion Center at Princeton to "conduct an investigation of the general problem of combustion instability in liquid propellant rocket engines. This program shall consist of theoretical analyses and experimental verification of theory. The ultimate objective shall be the collection of sufficient data that shall permit the rocket engine designer to produce power plants which are relatively free of the phenomena of instability. Interest shall center in that form of unstable operation which is characterized by high frequency vibrations and is commonly known as 'screaming'".

B. History

Interest at Princeton in the problem of combustion instability in liquid propellant rocket motors was given impetus by a Bureau of Aeronautics symposium held at the Naval Research Laboratory on the 7th and 8th of December 1950. This interest resulted in theoretical analysis by Professors M. Summerfield and L. Crocco of this Center.

Professor Summerfield's work, " Theory of Unstable Combustion in Liquid Propellant Rocket Systems" (JARS, Sept. 1951), considers the effects of both inertia in the liquid propellant feed lines and combustion chamber capacitance with a constant combustion time lag, and applies to the case of low (up to about 200 cycles per second) frequency oscillations sometimes called "chugging".

Professor Crocco advanced the concept of the pressure dependence of the time lag in mid-1951; his paper, "Aspects of Combustion Stability in Liquid Propellant Rocket Motors" (JARS, Nov. 1951 and Jan-Feb 1952), presents the fundamentals resulting from this concept, and analyzes the cases of low frequency instability with monopropellants, low frequency instability with bi-

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Section II INTRODUCTION (Cont'd)

B. History (Cont'd)

propellants and high frequency instability, with combustion concentrated at the end of the combustion chamber.

Desiring to submit the concept of a pressure dependent time lag to experimental test a preliminary proposal was made by this Center to the Bureau of Aeronautics in the summer of 1951 and, following a formal request, a revised proposal was submitted which resulted in the present contract dated 30 April 1952.

Analytical studies of distributed combustion had been carried on in the meantime under Professor Crocco and within the sponsorship of the Guggenheim Jet Propulsion Center by S.I. Cheng and were issued as his Ph.D. Thesis, "Intrinsic High Frequency Combustion Instability in a Liquid Propellant Rocket Motor", dated April 1952.

Time was devoted, in anticipation of the contract, during the first third of 1952 to constructing facilities, securing personnel, and planning the experimental approach.

Work since 30 April is described in some detail in the following sections of the report.

C. Facilities

As a part of the facilities for jet propulsion research (see Frontispiece) at its new James Forrestal Research Center, the University authorized construction of a modern test building with two cells for static operation of jet propulsion devices and a middle control room. The building is constructed of twelve-inch thick reinforced concrete with installed explosion proof electrical services and fog sprinkler and floor flushing systems. It is now complete and the larger test cell has been assigned to this contract.

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Section II INTRODUCTION (Cont'd)

C. Facilities (Cont'd)

A Central Recording Room, Component Test Room, and Storeroom are located in "E" building.

Building "B" contains Project Rooms 1, 2, and 3, a Blower Room, an Assembly Shop, a small Dark Room, Locker Room, Drafting Room and offices.

The Forrestal Center is located on Brunswick Pike (U.S. Route #1) about two miles north of the Penns Neck traffic circle near Princeton, New Jersey.

D. Personnel

During the period, assignments of personnel to the project have been made to the extent required by the contract both in number and competence. Although the efforts during the past month have emphasized the securing of qualified personnel and their indoctrination into the project, it has been possible to accomplish much of the planning and some design and development.

Key personnel now assigned to the project are listed below:

1. Professor-in-charge - Dr. Luigi Crocco
2. Assistant Professor (Theo. Studies) - Dr. S.I. Cheng
3. Research Engineer - J.P. Layton
4. Asst. Research Engineer - Dr. Jerry Grey
5. Graduate Assistants (2) - G.B. Matthews
   D.T. Harrje
6. A Technician and two Mechanics

In addition, personnel are assigned from our Supporting Services group for drafting, purchasing, instrumenting, and computing as required.

E. Schedule

The schedule of the work is shown on Fig. 1 (see following page) for the first year of the contract.

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Section II INTRODUCTION (Cont'd)

E. Schedule (Contd)

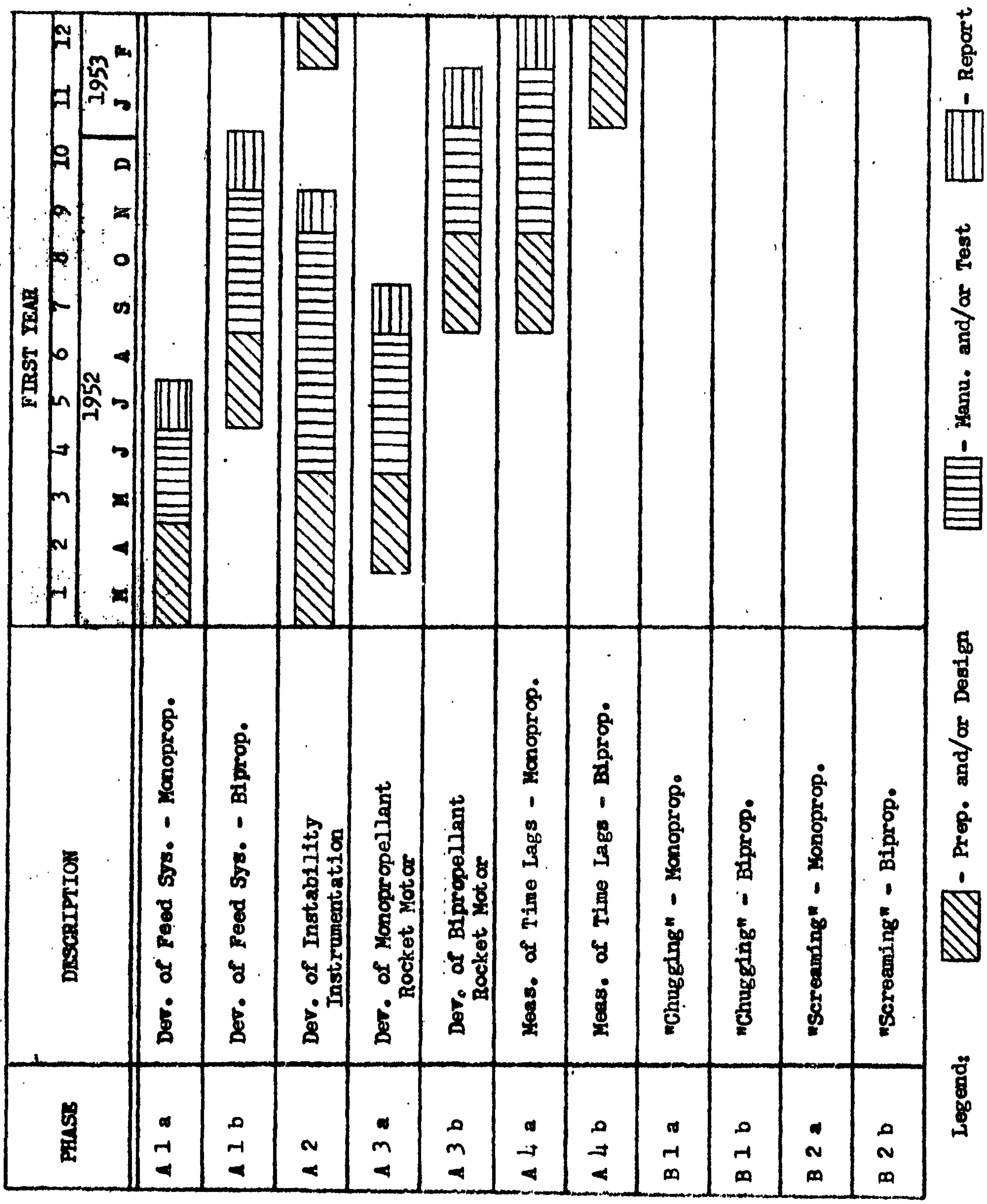

FIGURE 1 Schedule - Liquid Propellant Rocket Combustion Instability Project from 1 May 1952 to 30 April 1953

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Section II INTRODUCTION (Cont'd)

E. Schedule (Cont'd)

Permission was granted for work to proceed in anticipation of the contract as of 15 December 1951 although at a reduced level. This aided materially in making progress ahead of schedule until the contract was actually received, therefore the schedule is shown starting as of 1 March 1952; however, delays in adjustment of the provisions since that time have hindered progress considerably so that much of the time thus gained has been sacrificed.

At the present time work stands about on schedule, considering the contract date as the starting date, although continuing procurement difficulties with materials, mainly stainless steel, and instrumentation, caused by the lack of a signed contract with its priority provisions, will probably occasion further delays in the progress of the work. The work will be rescheduled when the magnitude of the delays is known.

Section III THEORETICAL STUDIES

In addition to the work of Crocco wherein both low frequency and high frequency intrinsic combustion instability (see Section II B) were presented, the theoretical analysis was extended during the first part of 1952 under the sponsorship of the Guggenheim Jet Propulsion Center.

The original analysis considered simple, constant-rate feed systems and used a simplified model of concentrated combustion at the injector end for a particular value of the index of interaction $n = \frac{1}{\gamma}$, where γ is the specific heat capacity ratio of the burned gas. The index, n, of interactions between the combustion processes and the pressure oscillations is defined through the pressure sensitive time lag $\bar{\tau}$ as follows:

$$\int_{t-\bar{\tau}}^{t} p^n dt' = \bar{\tau} p^n = \text{constant}$$

The analysis using the simplified model of concentrated combustion was extended by the thesis studies of Cheng and will be presented in two papers authored by Crocco and Cheng which are described below.

The paper "High Frequency Combustion Instability in Rockets with Concentrated Combustion" will be presented before the 8th International Congress of Applied Mathematics and Mechanics at Istanbul, Turkey in August, and covers arbitrary values of the index, n, and arbitrary positions of the concentrated combustion front along the combustion chamber axis. It is found that the position of a concentrated combustion front with respect to the nodes and the anti-nodes of the pressure oscillation is of great importance on the stability behavior of the system.

Systems with combustion distributed over a considerable portion of the combustion chamber axis are formulated in the paper, "High Frequency

Combustion Instability in Rockets with Distributed Combustion", which will be presented at the 4th International Combustion Symposium at MIT in September and where approximate solution of the resulting integro-differential equation is obtained for the extreme case of uniformly distributed combustion.

In both references results are given for a high frequency boundary condition corresponding to a nozzle whose converging part has a length about one third that of the chamber, and a low frequency boundary condition representing the limiting and ideal case of a converging part of zero length.

A. Concentrated Combustion

The most significant results obtained in the case of concentrated combustion are the following:

1. The frequencies of the unstable oscillations are close to the natural frequencies of the combustion system.
2. For a given configuration of a combustion distribution, unstable oscillations are possible if n is greater than some minimum value and if $\bar{\tau}$ is in certain ranges of values which are functions of n.
3. The minimum value of n compatible with instability of a given mode increases when the concentrated combustion front is further away from the anti-node of this mode, and this n_{min} is infinite if combustion is concentrated at the node of the given mode. The injector end is the most unstable position of a concentrated combustion front for all modes of oscillations.

4. The value of n_{min} of a given mode is higher than the value of n_{min} of a lower mode. This is the result when the high frequency boundary condition is used. The low frequency boundary condition does not show this variation. With the high frequency condition at exit, only the fundamental and/or the first few high frequency modes of oscillations can become unstable if the value of n of the combustion system is close to or less than 1.

5. Consequently, the length of the subsonic part of the nozzle has a marked effect on the stability of combustion, and long approaches to the throat can reduce longtitudinal-type instability. Of course, the one-dimensional treatment does not give any information on transversal-type instability.

B. Distributed Combustion

In the paper on distributed combustion it is shown that:

1. The minimum value of n for a uniformly distributed combustion system is of the order of $\frac{k\pi}{M}$ which is about 20 for the fundamental mode. Thus the high frequency oscillations in the uniformly distributed combustion system are most likely to be stable.

2. Conclusions similar to items 1,2,4 and 5 as given above in the analysis of concentrated combustion are also verified.

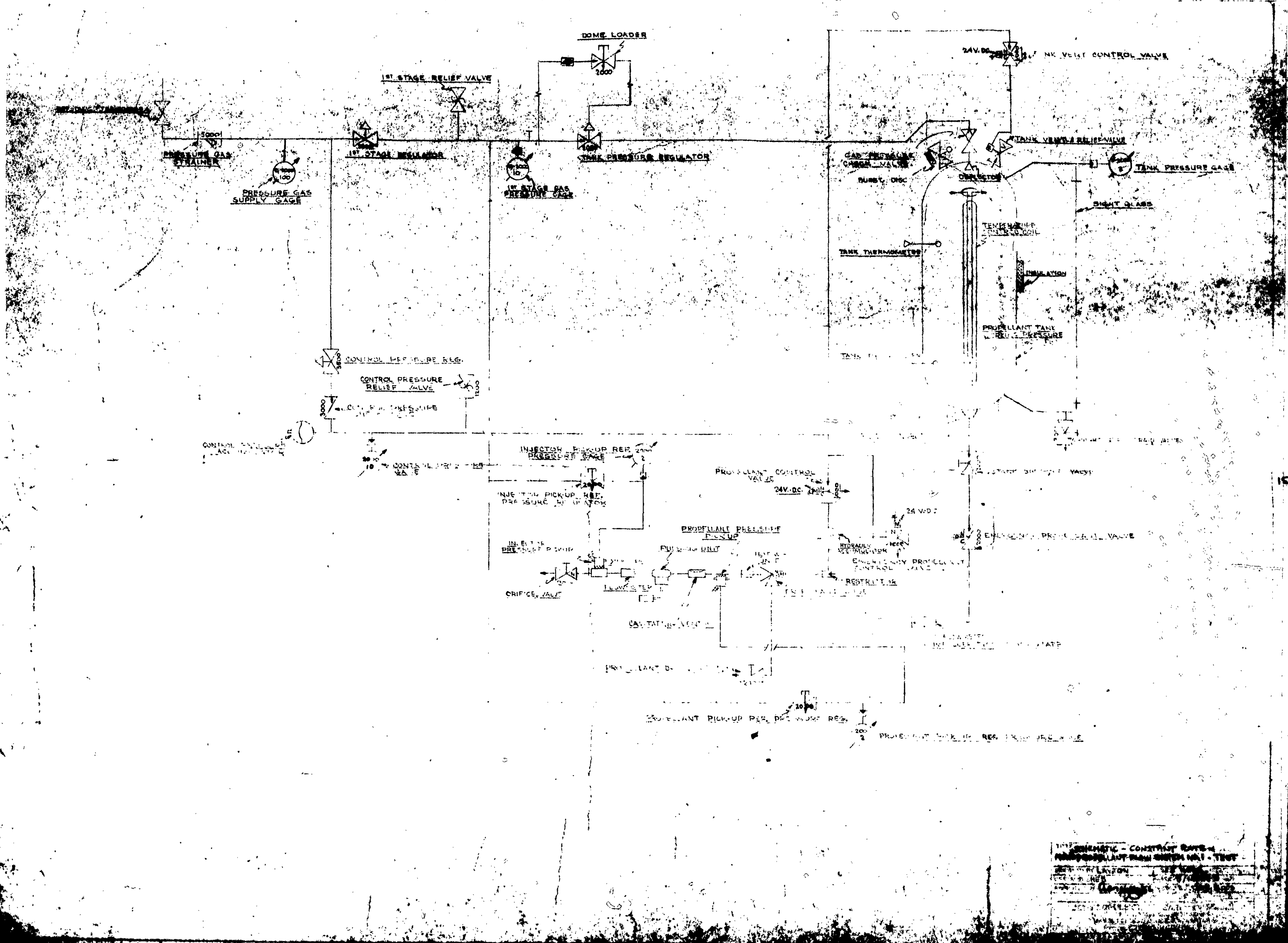
Section IV APPARATUS

The first phase of the research program to be undertaken under the subject contract is an investigation of low-frequency instability in a liquid monopropellant (ethylene oxide - C_2H_4O) rocket motor. It is planned to induce a sinusoidal ten percent variation in an otherwise constant rate monopropellant flow system at several frequencies, and to determine the "time lag", considered to be the time between an injection flow increase and a corresponding combustion pressure rise. Instantaneous measurements of propellant flow, chamber pressure, and injection pressure, made simultaneously, recording both frequency and amplitude will then provide a measure of the absolute values of the overall time lag and the beginning of an experimental check of the instability theory. Much special instrumentation is required to obtain even the above type of information; and, consequently, a rather extensive program has been undertaken in this connection.

A. Constant Rate Monopropellant Feed System

The feed system (see Fig. 2) is of the inert-gas pressurized type with electro-pneumatic and hydraulic control components. A cavitating venturi is used to maintain fundamentally steady flow, and a positive-displacement pulsing unit using a reciprocating piston has been designed to deliver the sinusoidal oscillation of ± 10% amplitude in propellant flow rate at frequencies up to 200 cps.

Before running tests on a rocket motor, it is necessary that some of the special equipment required for the instability investigation be tested and calibrated. The first series of tests will thus consist of water flow tests of the feed system with an orifice substituted for the rocket motor injections. These preliminary runs will test operation of


DOME LOADER
1ST STAGE RELIEF VALVE
PRESSURE GAS STRAINER
PRESSURE GAS SUPPLY GAGE
1ST STAGE REGULATOR
1ST STAGE GAS PRESSURE GAGE
TANK PRESSURE REGULATOR
GAS PRESSURE CHECK VALVE
BURST DISC
DEFLECTOR
TANK VENT & RELIEF VALVE
TANK PRESSURE GAGE
SIGHT GLASS
TANK THERMOMETER
INSULATION
PROPELLANT TANK
CONTROL PRESSURE REG.
CONTROL PRESSURE RELIEF VALVE
INJECTOR PICK-UP REF. PRESSURE GAGE
INJECTOR PICK-UP REF. PRESSURE REGULATOR
PROPELLANT CONTROL VALVE
24V. DC
PROPELLANT PRESSURE PICKUP
PULSING UNIT
ORIFICE VALVE
HYDRAULIC ACCUMULATOR
EMERGENCY PROPELLANT CONTROL VALVE
RESTRICTOR
PROPELLANT PICK-UP REF. PRESSURE REG.

Section IV APPARATUS (Cont'd)

A. Constant Rate Monopropellant Feed System (Cont'd)

the cavitating venturi and the pulsing unit, as well as the pneumatic and hydraulic valves and other components.

The system will also be used in a slightly modified form to establish the calibration of a method, which has been theoretically worked out, for determining the instantaneous flow through an injector orifice by passing an oscillatory flow and evaluating the variation of instantaneous pressure drop across it. The required modifications to the system are shown in Fig. 3, and consist basically of connecting the injector section of the rocket motor onto a pressurized tank to simulate actual rocket operating conditions, and the use of high frequency response pressure pickups and dynamic flowmeters to get pressure and flow correlations. The theory and procedure for this determination will be described in a later report. The dummy motor, injector, and pressure tank are also intended for use in the injector flow-pattern studies, the tank being equipped with a camera window for this purpose.

B. Monopropellant Rocket Motor

Monopropellant tests will be run at three rocket motor combustion chamber pressures: 300 psi, 600 psi, and 900 psi, corresponding to thrust ratings of 200 lb., 400 lb., and 600 lb. .

Full advantage has been taken of the experience of the Wyandotte Chemicals Corporation on BuAer Contract NOas 10647 (see Appendix A2) in determining the fundamental features of the motor and injector design which are shown in a preliminary drawing, Fig. 4. The only difference between operation at the several chamber pressures will be in the exhaust nozzle area and injector orifice size. As shown on the drawing, eight

Section IV APPARATUS (Cont'd)

B. Monopropellant Rocket Motor (Cont'd)

radial injectors will be installed at a single radial plane in a section near the head end of the motor with provision for alternate installation of some of the injectors in a second downstream section. The injectors will be of the full-cone swirl type for the first series of tests. Other injection methods will be tested later in the program.

Starting will be accomplished with gaseous oxygen and a recessed electrode spark plug. This arrangement has been quite successfully used at low propellant flow rates by Wyandotte in their uncooled inconel motor.

C. Instrumentation

As in any research where quantitative values of physical variables are required, the selection of instrumentation must be approached with care. In the present case of experimental work on rocket combustion instability where transient phenomena must be measured under conditions of elevated temperatures, high pressures and pulsating flows, adequate instrumentation lies near the heart of the problem. Considerable effort has been spent in finding satisfactory answers to the difficult instrumentation problems although they are manifest in only their least restrictive forms in the initial phases of our experimental work. For example, in the first phase we will try to assess the magnitude of the total time lag from pressure measurements while using the monopropellant ethylene oxide which gives a reasonably low combustion temperature while impressing only low frequency oscillations so that there will be time to become acquainted with the behavior of the pressure pickups and to work out any development troubles before encountering higher temperatures and frequencies.

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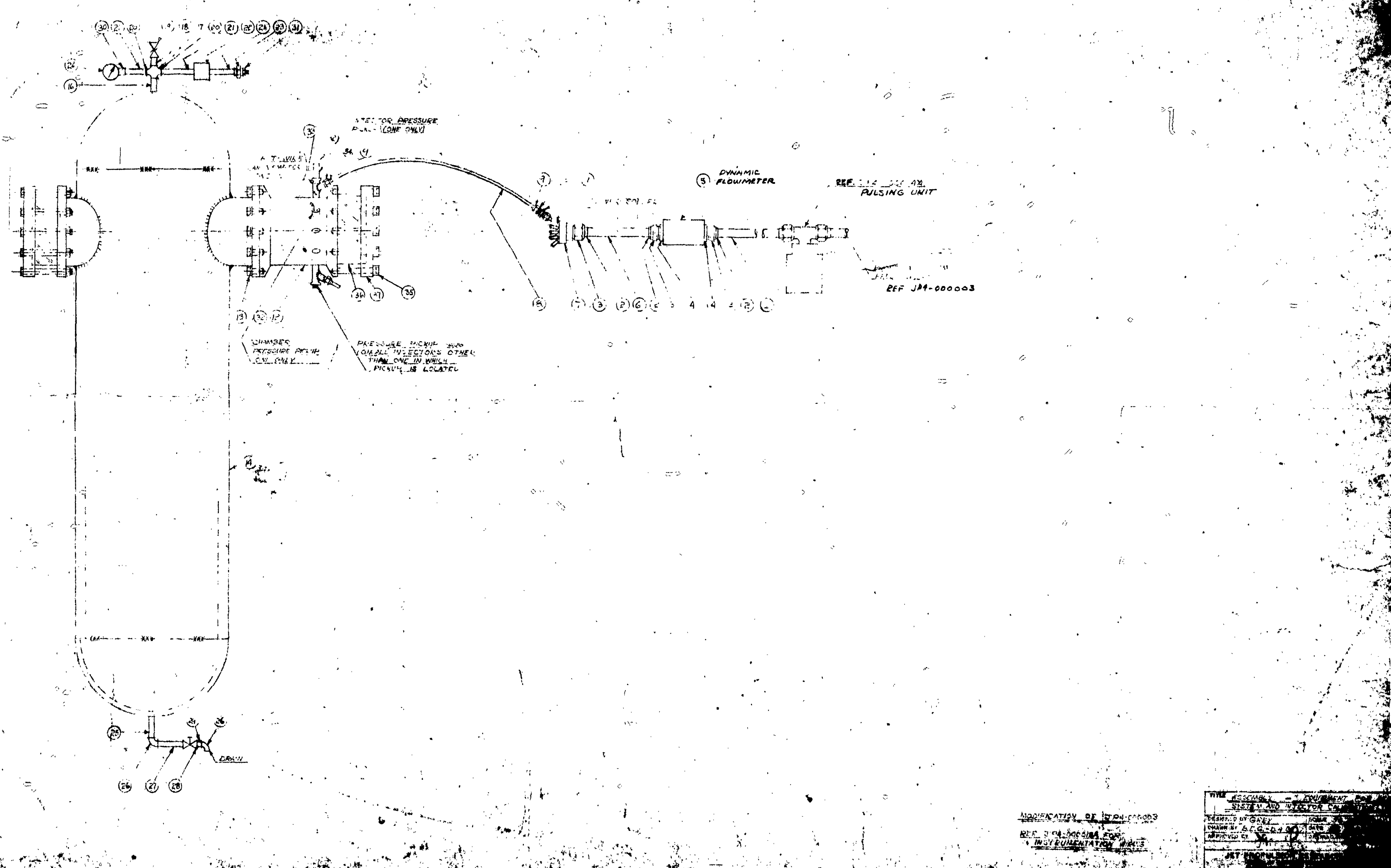

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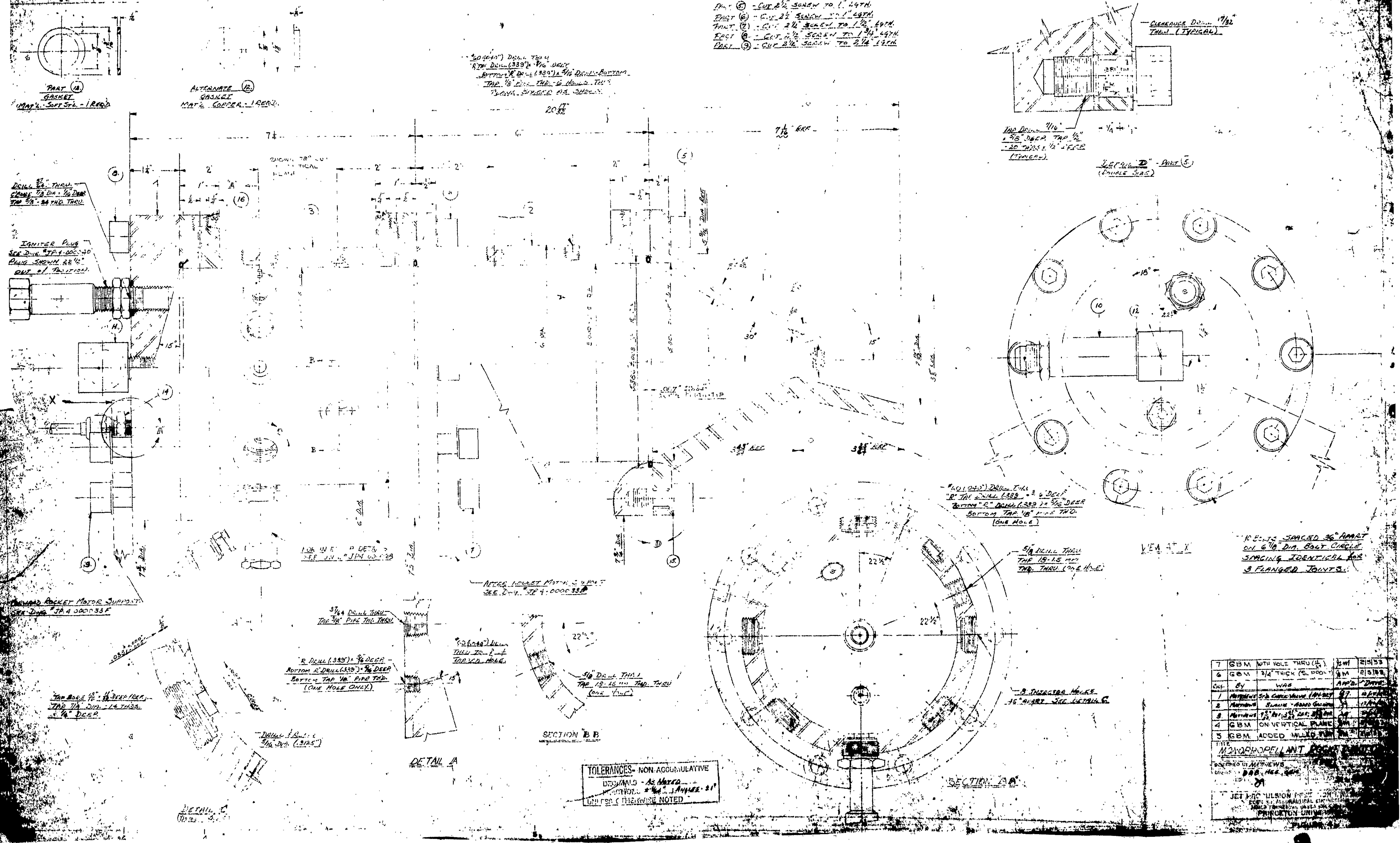


Section IV APPARATUS (Cont'd)

C. Instrumentation (Cont'd)

Schematics of the arrangement of instrumentation for the feed system calibration, Fig. 5, and time lag measurements, Fig. 6, are included to show the present, although preliminary, hookup of various prospective items of equipment. These arrangements will be discussed in more detail in the next report when they have become more settled.

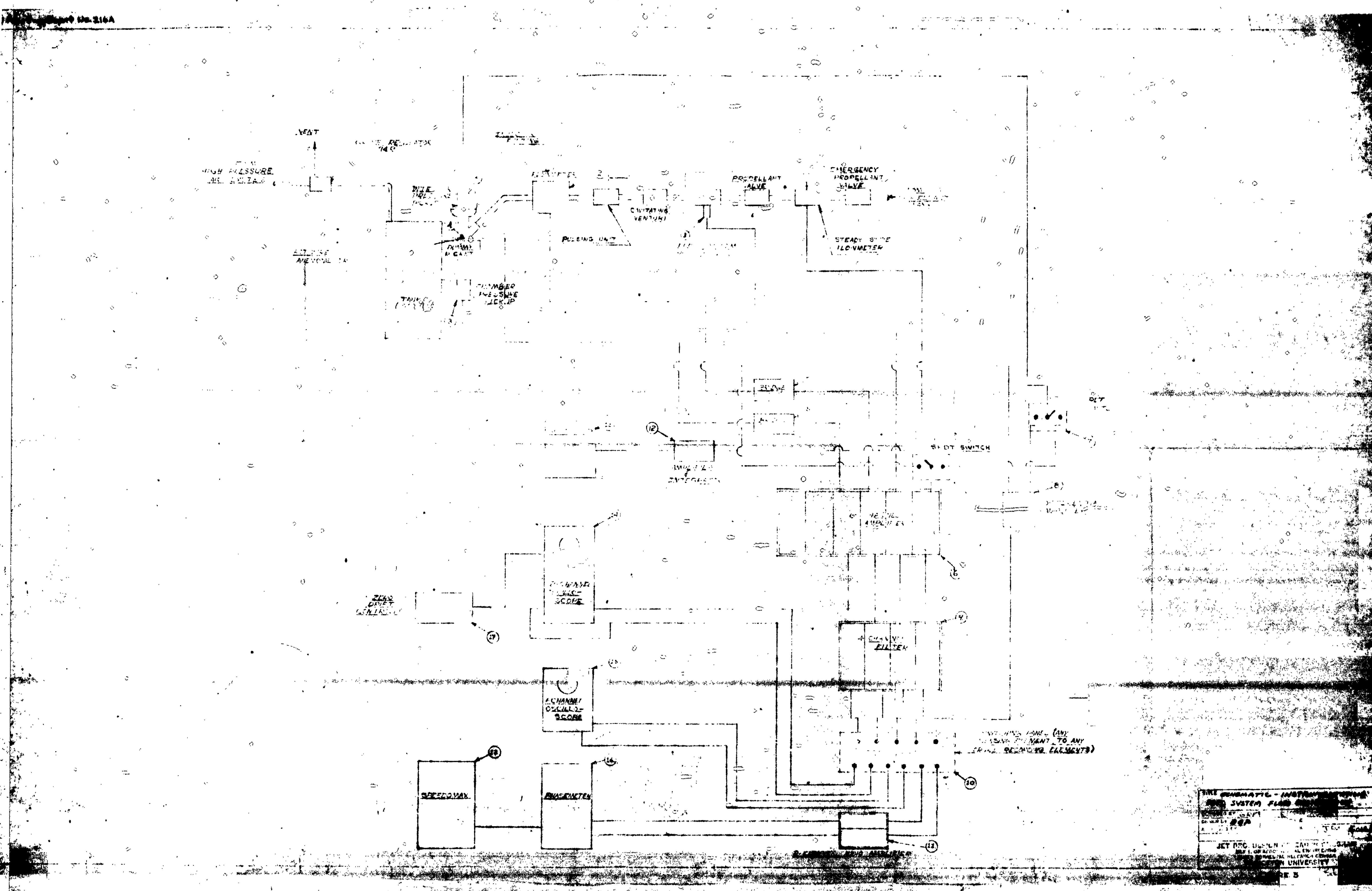
1. Sensing Elements

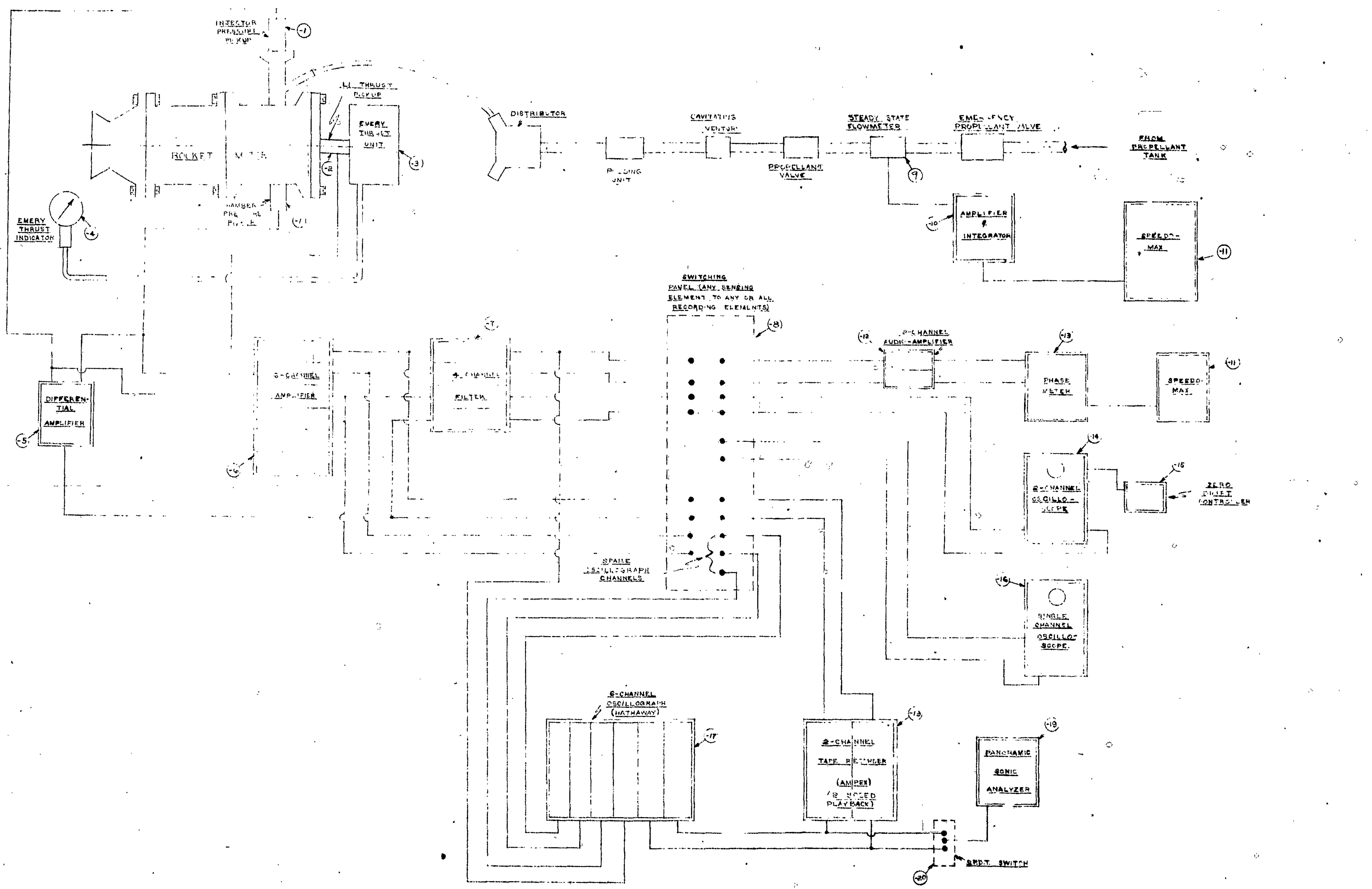
a. Pressure

Considerable time was spent reviewing commercially available pressure pickups when the critical nature of dynamic pressure measurements was realized in the determination of time lag, both from frequency and amplitude response standpoints. It was found that none of the other agencies working on instability phenomena were using a completely satisfactory sensing element for pressure although there were a considerable number of different type pickups available.

For this reason a special design of the MIT Instrumentation Laboratory Li-Draper catenary diaphragm strain-gage transducer was worked out to our specifications by Dr. Y.T. Li of MIT and Dr. F.F. Liu of Princeton to meet the requirements of this contract. It is known as the "Princeton-MIT Unit", and is being procured from Control Engineering Corporation, Norwood, Massachusetts.

The features of this pickup meet the following necessary requirements:


VENT
HIGH PRESSURE
PROPELLANT VALVE
EMERGENCY PROPELLANT VALVE
STEADY STATE FLOWMETER
CAVITATING VENTURI
PULSING UNIT
CHAMBER PRESSURE PICKUP
DUMMY
ZERO DRIFT CONTROL
SCOPE
4 CHANNEL OSCILLOSCOPE
CHANNEL FILTER
SPDT SWITCH
SPEEDOMAX
PHASEMETER
JET PROPULSION



TITLE INSTRUMENTATION SCHEMATIC: TIME LAG MEASUREMENTS

DESIGNED BY GREY	SCALE NONE
DRAWN BY BES	DATE
APPROVED BY	

JET PROPULSION RESEARCH PROGRAM
DEPT OF AERONAUTICAL ENGINEERING
PRINCETON UNIVERSITY

FIGURE

Section IV APPARATUS (Cont'd)

C. Instrumentation (Cont'd)

1. Flush mounting of the pickup directly in the rocket motor wall is made possible by the watercooled double diaphragm so that all of the oscillations are sensed without alteration up to the frequency response limit of the unit.

2. Response to high frequency oscillations up to 5000 cps is made possible by the good natural frequency (above 10,000 cps) of the gauge even with the double, waterfilled diaphragms.

3. Application of a reference pressure to the back side of the diaphragm will permit high accuracy in delineation of transient response wave forms and amplitudes.

4. Diaphragm stops permit high sensitivity without the danger of recurrent diaphragm rupture.

Although some development troubles may ensue, it is felt that the problem of a satisfactory pressure transducer for work on rocket combustion instability will be solved by the unit described above. On delivery it will be tested to see if it meets the performance specified and is otherwise suitable.

b. Flow

The problem of measuring transient flow is a very difficult one, and it has not been possible to find a solution that provides a sure answer to this problem as posed by the present work. For this reason several possibilities are being followed simultaneously.

Section IV APPARATUS (Cont'd)

C. Instrumentation (Cont'd)

First will be an attempt to measure the pulsating flow by sensing the instantaneous pressure on both sides of an injector orifice and converting the differential pressure thus obtained into instantaneous flow rate values using analytical relations developed from fundamental fluid flow considerations. Certain constants in these relations, which will be presented in a later report, require initial calibration of the method for a specific configuration by one of the other flow-meters described below.

Secondly, a mass rate flowmeter which is considered to promise good low frequency transient flow response has been developed by Dr. Y T. Li of the MIT Instrumentation Laboratory. This meter is based on measurement of the force resulting from the Coriolis acceleration of the fluid as it passes through a revolving tube.. A version of this meter specifically designed for our work is being procured and will be tested for frequency response and other factors on delivery.

A third method will be employed if it is possible to obtain the loan of one of two electromagnetic flowmeters being procured by the Bureau of Aeronautics from the Mittelman Electronics Division, Century America Corporation, Chicago, Illinois. It is understood that the development of these meters has been slowed by pressure leakage problems and that the frequency response is limited by the excitation frequency of the magnet. However, and although a further limitation lies in necessity for the fluid to have a conductivity above a certain minimum

C. Instrumentation (Cont'd)

value, this meter can be used to very good advantage for calibration of other transient flow measuring methods using water.

Despite the existence of the methods described above, it must be remembered that so far they cover only the low frequency range. Continued effort will be made to reach a solution for the measurement of instantaneous flow rates at high frequencies.

c. Performance

Measurements will be taken of the basic performances of the rocket motor being tested to ascertain variations in average values of specific impulse, heat transfer, etc., under unstable operating conditions. Thrust will be sensed simultaneously by a strain gage tension unit and an Emery load cell. Some idea of the variation in thrust will thus be possible and an average value will also be available for correlation purposes. Steady averaged flow rate will be obtained from a Potter electronic flow sensing element incorporating a vaned rotor which generates electric pulses proportioned to flow rate. Temperatures along the motor walls will be measured by thermocouples. Certain system operation pressures will be sensed by bourdon tube action.

2. Intermediate Elements

Some of the items of intermediate usage are shown on Figs. 5 and 6. An extremely stable direct current amplifier is being obtained for use with the pressure pickups, etc., from Advance Elec-

Section IV APPARATUS (Cont'd)

C. Instrumentation (Cont'd)

tronic Co., Passaic, N.J., according to a new design.

Filters with very sharp cutoff of unwanted frequencies are being developed and manufactured by Beva Laboratories, Trenton, N.J.

Additional amplifiers, integrators, switching circuits, etc., are being worked up by project personnel.

3. Indicating and Recording Elements

In addition to familiar pressure gage faces it is necessary, because of the transient phenomena, to invest heavily in rather complex indicating and recording elements.

Transient data will be recorded directly on a two channel Ampex magnetic tape recorder from which it can be played back at one of two speeds. In addition, data will be recorded using a 6 channel Hathaway oscillograph.

A Panoramic Sonic Analyser, which displays a plot of amplitude vs. frequency, and a dual beam Dumont oscilloscope will be used in delineating the phenomena. These latter two instruments will use a Dumont oscilloscope camera for recording purposes.

Steady state signals will be penned on Leeds and Northrup recording potentiometers.

Section V INFORMATION and DATA

As might be expected, no experimental data have been obtained during the first few months of the contract and efforts to collect information have consisted so far of studying literature sources and making trips to visit activities and consult with persons who have been working in the field. These efforts are described in the paragraphs that follow.

A. Literature Sources

Literature searches have been made and are included as Appendix A. The searches made so far cover the basic subject, combustion instability, and the monopropellant which will be used in our initial tests, ethylene oxide.

B. Visits

During the period covered by this report, a number of visits were made to various rocket activities in the northeast United States to exchange information pertaining to our work under this contract. The results of these discussions are summarized below.

1. Reaction Motors, Incorporated (Rockaway, N.J.)

The phenomenon of combustion instability is recognized as a definite problem in the design of both high- and low-thrust motors. The occurrence of low-frequency instability, commonly referred to as "chugging", has been essentially eliminated (barring unforeseen accidental occurrences) by feed system and injector development, particularly by increasing injector pressure drops. High-frequency instability, or "screaming", has been encountered frequently, and sometimes destructively. The improvement in performance of a "screaming" rocket motor has been clearly noted, some test results having indicated the attainment of nearly 100% theoretical impulse.

B. Visits (Cont'd)

Of all the activities surveyed, RMI has probably the most complete instrumentation for instability studies but its utilization has been limited. They have been "canning" their data on magnetic tape for some time, their strain-gage type pressure transducers appear to have good frequency response although compromised somewhat by mounting limitations, and much specialized instrumentation such as a Panoramic Sonic Analyzer is available.

2. The M.W. Kellogg Company - Special Projects Division (Jersey City, N.J.)

Kellogg has done a considerable amount of fundamental research on the problem of high-frequency instability. They have essentially eliminated destructive "screaming" in a 5,000-lb thrust cylinder by employing an injector configuration utilizing film-cooled splash surfaces. Extensive studies of 50-lb thrust bipropellant motors lead them to believe that "screaming" instability is primarily a function of combustion chamber phenomena, and is, unlike "chugging", independent of the feed system.

A relationship appears to exist between "fizz-gas" formation (i.e., formation of radicals, aromatics, etc., just prior to combustion) and high-frequency instability.

Experimental results indicated that "screaming" could not be induced when "fizz-gases" were not present in the combustion reaction. Kellogg is presently conducting theoretical studies which will attempt to relate high-frequency instability phenomena primarily to the thermochemical reaction processes in the chamber, and secondarily to injector configuration.

One interesting result of experiments conducted with 50-lb thrust

Section V INFORMATION and DATA (Cont'd)

B. Visits (Cont'd)

motors was the marked independence of exhaust velocity, c^*, (i.e., combustion efficiency) with respect to characteristic length, L^*. Using an acid-ammonia propellant combination, L^* was decreased to a value of 8 inches before a dropoff in c^* was noted. This led to a conclusion that, with an impinging jet injector, combustion was essentially complete within an inch of the injector. Similar conclusions have been drawn by other companies using different propellant combinations (e.g., alcohol-oxygen and gasoline-oxygen).

Kellogg's present instrumentation is inadequate for high-frequency instability studies, so most of their results have been obtained by use of high-speed photographs both of transparent (lucite) rocket motors and of the exhaust jets of conventional motors.

3. Curtiss-Wright Corporation - Rocket Division (Caldwell, N.J.)

Curtiss-Wright has not encountered difficulties with combustion instability in its oxygen-alcohol motor. The stable character of this motor is attributed by Curtiss-Wright personnel to the injector design, which uses a rather complicated series of impinging streams in conjunction with a central splash disc, and to their use of practically full film cooling, and to the extremely short feed lines down stream of the propellant valves.

Both thrust and pressure oscillations have been detected, at frequencies corresponding to the motor mass resonance and the fundamental closed-pipe mode of the chamber, but these oscillations are apparently of small amplitude. Increases in heat transfer and performance have been noted in conjunction with what they consider to be occasional partial breakdown of the cooling film, but no burnout or destructive vibrations have occurred.

4. General Electric Company - Malta Test Station (Ballston Spa, N.Y.)

The Hermes project has done some excellent work in high-speed strip photography of rocket motor combustion, and has identified a type of high-frequency instability of a highly nonlinear nature. The photographs indicate that the pressure waves associated with high frequency instability are actually shock waves, propagating down the chamber at about 4700 ft/sec (Mach number between 1.2 and 1.5) and sufficiently strong to cause flow reversal. Both upstream- and downstream-running waves appear in the photographs with reflections occurring at the injector face and in the converging section of the nozzle, upstream of the throat. The high-amplitude shock-type instability was eliminated when the convergent nozzle cone angle was reduced from 43° to 10° (i.e., making the nozzle convergent section longer and shallower), and low amplitude non-shock pressure waves were then observed. The frequencies of both shock and non-shock instability were approximately equal to the closed-pipe frequency of the chamber, with the slightly lower non-shock frequency explained as being caused by the increase in effective length resulting from the lengthened converging section of the exhaust nozzle.

G.E. has noted no consistent change in performance during unstable operation, partly due to the necessary brevity of the periods of instability. Results of their tests on a 1200 lb. oxygen-alcohol motor have shown that a smaller L^* (i.e., shorter motors) tends to

Section V INFORMATION and DATA (Cont'd)

B. Visits (Cont'd)

correct instability. Observed instability frequencies decrease with motor length in the same manner as do chamber resonant frequencies.

The test motors are instrumented with Photocon pickups, mounted about one inch from the chamber, recording on a G.E. oscillograph. Thrust readings are obtained from a mechanical-hydraulic linkage connected to a Tate-Emery pressure gage unit.

Some preliminary work has been done in observing the pulse attenuation obtainable with a cavitating venturi. Input oscillatory flow (300 to 1100 cps) was obtained by use of a rotating disc in a shunt line, and the venturi indicated 50% to 90% reduction in input pulse amplitudes.

5. Bell Aircraft Company - Rocket Research Section (Buffalo, N.Y.)

Bell has encountered instability frequencies of from 90 to 300 cps both in 4,000 lb. regeneratively cooled motors and in 1500 lb. uncooled test motors, operating with white fuming nitric acid and gasoline. This instability has been reduced in amplitude by installing an orifice upstream of the injector, but has not been eliminated entirely. They have observed no high-frequency instability, although this may be partly due to inadequacy of pressure pickup instrumentation.

Improvement in performance (up to nearly 100% of theoretical impulse), and increases in thrust and heat transfer have been observed, always occurring in a given motor at the same mixture ratio as the ratio is richened. The Bell personnel feel that instability is a function primarily of the injector and of the chemical reaction kinetics, but have not yet been able to put their theories on a firm basis.

Section V INFORMATION and DATA (Cont'd)

B. Visits (Cont'd)

Much work has been done on injector characteristics and their effect on rocket motor instability. An extensive injector flow stand, using dyed water to represent the propellants, has been used for this work, and current construction of a pressurized transparent tank is expected to provide more realistic atomization data. Briefly, the preliminary results of the injector studies are as follows:

a. Full and hollow-cone sprays: Very stable but only fair combustion efficiency, and low impulse.

b. "Hypoid": Burns hot, but runs ordinarily are stable and efficient.

c. Multiple-jet impinging streams: Poor stability characteristics, but, despite poor stream mixing, good performance.

d. Showerhead: Excellent stability, but poor performance.

e. Combination - Showerhead and cone sprays: (No data yet recorded)

Other work of interest in rocket instability research includes a determination of the compressibility of various common propellants. The results of this study have been tabulated, and it is hoped that they will become available in the near future.

6. Wyandotte Chemicals Co. - High-Pressure Research Division (Wyandotte, Mich.)

This visit was highly informative with regard to details of the operational technique for testing of ethylene oxide rocket motors. All formal results appear in their reports (see Appendix A2), but many of the details of ethylene oxide operation were discussed and clarified.

No accurate instability data was available due to the nature of the instrumentation, but indications were that, given proper "warm-up"

B. Visits (Cont'd)

time (i.e., approximately seven seconds oxygen flow duration), chamber pressure oscillations were less than ± 1% in amplitude. Operation on ethylene oxide was extremely quiet for the 60-lb. thrust test motor, and the exhaust was entirely smokeless and odorless.

7. NACA - Rocket Laboratory (Cleveland, Ohio)

A large number of tests were run on acid-gasoline and oxygen-ammonia motors of varying lengths. A plot of theoretical closed-pipe resonant frequencies (including harmonics) against the parameter c^*/Length was made from these tests and data collected from various sources on unstable operation. Data points thus obtained were in excellent agreement with the predictions from the longitudinal resonance theory.

Performance changes with "screaming" were noted, indicating heat transfer increases over stable operating conditions by factors of from 2 to 5, and typical c^* (expressed as percent of theoretical) increasing from 70% during stable operation to 98% with "screaming". Both propellant combinations and two injector configurations indicated the same trend in this respect. Instability seemed to occur randomly, sometimes requiring changes in propellant feed rates and pressures to initiate it, and sometimes starting spontaneously.

Extensive studies of both Mittelman and an NACA-designed electromagnetic flowmeter have been made. The Mittelman sensing unit has been deemed unsatisfactory from the pressure-seal standpoint and in frequency response (30 cps), while a 435 cps carrier frequency limits response of the NACA meter to about 50 cps. Pressure oscillation fre-

Section VI DISCUSSION

A. Literature Searches

Much of the material listed in Appendix A - LITERATURE SEARCHES - is available locally in the Forrestal Research Center Library and will be obtained and examined for pertinence and worth in connection with the work of this contract. Efforts will be made to obtain additional references from other activities engaged in similar work. Searches on allied subjects will be instituted as the desire for published information is felt. The ultimate aim is the compilation of a selective bibliography of published material of use to persons interested in combustion instability in liquid propellant rocket motors.

B. Visits

General results of visits to date are summarized below:

1. All activities visited, with only one exception, feel that instability is a major problem in rocket motor operation. Much enthusiasm was expressed with regard to present instability studies under our contract, and nearly all personnel stated the opinion that such a program was necessary and quite timely.

2. Definitions of "instability" varied considerably, extending from "any pressure oscillation, regardless of amplitude" through "a loud screaming noise" to "any oscillation which causes mechanical failure or burnout". The reason for these discrepancies lies perhaps in the difficulty of measuring the phenomena in an objective way, especially at high frequencies, so that many times the definition of unstable conditions are purely based on subjective noise appreciation or on resulting damage to the rocket. It seems to be commonly accepted that "chugging" refers to frequencies up to the order of 200-300 cps, whereas "screaming" refers to frequencies of the order of 800 cps and higher, but this classi-

Section VI DISCUSSION (Cont'd)

B. Visits (Cont'd)

fication is, of course, inadequate from a causative viewpoint. Additional effort needs to be made to identify the phenomena of instability and to establish more precisely their effects in liquid propellant rocket motors.

3. The general opinion is that "chugging" frequencies appear to be tied up with the feed system and injector pressure drop. "Screaming", on the other hand, almost always manifests itself at resonant frequencies (and harmonics) of the combustion chamber, and most activities feel that this high frequency instability is closely tied in with chemical reaction kinetics and injector spray pattern characteristics. Oscillations at intermediate frequencies have also been noted. It must be observed that there can be different kinds of instability, as can be shown from the following simple considerations. So-called stable combustion is never completely smooth. As a consequence of the mechanism of combustion, pressure and velocity fluctuations are always present, but they are characterised by the fact that they take place nearly at random, since for stable combustion there is very little correlation between what happens at two different locations in the combustion chamber. However, if one of the parameters affecting the combustion is made to change throughout the chamber, there will be a correlated effect on combustion at every location, which in turn can interact with the affecting parameter and create unstable conditions. Additional oscillations of pressure and velocity appear as a consequence, but they differ from the random fluctuations existing in the so-called stable case because they are organized, and for this reason they can have important mechanical and thermal effects even if their level is not higher than that of the random fluctuation. The different types of instability are due to the interaction of the combus-

B. Visits

tion process with different parameters; for the low frequency case the interaction is between rate of combustion and rates of exhaust and injection; for the high frequency case between rate of combustion and wave motion of the gases in the chamber; for the intermediate frequency case it might be between rate of combustion and wave motion of the propellants in the feeding system. In turn, the rate of combustion can be affected by such parameters as pressure, temperature, velocity, or mixture-ratio; and each one of these parameters can be responsible for the appearance of instability. However, temperature effects can probably be correlated with pressure effects; and the effects of this parameter, which is likely to be the most important, will be the first object of the present research.

4. Instrumentation at all activities is inadequate for proper instability measurements, particularly at high frequencies. The chief failure here is the necessity for mounting chamber pressure transducers some distance from the chamber wall in order to prevent burnout of the transducer sensing element, thus introducing a resonant compressible column into the system, which disturbs the high frequency response of the instrument. Another important reason can be that in order to give the necessary indications, the pressure measurement must be made in such a way that one can distinguish the random process discussed above from the organized process present in the case of instability. No satisfactory attempt has been made so far in this direction, since the use of the sound analyzer for this purpose is open to question. The overall appreciation of the phenomenon is more satisfactorally obtained from visual means in transparent chambers, where the possibility of observing more

B. Visits

than one point allows the distinction between random motion (turbulence) and organized motion (oscillations). Dynamic flow measurement at frequencies higher than about 50 cps has not been successful, and only one activity visited had made any attempt at all to measure dynamic flow.

5. The results of the G.F. work show that the pressure oscillations can reach quite large amplitudes and the waves can develop into shock waves. When this happens the system cannot be treated by means of the small perturbation assumption. Therefore, the linearization of the systems becomes impossible, with the result that no reasonable theoretical analysis can be performed. However, this does not mean that the results obtained from a linearized theory completely lose their significance. In fact, the linearized theory still predicts the ranges of instability based on a given interaction mechanism without giving any description of what happens if the operation falls in one of these ranges, except that the amplitude of the oscillations will increase without limit. This is, of course, impossible, and the amplitude of oscillation is limited by the presence of dissipative forces and by effects of the non-linearity, this last being probably the most important. We see that in this respect the non-linearity has a limiting, and therefore a kind of stabilizing, effect on the oscillations. In other words, it is possible that close to the limits of the ranges of instability the non-linearity may prevent large-amplitude oscillations, and this to all practical effects reduces the range of instability. For the given interaction mechanism it seems therefore that the predictions of the linearized treatment give the most unfavorable results and are on the safe side, because in order to have any large-amplitude oscillations develop, the system must first be unstable for

Section VI DISCUSSION (Cont'd)

B. Visits

the small perturbations. There is also the possibility that for large amplitudes some different type of interaction mechanism may appear, in which case large-amplitude oscillations might be entertained even in conditions that are stable against small perturbations. In this eventuality, however, the oscillations cannot be self-developed, and some kind of large-amplitude, external disturbance is necessary to trigger them. No information on this type of instability would be given by any small perturbation theory, on the other hand there is no substantial evidence that such a type can exist, and therefore this possibility is neglected for the time being.

Section VII RECOMMENDATIONS

When, in the progress of the work, it is possible to make recommendations of value to the rocket engine designer in alleviating the harmful effects of rocket combustion instability, they will be presented in this space.

Appendix A

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1. Combustion Instability, with particular reference to liquid propellant rocket motors.

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