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i (title page)	APPLIED RESEARCH INCORPORATION	BOOZ·ALLEN APPLIED RESEARCH, INC.
ii(first line)	Booze	Booz
1 (6th line)	Incorporation	Incorporated
7 (2nd paragraph 14th line)	responce	response
11(line 11)	clearly	delete
(line 12 & 13)	and the transition to steady burning caused by fuel accumulation in the chamber.	delete
16(5th line under Instrumentation)	platinum	platinum-
20(1st paragraph 8th line)	P_{co}	P_{Co}
(1st paragraph 9th line)	T_{co}	T_{Co}
(1st paragraph 10th line)	T_{co}	T_{Co}
21(3rd par. 2nd line)	at	delete
23(2nd par. 12th line)	Reference (4)	Reference (9)
1B(Appendix - References 3, 4, 5, 6, and 7)	Booze	Booz
Fig. 26	T_c	t_c (in 4 places)
Fig. 27	T_c	t_c
Fig. 28	T_c	t_c

TECHNICAL REPORT

AN EXPERIMENTAL INVESTIGATION OF A COMBUSTOR FOR AN EXPLOSION CYCLE GAS TURBINE

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I - INTRODUCTION

This report presents the results of an experimental program to determine the performance and operating characteristics of a combustor for an explosion cycle gas turbine. The subject program constituted a small portion of an over all program to investigate the potential of an explosion cycle gas turbine. The test work was performed on a subcontract from Booz · Allen Applied Research, Incorporat~~ion~~ED under Naval Bureau of Ships prime contract NObs - 72249 and covered a working period from 1 April 1957 to 31 January 1958.

The terms of the subcontract included both single pulse and cyclic tests of a contractor supplied combustor assembly which included air valves, fuel injectors, ignition system and exhaust nozzle. The overall objectives to be achieved during the program were:

(1) - Determination of the operating characteristics of the contractor furnished combustor.

(2) - Comparison of experimental test data with appropriate portions of a theoretical analysis.

(3) - Determination of suitable time - varying combustion parameters for application to turbine design.

The financial support of the University of Michigan Engineering Research Institute made possible the reduction of the final test data from the Aircraft Propulsion Laboratory chamber and the preparation of a summary report.

II - PROBLEM BACKGROUND

Powerplants which utilize the constant volume cycle appear to offer, from a theoretical standpoint, gains in thermal efficiency and specific work as compared to the constant pressure cycle. The constant volume or explosion cycle gas turbine was a competitor of the more commonly used constant pressure gas turbine at the turn of the century. The explosion cycle turbine utilized a series of radially spaced combustion chambers and nozzles which discharge cyclically into a turbine wheel. Two basic types of explosion cycle gas turbines are described in References (1) and (2). The Holzwarth turbine applied the constant volume cycle to a large stationary gas turbine. This engine utilized valves in both the inlet and the exhaust ports of the combustor to achieve constant volume combustion. The Karavodine turbine did not utilize exhaust valves and most closely represents the type of unit investigated in this program.

Among the individuals who have applied the constant volume cycle to gas turbine powerplants is E. A. Maynor of Chicago, Illinois. The equipment supplied by the contractor for this test program was designed and fabricated by Mr. Maynor and is shown in the photograph of Figure (1). In the Maynor design, six cyclic combustors were used to drive an aircraft turbo-supercharger which supplied compressed air to the combustion chambers in addition to delivering net work to an external load. The quality and condition of the Maynor equipment, as received, was such as to preclude any extensive usage in the test program and a considerable amount of mechanical rework was necessary to allow testing of a single isolated combustor unit.

A theoretical analysis of the constant volume gas turbine cycle was conducted by Booz · Allen Applied Research, Inc. during the contract period and the results of this study are presented in Reference (3). This work resulted in a non-steady analysis of the constant volume cycle which identified the role of a number of basic cycle parameters in determining the performance capabilities of an actual powerplant. The experimental investigation with which this report deals was designed to supplement the theoretical analysis by checking the validity of some of the basic assumptions in addition to investigating some facets of the problem which were not amenable to theoretical analysis

Consideration of the various component processes which make up the explosion cycle indicated that the intermittent combustion process involved the greatest amount of uncertainty in establishing a suitable analytical representation. Accurate analytical description of a time varying deflagration process is not possible with the present state of basic combustion knowledge and recourse must be taken to experimentally determined modifications to an idealized analytical model. Other areas of uncertainty existed with respect to the non-steady flow effects on the performance of the combustor exhaust nozzle and the matching with the turbine wheel. In view of the extremely limited time and funds, it was necessary to confine the investigation to the combustion process alone and to conduct tests on a single isolated combustor using the Maynor equipment for this purpose.

III- EXPLOSION GAS TURBINE CYCLE:

The general nature of the explosion cycle gas turbine is shown in the schematic diagram of Figure (2) which represents the system analyzed in Reference (3) and investigated in the subject program. Air is drawn into a compressor, its pressure increased and delivered to a plenum chamber which feeds a series of cyclic combustors of the type shown. The air is admitted to a typical combustor through a pressure actuated check valve. Liquid fuel is delivered cyclically in metered amounts and atomized by a fuel injector in each combustion chamber. The fuel-air mixture is ignited by a spark or glowplug ignitor.

When the mixture is ignited, the pressure and temperature in the combustor rise rapidly and the air check valve closes terminating the airflow to the combustor shortly after ignition occurs. The high temperature reaction products are expanded through the nozzle to a supersonic velocity. After doing work on the buckets of a single stage impulse turbine wheel, the spent gases are then exhausted to the atmosphere. The turbine drives the compressor, auxiliaries and delivers net work to an external load.

After combustion, the pressure in the combustor decreases with time until it approaches the compressor discharge pressure. At a point determined by the valve characteristics, the air check valve re-opens and airflow through the chamber is re-established. The fresh charge of air sweeping through the combustion chamber, scavenges the burned gases at a constant pressure equal to the compressor discharge pressure. Upon completion of the purging process, fuel is again injected and the cycle is repeated.

A characteristic feature of this system is the absence of a valve in the combustor nozzle. As a consequence, there is always a gas stream impinging on the turbine blades. The velocity of the fluid leaving the combustor will then vary from a maximum immediately after combustion to a minimum value which is constant during purging.

The non-steady nature of the operating explosion cycle combustor is indicated on a pressure - time basis in Figure (3). The component times which constitute one cycle are shown sequentially on the figure and consist of the combustion time, the blowdown time, the purge time and the fuel injection time. The analytical study of Reference (3) presents a method for calculation of the blowdown time and purge time which depends upon a knowledge of the combustor geometry, the initial charge temperature and the combustion pressure ratio. Analytical prediction of the combustion pressure ratios obtainable with a chamber of this type is not feasible with the present status of combustion theory, hence experimental data is necessary to allow realistic cycle evaluation.

IV - PROGRAM ORGANIZATION

The experimental work conducted on this program can best be presented in terms of each of the three sequential phases which constituted the investigation. For purposes of presentation, these phases are designated as:

(1) - Single pulse tests of the Maynor combustor
(2) - Cyclic tests of the Maynor combustor
(3) - Cyclic tests of the A.P.L. combustor

The foregoing subdivisions of the program evolved as a result of various redirections of effort which stemmed in turn from both equipment limitations and from data obtained in the course of the investigation. The results obtained from each of these phases of the program will be presented and discussed separately in subsequent sections of the report. The experimental techniques and results of phases (1) and (2) have previously been reported in detail in the monthly progress reports of the prime contractor. In view of this fact and the limited value of the results, these phases of the program will be only briefly summarized and the major emphasis of the report will be on the work conducted under phase (3) that proved to be the most beneficial of the program and has not been reported previously other than in a preliminary fashion.

V - SINGLE PULSE TESTS OF THE MAYNOR COMBUSTOR

Initial consideration of the problems associated with determining the optimum performance of a cyclic constant volume combustor, indicated the desirability of simplifying the processes as much as possible to allow segregation of the important variables. The single pulse or single "shot" tests appeared to be a logical starting point since this technique permitted precise control of the mixture ratio and the initial conditions in the chamber prior to combustion. It was believed that this scheme would eliminate such complicating and spurious effects as non-uniform mixture ratio distributions, uncertain initial conditions and transient ignition difficulties. Performance data obtained by this method would then be independent of the air valving geometry, the fuel injector type and the particular ignition system involved and would form a logical basis for progressing to cyclic tests of the combustor.

The experimental equipment used in conducting the single shot tests is described in detail in Reference (4) and is shown in the photograph of Figure (4). A reworked Maynor combustor was used for the tests and was instrumented to obtain transient chamber pressure, chamber temperature and thrust. The combustor was modified to lock the air valves shut and cap off the fuel injector. The nozzle exit was covered with a calibrated foil burst diaphragm to permit initial charging of the chamber. The chamber was charged with a metered, premixed propane-air mixture to a predetermined initial pressure The recording oscillograph was started first prior to energizing a spark plug which ignited the mixture. The detailed test procedure and the various modifications are described in Reference (5).

A variety of single pulse tests were made using various combinations of mixture ratio and initial charge pressure. The mixture ratio range was investigated through the interval from 15% lean to 15% rich. The initial charge pressure was varied over the range from atmospheric to approximately 80 psig. A typical record obtained during these tests is reproduced in Figure (5) and depicts the time variation of chamber pressure, chamber temperature and thrust during the combustion and blowdown processes.

All single shot test data indicated the occurrence of a relatively slow heat release rate and hence did not under any circumstances approximate a constant volume combustion process. Within a certain range of initial charge pressures and with the use of a fuel rich mixture, detonation of a portion of the charge was found to occur when the duration of the combustion exceeded 70 milliseconds. The shape of the chamber pressure and temperature curves was greatly influenced by the number and location of the spark ignition sources. The data obtained provided a means of comparing the theoretical and experimental values of the blowdown time for the Maynor chamber. These data are shown in the plot of Figure (6). The agreement between the theoretical and experimental pressure histories is excellent. The calculated and measured temperature histories did not exhibit the same agreement. The major portion of the difference in this instance is believed to be due to the poor frequency responce of the thermocouple. Radiation from the hot walls of the chamber can also contribute to the error since the theoretical analysis is based upon an isentropic blowdown process.

The absence of any pressure rise rates approximating constant volume combustion during the single shot tests, regardless of initial conditions, indicated the necessity of proceeding to cyclic tests of the Maynor combustor. As a consequence, the experimental apparatus was modified to permit cyclic operation of the chamber.

VI - CYCLIC TESTS OF THE MAYNOR COMBUSTOR

Apparatus:

The test installation used for cyclic operation was basically the same as that which was used for the single shot tests previously described. Additional equipment was required however to supply fuel and air to the combustor and to permit control of the cycling frequency. A detailed description of the equipment, installation and instrumentation is given in Reference (6) and the general nature of the test installation is shown in the photograph of Figure (7).

Air supplied to the combustor was throttled from 100 psig to the desired initial chamber pressure through a pressure regulator and was continuously variable from 15 to 65 psia. The original Maynor air valves were replaced with two spring loaded check valves which were always normally open prior to combustion. This was necessitated by the difficulty of adapting the Maynor valves to the air supply system and also because of their heavy construction which limited their response rate severely.

The Maynor fuel injector consisted of a solenoid actuated metering pintle used in conjunction with a pressurized fuel system. The pintle was equipped with a conical tip which was spring loaded shut in the fuel injection port. When the solenoid was energized, the pintle was retracted and a stream of fuel released which impinged upon a splash probe. A photograph of this injector is shown in Figure (8) and its spray pattern is shown in Figure (9). Although extensive effort was devoted to rework and repair, the basic design and construction of the injector was such that it was virtually unusable for test purposes. Calibration of the device was impossible due to the continuous deformation of the soft pintle on the injection port. Other shortcomings of the injector are discussed in Reference (6).

Cyclic operation of the Maynor chamber was achieved by using a Bosch fuel injection pump and high pressure fuel injector in conjunction with a variable speed drive motor. The pump is of the positive displacement type with the capacity for altering the fuel volume pumped per stroke independently of the pump drive speed. The associated Bosch injector has a delivery pressure drop of approximately 1500 psia and hence the finely atomized spray has a considerable amount of kinetic energy with a spray apex angle of only 10°. The spray pattern is shown in the photograph of Figure (10). Because of these considerations, upstream injection was employed and the injector was mounted opposite one of the air inlet valves to further increase the vaporization and mixing rate. The pump and fuel injector were readily calibrated and an electric tachometer was attached to the pump drive to permit more accurate adjustment of the cycling frequency. The pumping capacity of the unit was such that operation of the Maynor chamber above initial charge pressures of 35 psia was not possible due to excessively lean mixture ratios. Complete details on the pump, injector and calibration are given in Reference (6).

Because of the consistent difficulty of securing reliable ignition in the Maynor chamber, two different ignition systems were used in the course of the investigation. Commercial automotive spark plugs were used initially in conjunction with a 12,000 volt spark coil. A subsequent and more satisfactory system consisted of a special electrode assembly located in the center of the chamber with the power supplied by a 10,000 volt neon lighting transformer. In all tests the spark ignition source was operated continuously since this favored the combustor performance and a timed ignition system would have constituted an additional variable in an already complicated process.

Instrumentation:

The measurements made during these cyclic tests were essentially the same as those made during the single shot tests. An exception in this case was the measurement of transient thrust using the Baldwin load cell. As reported in detail in Reference (6), it was determined that the dynamic characteristics of the load cell- combustor system were such as to constitute a second order oscillatory system. The natural frequency of the system was of the correct value to permit coupling with the rapid pressure rise rates characteristic of cyclic operation. Since the inclusion of damping was impractical, the single shot test data was used to determine an effective thrust coefficient as a function of chamber pressure to be used in evaluating the combustor performance.

In an attempt to improve the frequency response of the exhaust thermocouple, new sensing elements were fabricated using a platinum and platinum-rhodium system with a wire diameter of 0.010 inches. Details of the thermocouple geometry and calibration are given in Reference (6). Limitations on time and funds permitted only a steady-state calibration of the thermocouples.

Results and Discussion:

Extreme difficulty was encountered continually with attempts to secure regular cyclic operation of the Maynor chamber. Initial efforts which utilized Diesel fuel resulted in erratic operation, incomplete combustion and sufficient fuel accumulation in the chamber over a short period of time to result in continuous rather than cyclic combustion. All subsequent tests were conducted with liquid octane as a fuel with slightly improved results, however, the combustion was still incomplete and the operation very erratic. The sequence of test operations and configuration changes used during this phase of the program are described in complete detail in Reference (6). A portion of a typical record obtained during cyclic operation of the chamber is shown in Figure (11) and [redacted] shows the shifting operation produced by the Maynor fuel injector design [redacted] Operation of the Maynor chamber with the Bosch fuel injection system was not a great deal more successful. Despite the use of a high voltage ignition system, operation was erratic and unreliable and fuel accumulation persisted resulting in the inability to obtain combustion above an initial charge pressure at 25 psia. In most instances cyclic operation was sustained for less than a minute before fuel accumulation in the combustor resulted in steady burning. The specific mechanism postulated for this occurrence is explained and discussed in Reference (6).

Conclusions:

The lack of success in achieving regular cyclic operation demonstrated clearly that the Maynor chamber and its auxiliary equipment were inadequately designed from the standpoint of both mechanical and aero-thermodynamic principles The results of the tests make it difficult to believe that the chamber was ever capable of providing the heat release process in a cycle designed to deliver net work. Detailed consideration of each of the areas of difficulty in the Maynor chamber design is given in Reference (6) and the specific mechanisms involved are discussed.

Examination of the test data indicated, however, that extremely rapid heat release rates were obtainable with cyclic operation and that the combustion process could be made to approximate that of a constant volume system. The pressure - time traces established that combustion of the charge was occuring in time intervals from 4 to 10 milliseconds under the proper conditions of mixture ratio and fuel injection rate. The difference between the relatively long combustion times observed in the single shot tests and the extremely short times characteristic of cyclic operation is attributable to the difference in reaction rates between a laminar combustion process and a so-called "turbulent" combustion process. It is known from basic combustion studies that a flame front moves more slowly through a quiescent air-fuel mixture than one in which turbulence exists. This is approximately the distinction in the case of the single shot tests as compared to the intense turbulence created in the chamber during cyclic operation.

It is believed that the cyclic frequency of a combustor for use in the constant volume gas turbine cycle should be as high as possible to obtain reasonable turbine operation. To achieve such a condition, the value of L* for the combustor must be close to, but no greater than the minimum value that produces nearly constant volume combustion. Significant departures from constant volume combustion result in a reduced combustion pressure ratio and hence less energy available to the turbine wheel. This is another basic shortcoming of the Maynor combustor which has an L* of 1008 in. Although this value is more than sufficient to produce almost constant volume combustion, it is too large to produce cycling rates much in excess of 3.0 C.P.S. This value can be computed from the theoretical analysis of Reference (3) and was substantiated experimentally by the test results obtained with the Maynor combustion chamber.

In general, this phase of the program indicated that, despite the lack of success with the Maynor chamber, a combustion chamber of the explosion cycle type merited further examination both experimentally and analytically. In particular the short combustion times obtained suggested that, with the proper design considerations, a combustor configuration could be conceived which would produce efficient and reliable cyclic operation. Consequently, since modification of the Maynor chamber was impossible and further testing of the combustor would have been unproductive, a new combustion chamber was designed and constructed.

VII- CYCLIC TESTS OF THE AIRCRAFT PROPULSION LABORATORY COMBUSTOR

A.P.L. Combustor:

In establishing the design of the new combustion chamber, a definite effort was made to eliminate the defects inherent in the Maynor design and to apply the experience gained from the previous phases wherever possible. Some of the more important design criteria which established the design of the new chamber are:

(1) - Diffuse the inlet air streams as rapidly as possible to improve the mixing rate.

(2) - Provide a symmetrical distribution of atomized fuel over the cross-sectional area of the chamber in the mixing zone.

(3) - Provide a high turbulence level in the mixing zone to promote complete mixing and rapid heat release rates.

(4) - Contour the downstream end of the chamber to provide smooth entry to the nozzle and to improve the scavenging of the burned gases.

In considering the design of a new chamber, it was decided that a value of L* less than that of the Maynor chamber would be desirable. The theoretical analysis of Appendix - C and further work as shown in Figure (27) indicated that near constant volume combustion could be obtained with a considerably reduced L* which would result in a shorter blowdown time and hence a higher cyclic operating frequency. Based on this information, a chamber with a L* of approximately 350 inches was designed.

The combustor was fabricated from a section of steel pipe having a wall thickness of 3/8" to permit ease in mounting the various transducers and other test instrumentation. Figure (12) shows a longitudinal, cross-sectional view of the A.P.L. combustion chamber. The upstream end of the combustor was bolted in place to permit access to the air deflection ring and the fuel splash plate. At the downstream end of the chamber, the nozzle was bolted to a partial end plate. This type of construction was used to permit the use of nozzles of various throat areas for studies concerning the effect of L* variations.

Attached to the upstream end plate are the air deflection ring and the fuel splash plate. The air deflection ring functions as a baffle plate which quickly diffuses the inlet air stream and, at the same time, creates a highly turbulent flow pattern in the fuel injection and mixing zones. Since the Bosch fuel injector (Reference 6) was to be used, a splash plate was required to disperse the concentrated spray pattern and thereby create a more uniform fuel distribution across the chamber. When fuel is injected along the centerline of the chamber, the fuel spray is deflected into a uniform curtain of atomized fuel which is almost parallel to the splash plate and lies between the air deflection ring and the splash plate. Incoming turbulent air is constrained to pass through this curtain of fuel. As a result, a uniform fuel-air mixture is obtained almost instantaneously which produces reliable and efficient combustion.

The spark plug shown in Figure (12) is a standard J-47 jet engine ignition plug. This type of plug was used as a means of obtaining ignition away from the walls of the chamber where fuel deposition and flame quenching effects could produce erratic ignition. For these tests, the spark plug was driven continuously by a high voltage spark coil.

Test Installation:

The test installation used for this phase of the program was the same as that used in conducting cyclic tests with the Maynor chamber. The schematic diagram of Figure (13) summarizes the features of the installation and measuring equipment. The A.P.L. chamber is shown mounted in the test apparatus in the photograph of Figure (14).

Instrumentation:

The instrumentation used in these tests consisted of the same items as previously used with a few modifications. In this test sequence, only one pressure transducer was used since previous tests had demonstrated that the pressure distribution was uniform within the chamber at any instant in time. Three thermocouples were used in this test sequence, all of which were of the platinum 7 platinum and rhodium type previously described in Reference (6). The three thermocouples were used to measure inlet air temperature, chamber temperature and exhaust total temperature and their location is indicated in the drawing of Figure (12).

In addition to the foregoing measurements, an event marker was attached to the Bosch fuel pump to indicate the beginning and the time duration of fuel injection. A cam follower on the pump drive wheel was used to actuate a microswitch and impress a signal on the recording oscillograph.

No thrust measurements were made for the reasons previously discussed in the foregoing section of the report. Had time and funds permitted, a series of single pulse tests would have been conducted to determine the thrust coefficient for the chamber. Such a method would have permitted evaluation of the chamber on the basis of energy conversion into thrust. The chamber pressure - thrust relationship previously obtained for the Maynor chamber was not applicable since the A.P.L. chamber has a different nozzle divergence angle and entrance angle.

Test Procedure:

The tests conducted with the A.P.L. chamber were initially of a preliminary nature to investigate the effect of longitudinal spark plug location and to evaluate the operation of the air valves. After modifying the chamber in a fashion dictated by the results of these tests, final tests were conducted. The final tests consisted of a systematic variation of initial charge pressure and mixture ratio over a range of values of interest for power plant operation.

The spark plug location shown in Figure (12) proved to deliver the best performance over the range of initial charge pressures used. The combustor performance was extremely sensitive to this variable because of the continuous ignition system used. Positioning of the plug further upstream appeared to reduce the charge weight per cycle while still providing reliable ignition. If ignition occurs too early in the cycle, a full air charge is not obtained, if it occurs too late, unburned mixture will be lost through the nozzle.

In Reference (6), it was noted that the air inlet valves used with the Maynor combustion chamber were spring loaded check valves. Identical valves were initially installed in the A.P.L. combustor, however, the cyclic operation was not as efficient as was desired. Test data indicated that the valves were oscillating or rebounding from their seats at the higher cyclic frequencies. After a number of attempts to alter the spring constant had failed, the valves were modified and the springs removed completely and successful operation was obtained. A longitudinal, cross-sectional view of a modified valve is shown in Figure (15). It should be noted that with the spring removed which holds the valve normally closed, it becomes a free-floating valve which is gas operated.

During the final tests, initial charge pressure and charge mixture ratio were varied in a controlled fashion. Tests were conducted at initial charge pressures between 5.0 psig and 40 psig, inclusively, in increments of 5 psi. At a constant initial charge pressure, the fuel-air ratio was varied over the entire range of values at which cyclic operation occurred. On the rich, or excess fuel side, this was defined by the cessation of regular cyclic combustion. On the lean, or excess air side, the limit was defined by the absence of ignition.

The mixture ratio was altered by varying the fuel volume delivered per stroke by the Bosch pump. This was manifested as a varying load on the electric motor used to drive the pump. Since the motor was not capable of holding constant drive speed under a varying load, the cycling frequency (as determined by the fuel injection frequency) shifted slightly with the mixture ratio. The frequency change over the mixture ratio range investigated was not excessive however, and in no way compromised the desired test results.

Experimental Data:

Typical oscillograph records obtained during the investigation are shown in Figures (16) and (17). Both records display a slight pressure increase which occurs near the end of the blowdown process. For mixtures progressively in excess of stoichiometric, this pressure rise became more pronounced. This is believed to be caused in part by the mixing and burning of excess fuel as the fresh charge of air is admitted to the combustor. These records also show a relatively steady chamber temperature. In part, this is due to the low velocity of the gases in the combustor. Examination of the chamber thermocouple after these runs disclosed that the junction was in contact with the stainless steel sleeve, this then would tend to give an average temperature of the sleeve and not the instantaneous temperature of the gases.

VIII-RESULTS AND DISCUSSION

The performance capabilities of a powerplant which operates on the explosion cycle are determined basically by the pressure rise developed in the combustion chamber during the combustion or explosion process. The results obtained from tests of the A.P.L. combustor are presented in terms of a non-dimensional explosion pressure ratio, π_c, in Figures (18) through (25). The explosion pressure ratio is the ratio of the peak combustion chamber pressure to the initial mixture pressure prior to combustion. The independent variable during the test sequence was the charge mixture ratio or pounds of fuel per pound of air prior to combustion. For convenience in presentation, the mixture ratio has been normalized and is presented in terms of a non-dimensional equivalence ratio, ϕ, in Figures (18) through (25). The equivalence ratio represents the actual fuel-air ratio divided by the stoichiometric or chemically correct value which is 0.068 for octane, the fuel used for these tests. Values of ϕ which are less than one then correspond to "lean" mixtures and values of ϕ which are greater than one indicate "rich" or excess fuel mixtures. The associated variation of the cycling frequency, f, as a function of equivalence ratio is also shown in Figures (18) through (25).

The pressure rise ratio, Π_c, was obtained from the oscillograph records and due to minor random variations in the explosion pressure rise in the course of a run, an average value over a number of cycles was used in plotting the data. The equivalence ratio, ϕ, is based upon an overall average value of the mixture ratio as determined from the fuel flow rate and the air flow rate. The fuel flow rate was obtained from the calibrated pump characteristics and the measured cycling frequency. The airflow rate was computed from the measured values of the initial charge pressure, P_{Co}, and the initial charge temperature, T_{Co}. Due to the limited frequency response of the inlet thermocouple, it was necessary to correct the measured value of T_{Co} by graphic means to account for the thermal inertia of the thermocouple element.

The effects of mixture ratio on the explosion pressure ratio are shown in Figures (18) through (25) for a series of initial charge pressures. The experimentally determined values of the pressure rise are compared to the theoretical values obtainable with constant volume combustion. The pressure rise developed with constant volume combustion is dependent upon the density of the charge prior to combustion. Hence, for a fixed initial charge pressure, P_{Co}, the associated measured charge temperature, T_{Co}, is inversely proportional to the weight of charge in the chamber prior to combustion. The inlet air temperature supplied to the combustor was approximately 100°F for all of the tests and the upper curve on each figure represents the maximum possible pressure rise obtainable with constant volume combustion from a charge temperature of 100°F. The lower curve shown on each of the figures indicates the theoretical constant volume pressure rise obtainable with a charge temperature corresponding to the average measured value of T_{Co} for the particular run. The theoretical thermochemical computations upon which these curves are based were conducted using the generalized charts of Reference (8) and hence consider the effects of variable specific heats and molecular dissociation.

The experimental values of the explosion pressure ratio exhibit fair agreement with the theoretical constant volume values based upon the average measured charge temperature prior to combustion. The tendency of the experimental values to be slightly above the calculated values in some instances is attributable to the uncertainty in the thermocouple measurements of T_{Co}. The fact that the experimental values of the Π_c peak at a mixture ratio less than stoichiometric is probably due to the use of an overall mixture ratio based on the air flow rate and the fuel flow rate. The consistent disparity between the measured values of Π_c and the theoretical constant volume values based upon a charge temperature of 100^oF is the result of inadequate scavenging of the combustor. As previously indicated, the charge temperature prior to combustion is inversely proportional to the charge density and is therefore a measure of the effectiveness of the scavenging process or the volumetric efficiency. In these tests, complete scavenging would have been indicated by measured charge temperatures in the vicinity of 100^oF whereas in actuality the measured values ranged from 600^oF to 950^oF.

Consideration of the experimental data shown in Figures (18) through (25) suggests that the combustion process was occuring efficiently near stoichiometric values of the mixture ratio as indicated by the agreement with the theoretical constant volume curves based upon the measured charge temperature. Comparison of the combustor performance to a theoretical constant volume combustion process is reasonable since as was previously mentioned the chamber L* was selected to approach near constant volume combustion as indicated by a theoretical analysis. Reference to the theoretical results of Figure (27) indicates a maximum decrease of 11% below the theoretical constant volume value for the A.P.L. chamber which is within the uncertainty of the T_{CO} measurement. In addition, the experimental results of Figures (18) through (25) also indicate that the maximum attainable explosion pressure rise for a charge temperature of 100°F is not being developed due to inadequate scavenging of the chamber and a resulting decrease in the charge weight induced per cycle.

The test data indicates a pronounced falling off of the explosion pressure ratio as the mixture is shifted from away from stoichiometric in either the rich or lean direction. It is believed that this sensitivity to mixture ratio occurs as a consequence of the increased time required for combustion of the charge as the mixture ratio is shifted away from the chemically correct value. The theoretical analysis indicates that increases in the time required for combustion will result in significant decreases in the explosion pressure ratio. Representative values of the measured combustion time, t_c, are shown in Figure (26) for several initial charge pressures. The variation of t_c with the equivalence ratio, ϕ, is such that the minimum values of t_c occur in the vicinity of the stoichiometric mixture ratio and the combustion time increases rapidly as the mixture ratio becomes either rich or lean. This marked sensitivity of the combustion time, t_c, to the mixture ratio is compatible with basic combustion kinetics and appears to be the reason for the observed variation of Π_c with equivalence ratio. The measured values of the combustion time varied from 0.0045 second to 0.008 second.

The study reported in Reference (9) was a theoretical and experimental investigation of an explosion cycle combustor for application to a jet propulsion system. The combustor configurations used in this program were unfortunately sufficiently different from the A.P.L. chamber to prevent any direct comparisons of performance. In particular, the combustors of Reference (9) covered an L* range from 6 to 18 feet and were equipped with mechanically driven inlet valves rather than the self actuated types used in this investigation. As a result of the low L* values, the explosion pressure ratios obtained were significantly lower than those of the present program, ranging from a minimum of 1.7 to a maximum of 2.90. The combustion times obtained, however, agreed well with those shown previously, varying from a minimum of 0.003 second to a maximum of 0.009 second.

From the standpoint of preliminary design considerations, the most important parameter to be determined is the L* of the combustor. As shown in the non-steady analysis of Reference (3), this quantity is a basic factor in determining the maximum cycling rate of the power plant as a result of the time required for blowdown and scavenging. In general, increasing values of L*, require operation at progressively lower frequencies. Equally important for design analysis is a knowledge of the effect of chamber L* on the peak explosion pressure and temperature developed by combustion. Lack of time and funds prevented varying L* experimentally to evaluate this effect with the A.P.L. chamber. The previously mentioned theoretical study was undertaken to determine the general nature of the phenomenon and the influence of L* in particular. The general approach taken was similar to that of Reference (4) (9), however, somewhat different results were obtained and the analysis was confined to near-constant volume combustion.

Typical results obtained from the study are given in Figure (27) which shows the influence of combustor L* on the explosion pressure and temperature. The calculated values are presented in terms of the percentage deviation from the maximum constant volume values of explosion pressure and temperature.

The analysis indicates an extreme sensitivity of peak pressure and temperature to chamber L* with pressure being by far the most sensitive. It is apparent that chamber L*'s below 25 feet will produce values of explosion temperature and pressure which are greatly reduced from the constant volume values. As a consequence, there appears to be sufficient performance penalty involved to preclude using combustors with an L* of much less than about 30 feet in the explosion cycle power plant.

A further defining feature of the explosion cycle system is shown in the results of Figure (28). The explosion cycle pressure ratio, as calculated from the previously mentioned analysis, and the maximum cycling frequency are plotted versus combustion chamber L* for the same typical conditions of Figure (27). The physical nature of the heat addition - blowdown process occuring in the explosion cycle combustor is such that large chamber L*'s result in near constant volume combustion but necessitate characteristically low frequency operation. Opposed to this is a low L* value chamber which permits operation at much higher cyclic rates but is subject to sizeable departures from constant volume operation. It is apparent that a compromise must be made and the results of the analysis indicate that such a compromise can be achieved in the combustor L* range from 30 to 80 feet depending upon the remaining cycle parameters as discussed in Reference (3).

IX - CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were reached as a result of the experimental and theoretical studies conducted on the explosion cycle combustion chamber.

(1) - Single pulse tests are an inadequate representation of the combustion process in an explosion cycle combustor.

(2) - The theoretical analysis of Reference (3) yields accurate results of the combustor blowdown pressure and temperature history.

(3) - The Maynor combustion chamber is inadequately designed from the standpoint of both mechanical and aerothermodynamic principles.

(4) - A properly designed explosion cycle combustion is capable of operating with near constant volume combustion at cyclic rates and combustion efficiencies of practical value.

(5) - With improved scavenging and inlet valve design, explosion cycle pressure ratios in excess of 6.0 can be produced.

(6) - A theoretical analysis of the combustion process is available which will predict explosion temperature and pressure ratios in terms of combustion chamber geometry and compressor outlet conditions.

(7) - For a given combustion chamber with a specified L* and air inlet temperature, there exists a useful range of mixture ratios and cycling frequencies over which the device will operate effectively and can be suitably controlled.

(8) - In general, it can be concluded that a constant volume combustor is a practical device, however, care must be exercised to realize the full performance capabilities of the chamber.

The following recommendations are made for future efforts to supplement the information gained from the subject investigation and to lead to a prototype unit on a minimum cost basis.

(1) - Although the present investigation has yielded a great deal of information concerning the performance of the explosion cycle combustor, there are still areas where more information is needed to permit rational preliminary design of such a device. The necessary work could be performed as previously on a single unit using a simplified test rig. The following items should be studied:

  (a) - Verify the effect of L^* on explosion cycle pressure ratio and cycling frequency.

  (b) - Investigate various techniques of fuel injection.

  (c) - Examine the effects of inlet valve dynamics on performance.

  (d) - Examine various techniques for cooling the chamber.

  (e) - Extend the study to include tests of fuels other than octane.

(2) - Investigate both theoretically and experimentally, the type of turbine which would most efficiently accomodate the velocity and mass flow histories produced by a constant volume combustor. It is essential that representative values of turbine efficiency be determined since this is the remaining component of the system with which there is a great deal of uncertainty associated.

(3) - Conduct a comparative preliminary design study of the explosion cycle gas turbine with respect to an equivalent constant pressure

gas turbine. The objective of such a study would be to arrive at comparative values of specific fuel consumption, horsepower per pound of weight and horsepower per cubic foot of power plant volume to establish a more concrete indication of the advantages of the explosion cycle turbine.

APPENDIX - A

SYMBOLS

f - Cycling frequency - (cycles/second)

L^* - Combustion chamber characteristic length - (feet) (combustion chamber volume divided by nozzle throat area)

P_C - Explosion pressure - (PSIA)

P_{Co} - Combustor charge pressure - (PSIA)

$(P_C)_v$ - Constant volume explosion pressure - (PSIA)

T_C - Explosion temperature - ($^{\circ}F$)

T_{Co} - Combustor charge temperature - ($^{\circ}F$)

$(T_C)_v$ - Constant volume explosion temperature - ($^{\circ}F$)

t_c - Combustion time - (seconds)

π_c - Explosion pressure rise - (P_C/P_{Co})

σ_c - Explosion temperature rise - (T_C/T_{Co})

ϕ - Equivalence ratio - (actual mixture ratio divided by the stoichiometric mixture ratio)

γ - Specific heat ratio (C_p/C_v)

APPENDIX - B

REFERENCES

(1)- Holzwarth, H., "The Gas Turbine", J. B. Lippincott Co., Phila., 1912.

(2)- Sawyer, R. T., "The Modern Gas Turbine," Prentice-Hall Inc., N. Y., 1947.

(3)- Nicholls, J. A., Morrison, R. B., et al., "Theoretical Analyses of the Constant Volume Gas Turbine (Explosion Turbine)", Booz~~e~~-Allen Applied Research, Chicago, March 1958.

(4)- Progress Report No. 9, Booz~~e~~-Allen Applied Research, Chicago, Nov. 1957.

(5)- Progress Report No. 10, Booz~~e~~-Allen Applied Research, Chicago, Dec. 1957.

(6)- Progress Report No. 11, Booz~~e~~-Allen Applied Research, Chicago, Jan. 1958.

(7)- Progress Report No. 12, Booz~~e~~-Allen Applied Research, Chicago, Feb. 1958.

(8)- Hottel, H. C., et al, "Thermodynamic Charts for Combustion Processes", Vols. I & II, Wiley, 1949.

(9)- Zipkin, M. A. and Lewis, G. W., "Analytical and Experimental Performance of an Explosion-Cycle Combustion Chamber for a Jet-Propulsion Engine", NACA TN-1702, Sept. 1948.

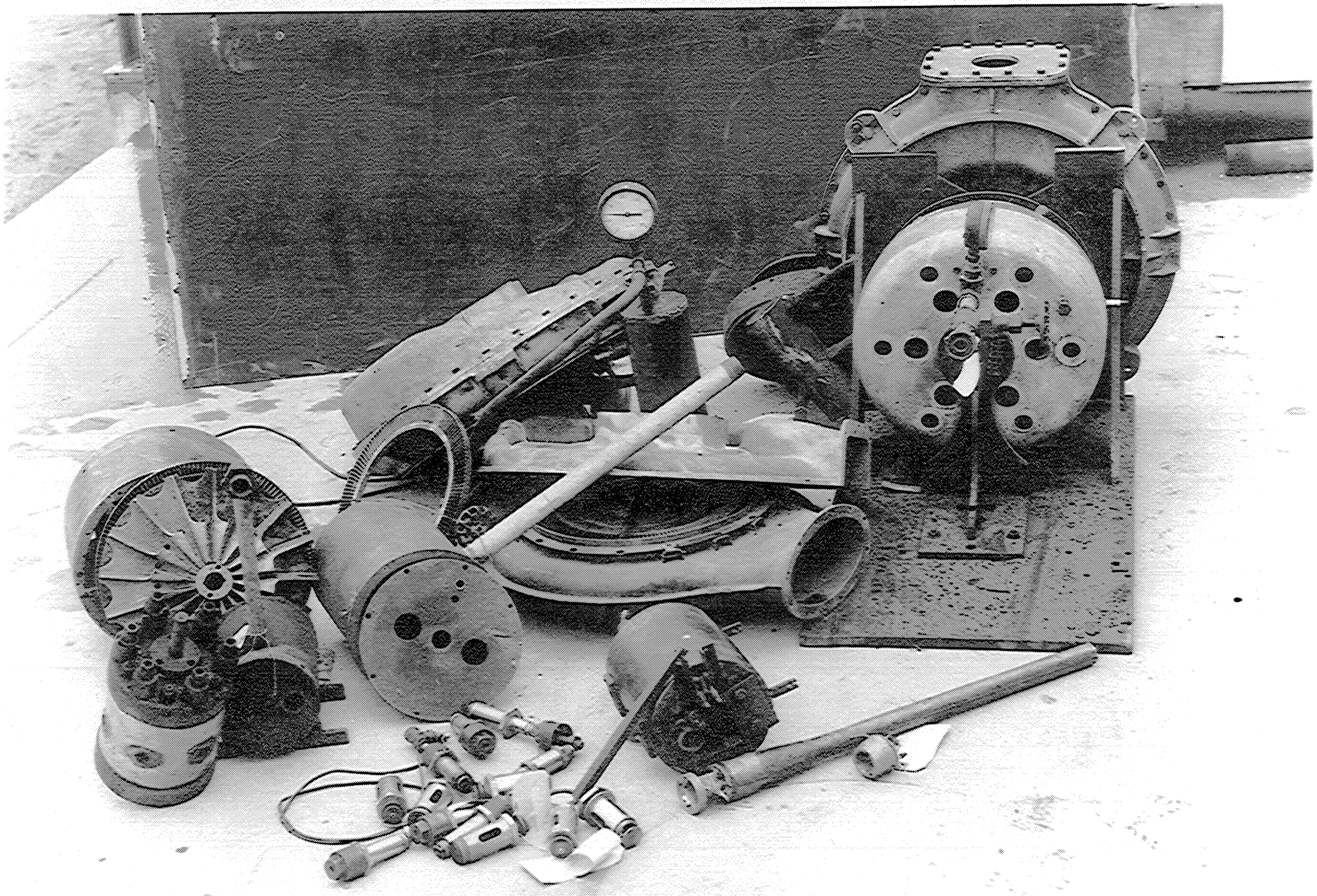
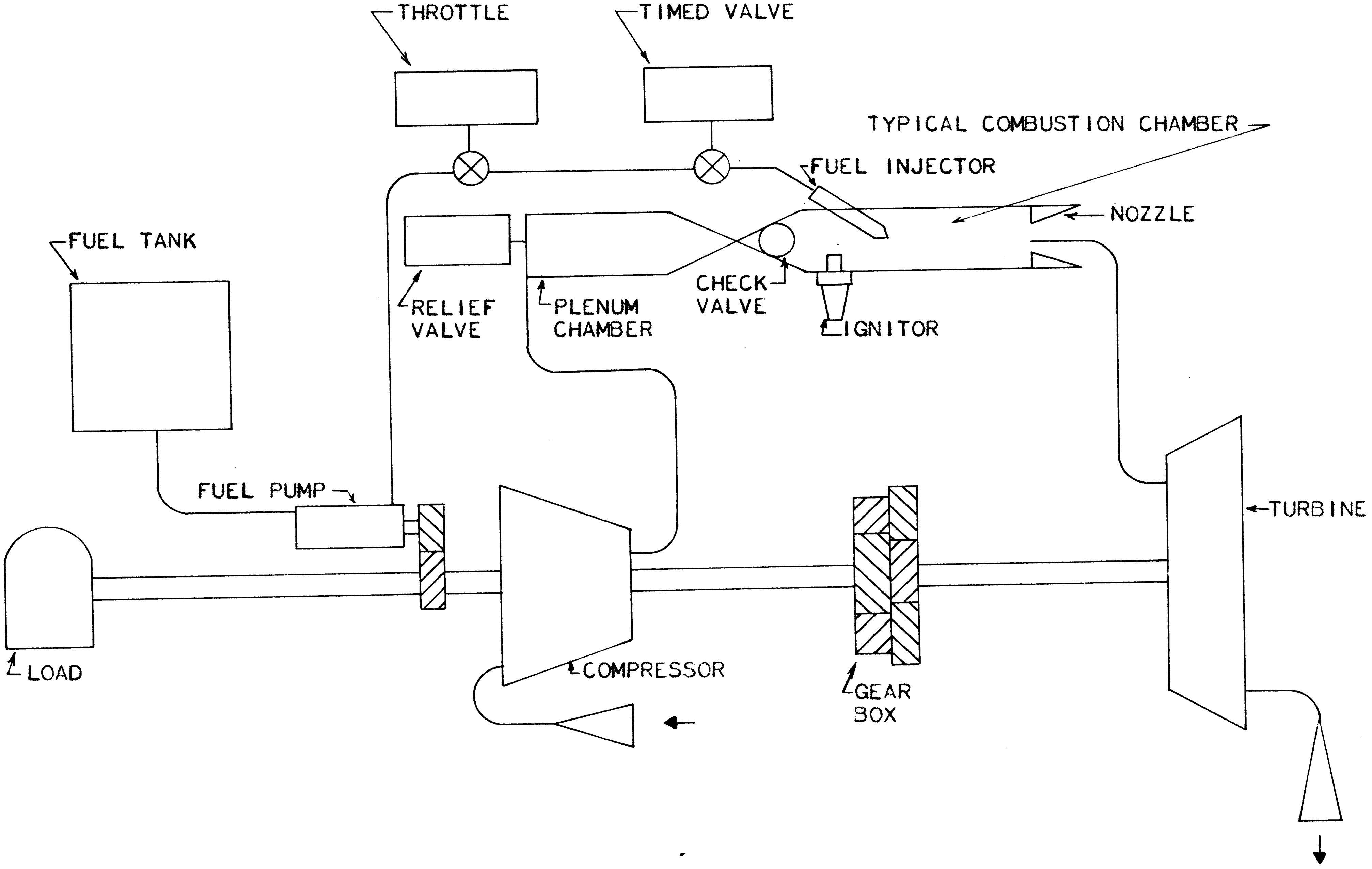


FIG. I. PHOTOGRAPH OF THE MAYNOR ENGINE COMPONENTS SUPPLIED BY THE CONTRACTOR

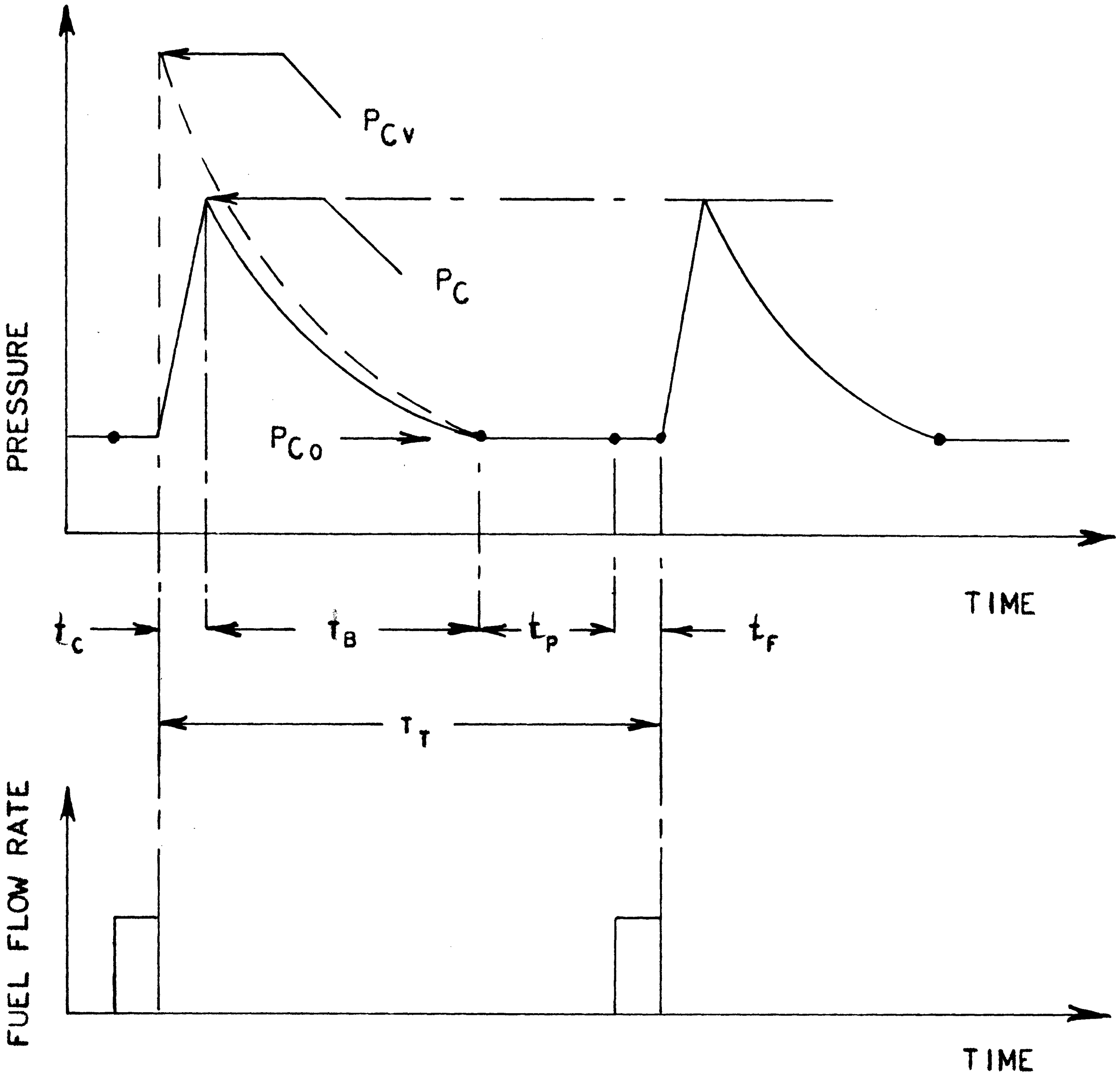


THE CONSTANT VOLUME GAS TURBINE

FIGURE - 2

PRESSURE - TIME CHARACTERISTICS OF AN
IDEALIZED EXPLOSION CYCLE COMBUSTOR

P_{Cv} = CONSTANT VOLUME COMBUSTION PRESSURE
P_C = ACTUAL COMBUSTION PRESSURE
P_{Co} = CHARGE PRESSURE PRIOR TO COMBUSTION



t_C = COMBUSTION TIME
t_B = BLOWDOWN TIME
t_P = PURGE TIME
t_F = FUEL INJECTION TIME
t_T = TOTAL CYCLE TIME

FIGURE - 3

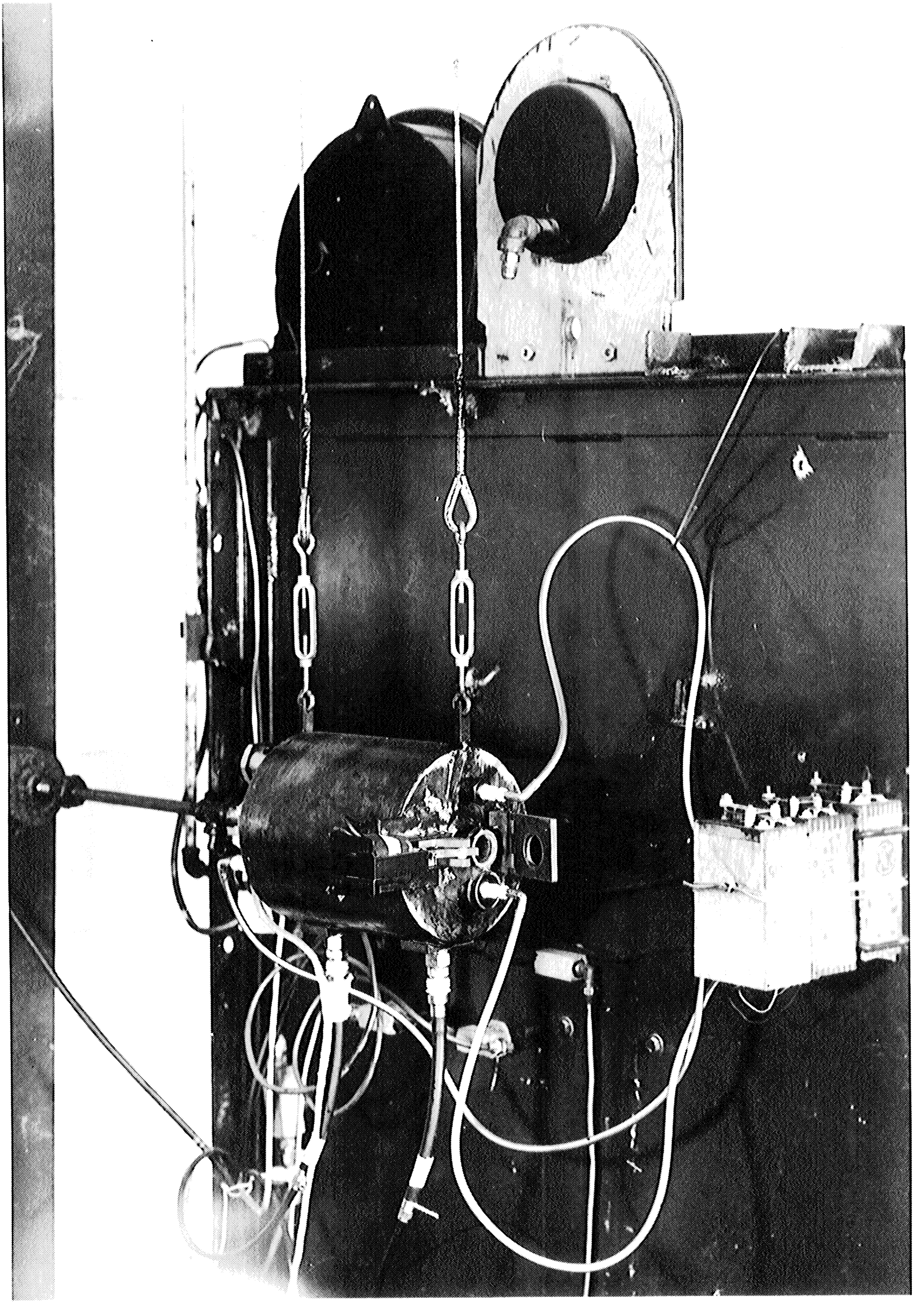


FIG. 4. PHOTOGRAPH OF THE SINGLE PULSE TEST INSTALLATION

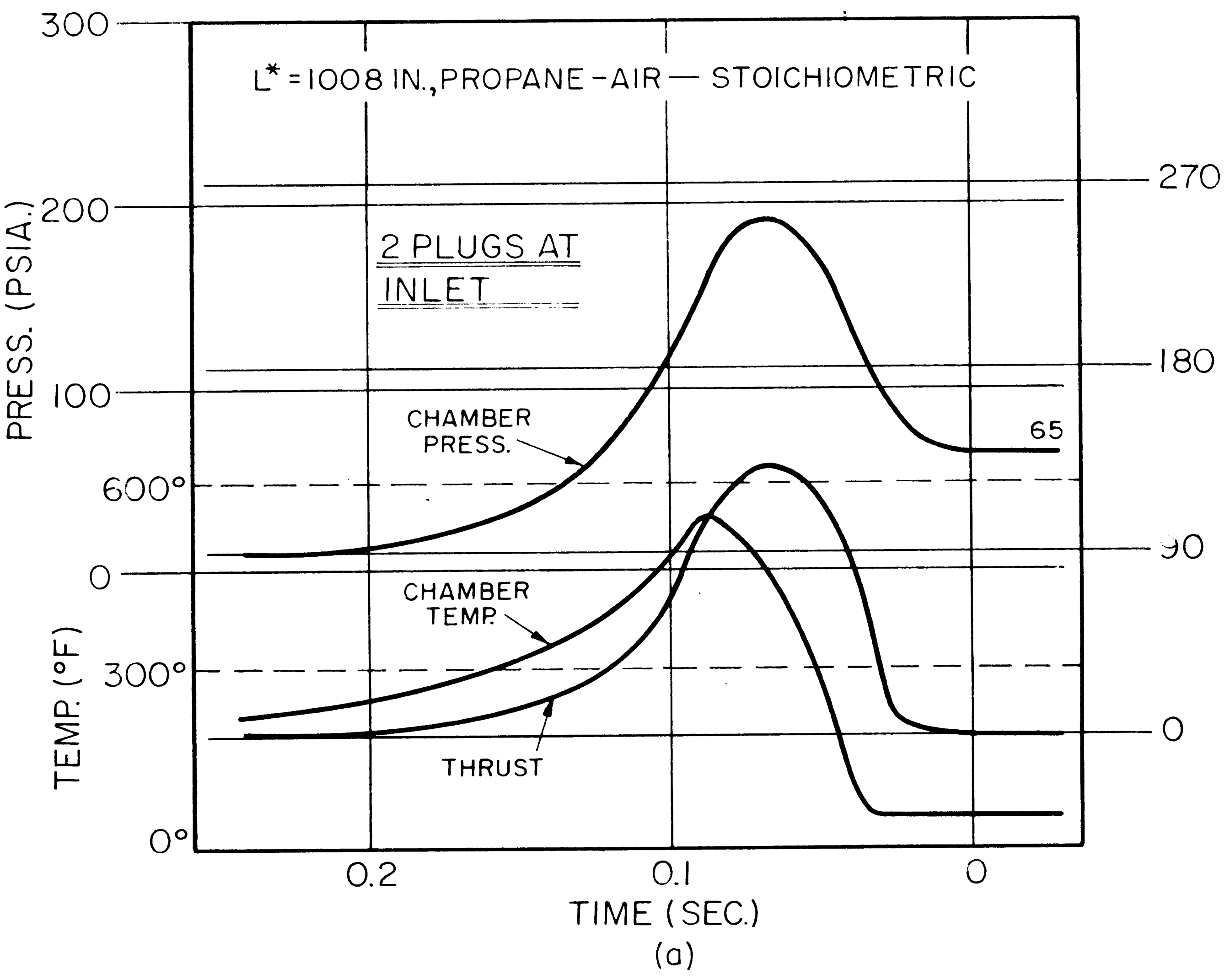


Fig. 5

Single-Shot Characteristics

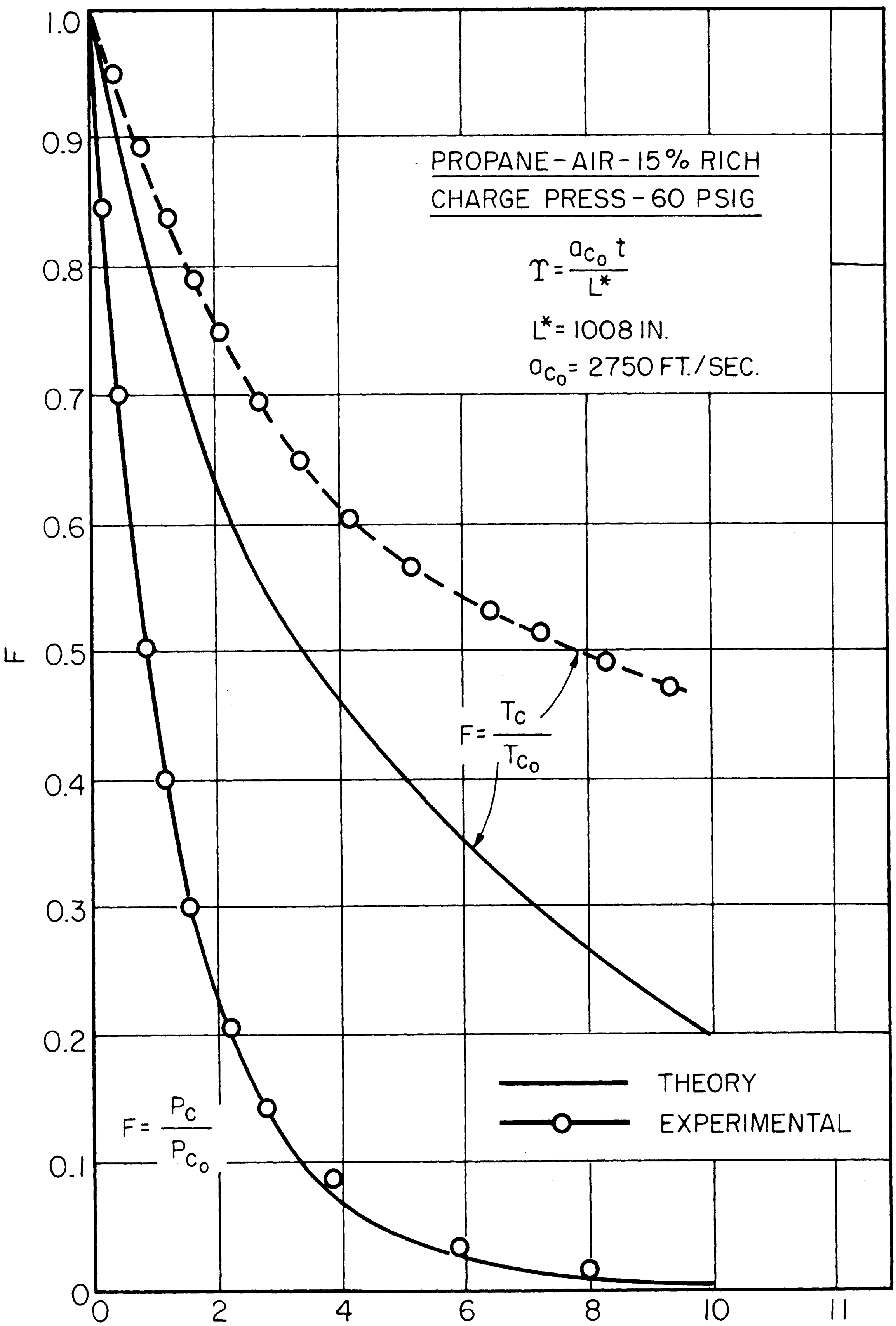


Fig. 6

Combustion Chamber Blow-Down Characteristics

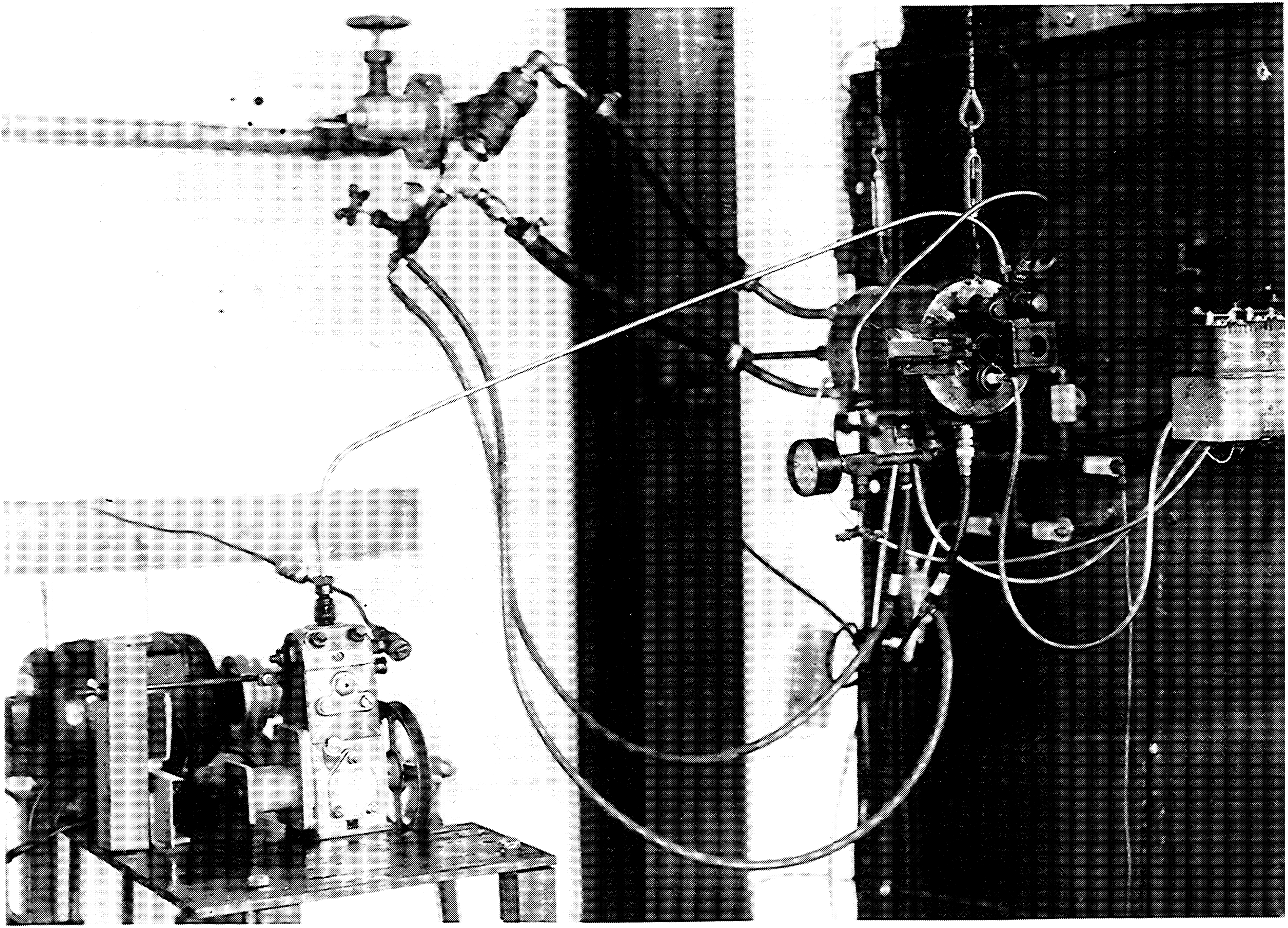


FIG. 7. PHOTOGRAPH OF THE CYCLIC TEST INSTALLATION FOR THE MAYNOR CHAMBER

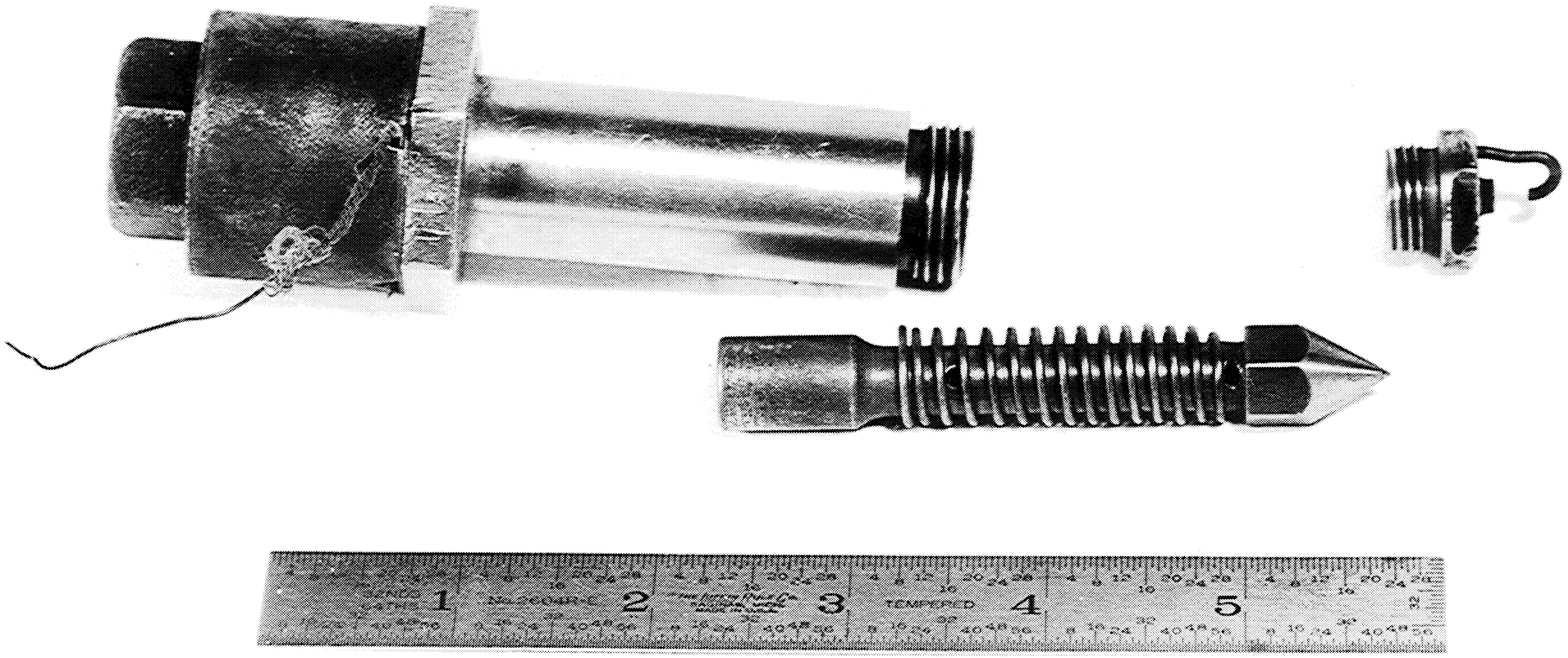


FIG. 8. PHOTOGRAPH OF THE MAYNOR FUEL INJECTOR

FIG. 9. PHOTOGRAPH OF THE SPRAY PATTERN FROM THE MAYNOR FUEL INJECTOR

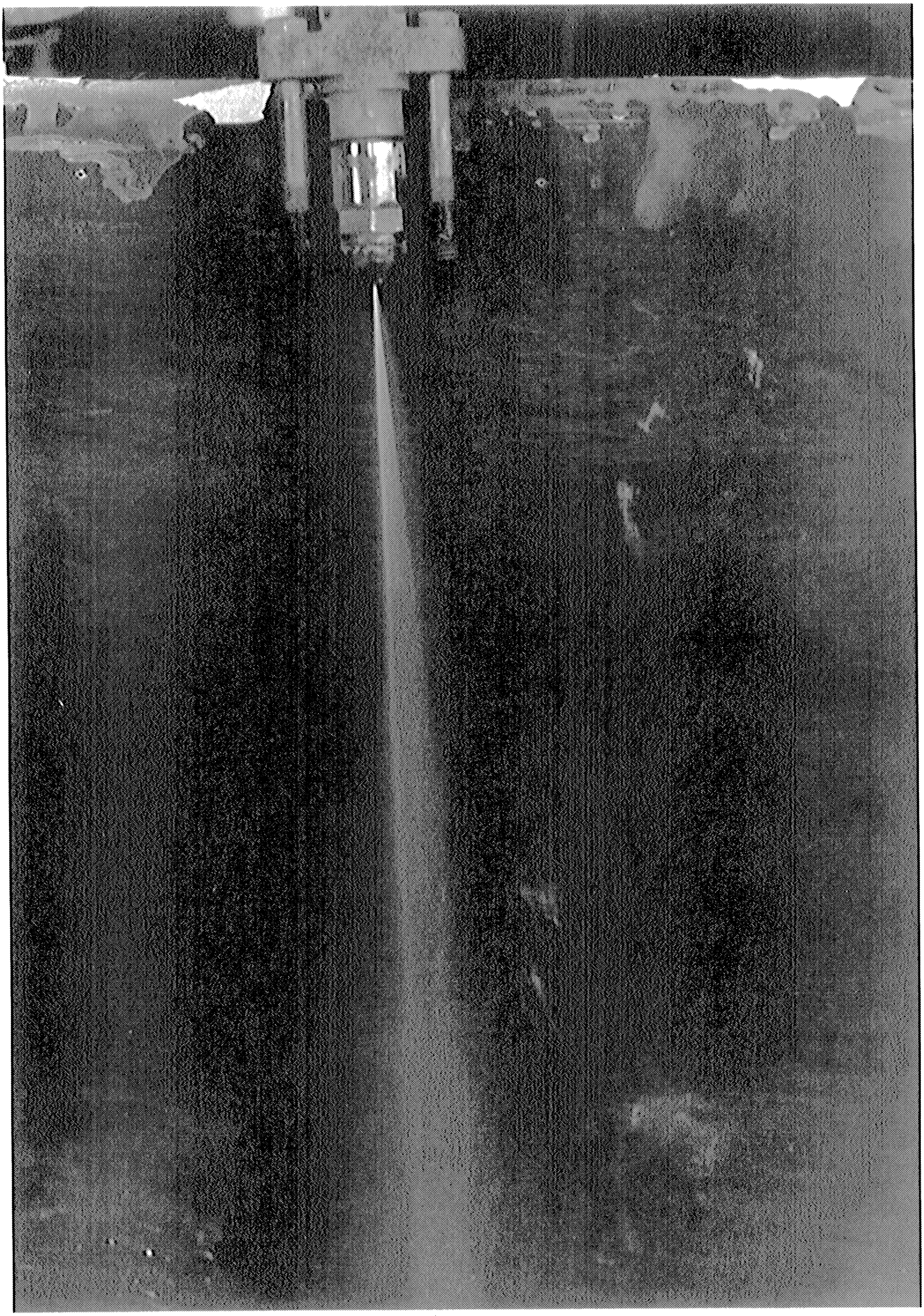


FIG. 10. PHOTOGRAPH OF THE SPRAY PATTERN FROM THE BOSCH FUEL INJECTOR

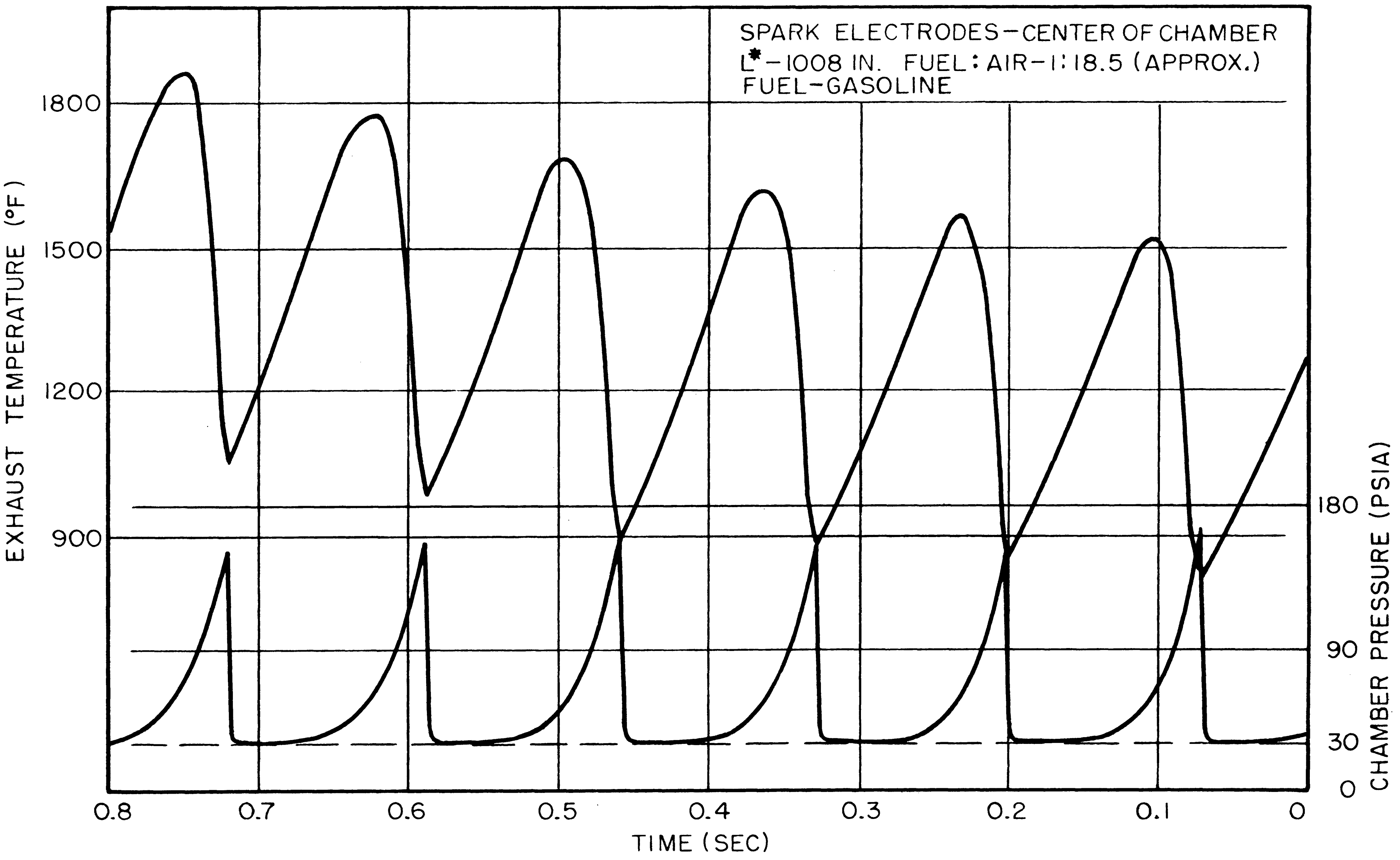


Fig. 11

Explosion Cycle In Maynor Combustion Chamber

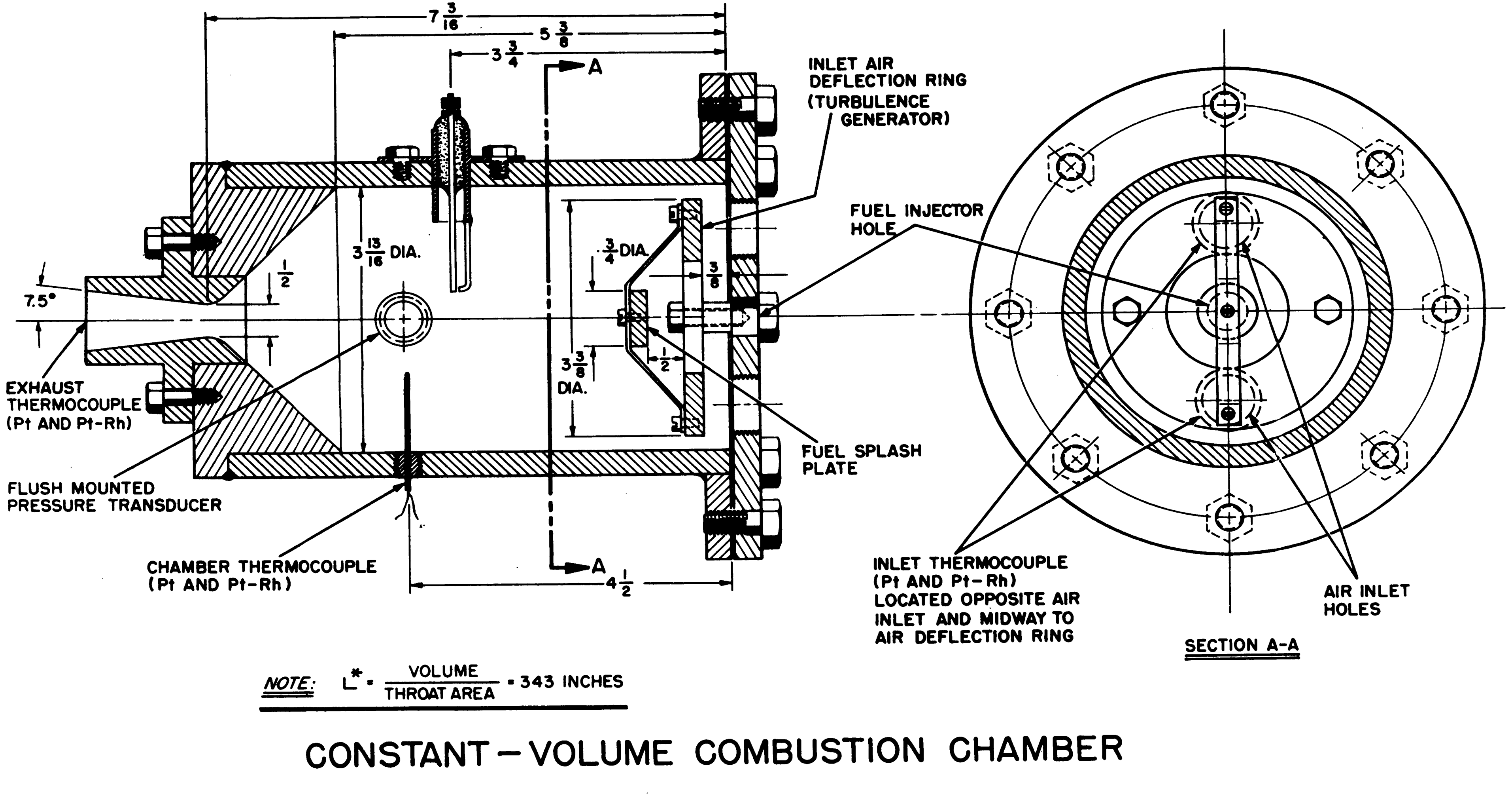
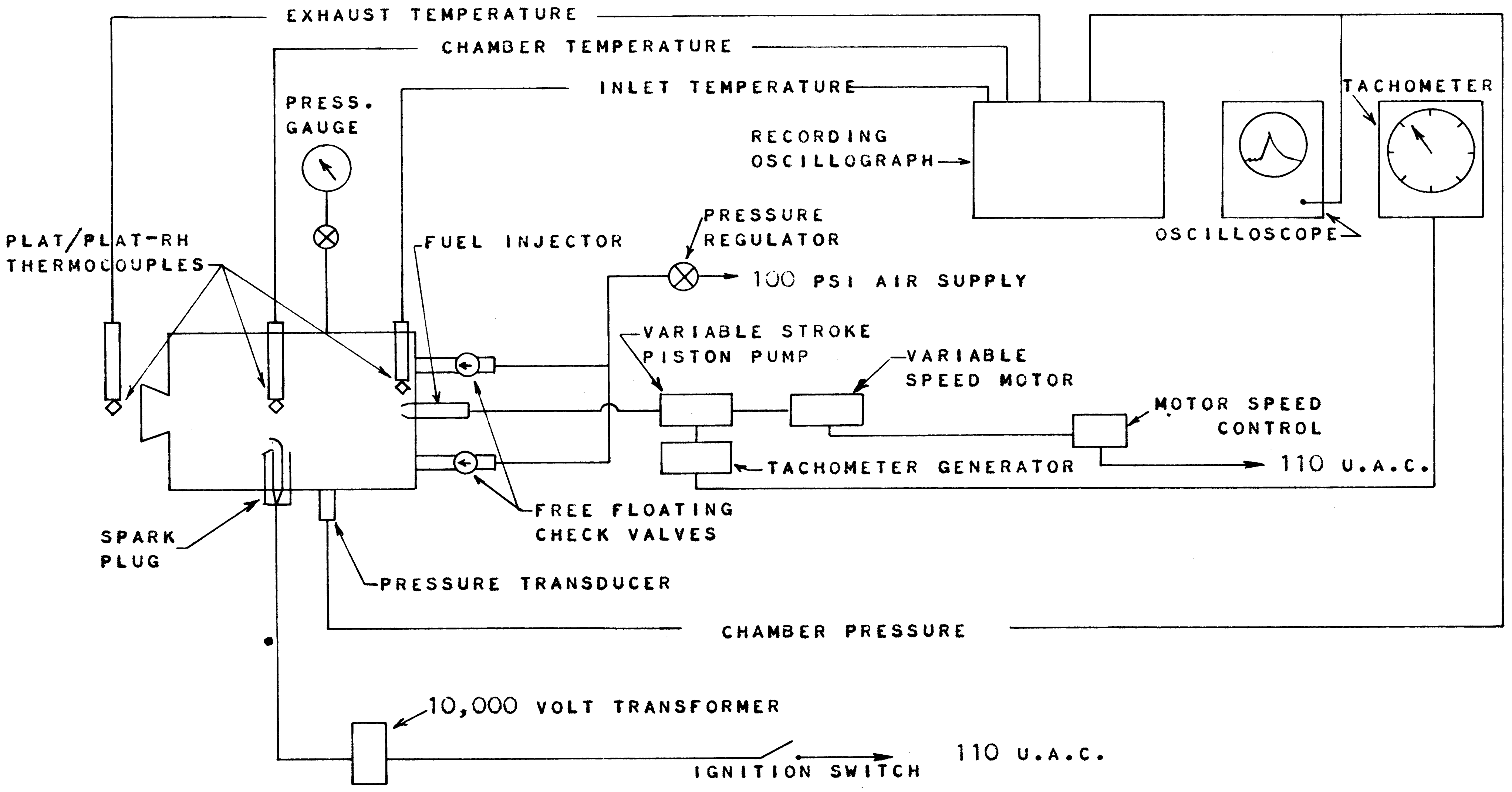


FIG. 12. DRAWING OF THE A.P.L. COMBUSTION CHAMBER



SCHEMATIC DIAGRAM OF THE TEST INSTALLATION
FOR THE AIRCRAFT PROPULSION LABORATORY COMBUSTION CHAMBER

Figure - 13

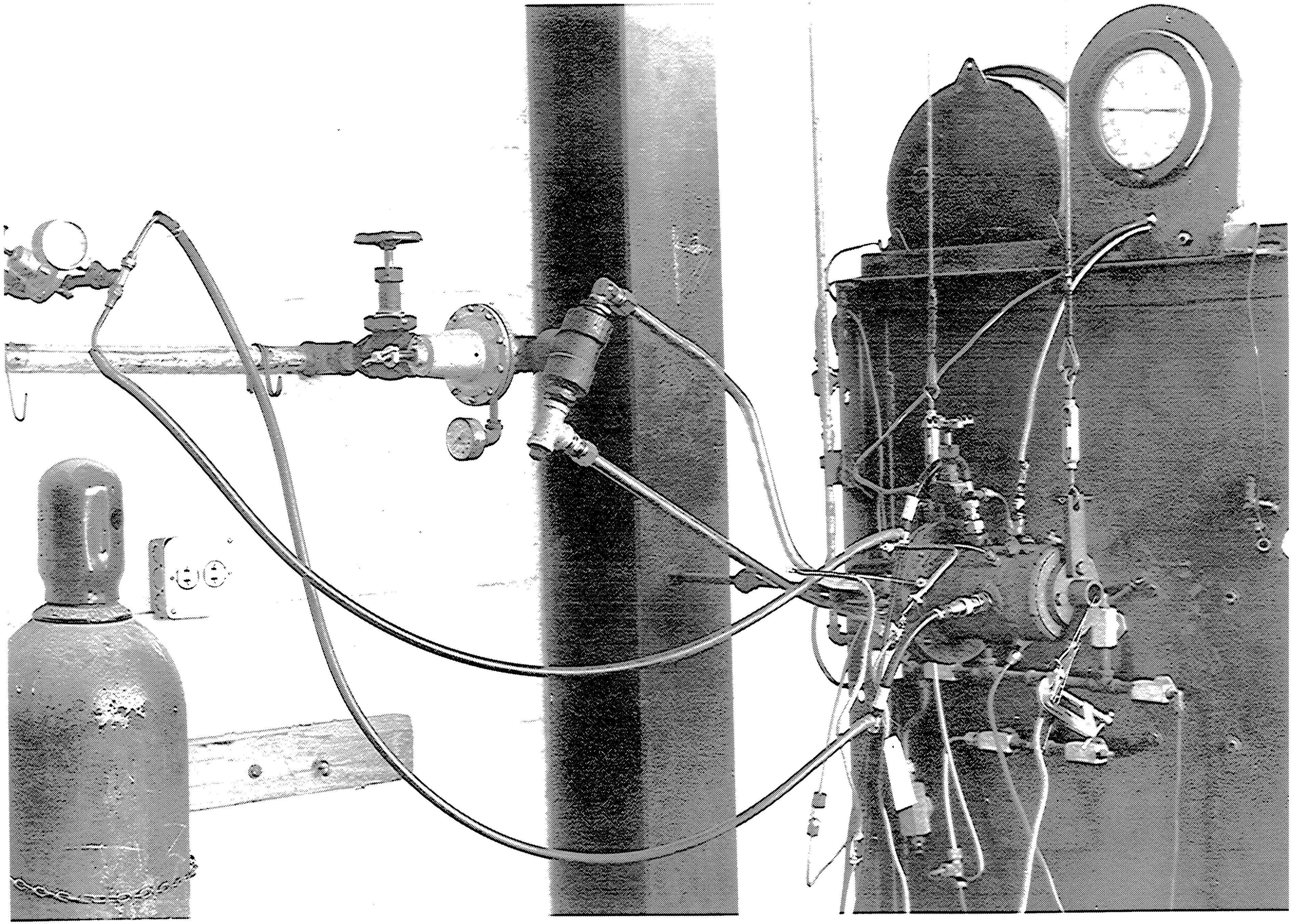


FIG. 14. PHOTOGRAPH OF THE TEST INSTALLATION FOR THE A.P.L. CHAMBER

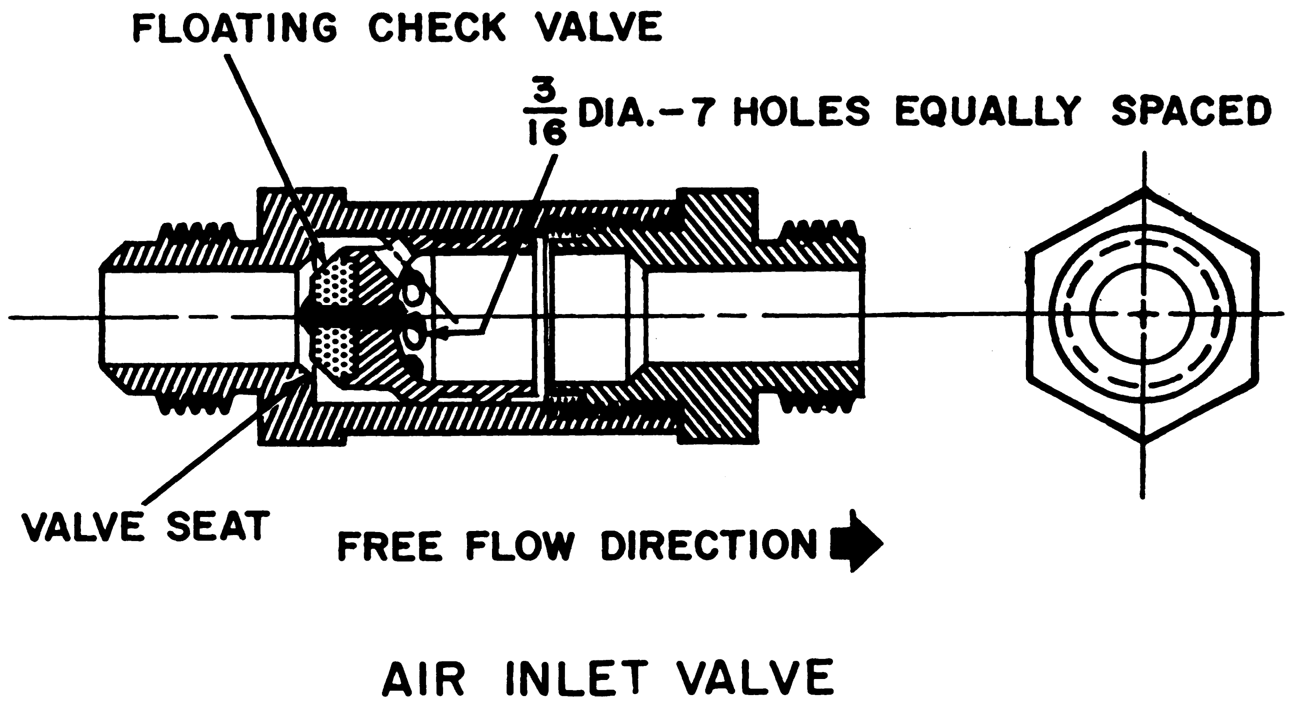


FIG. 15. DRAWING OF THE FREE FLOATING AIR VALVES USED IN THE A.P.L. CHAMBER

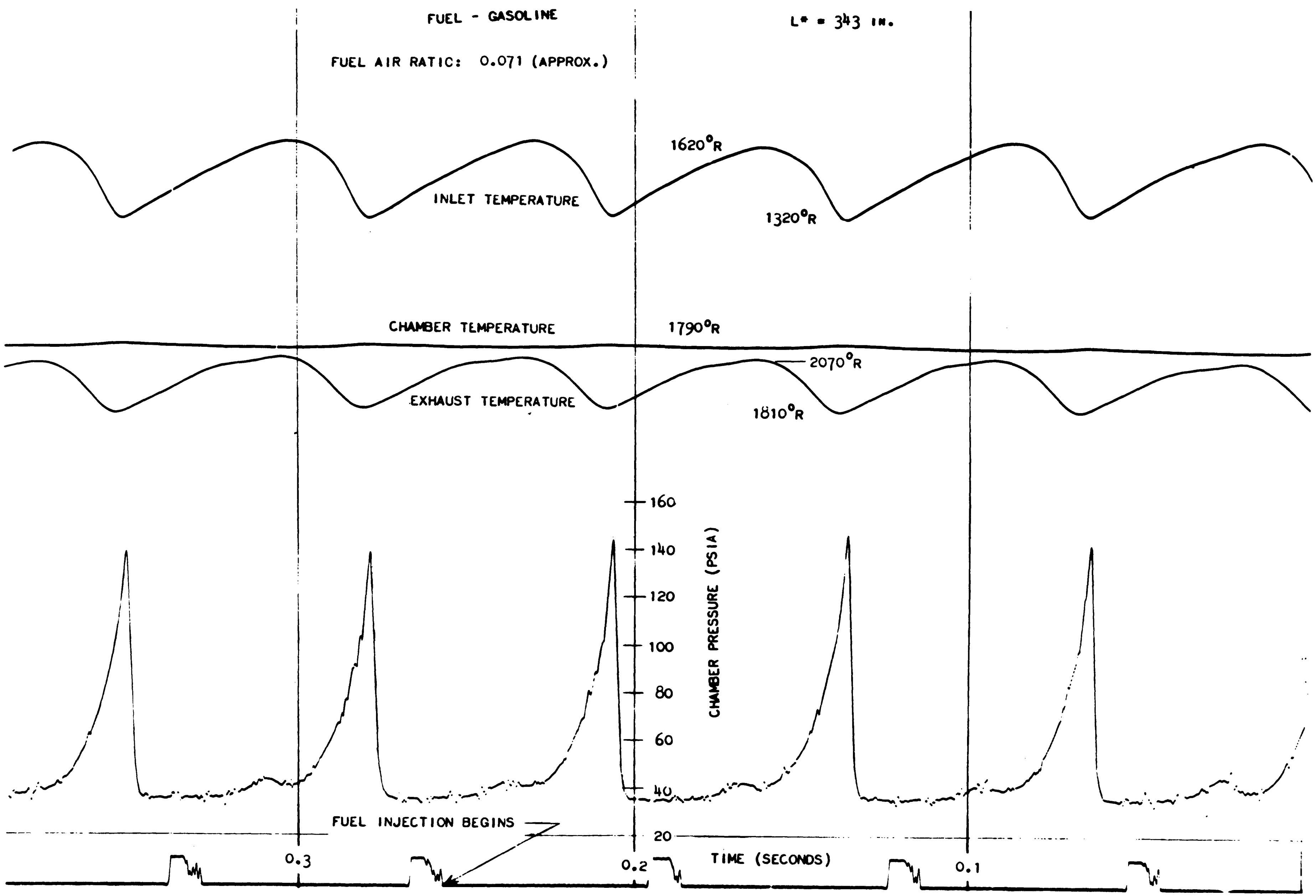


FIG. 16. EXPLOSION CYCLE TRACES FOR THE A.P.L. CHAMBER (P_{c_0} = 35 P.S.I.A.)

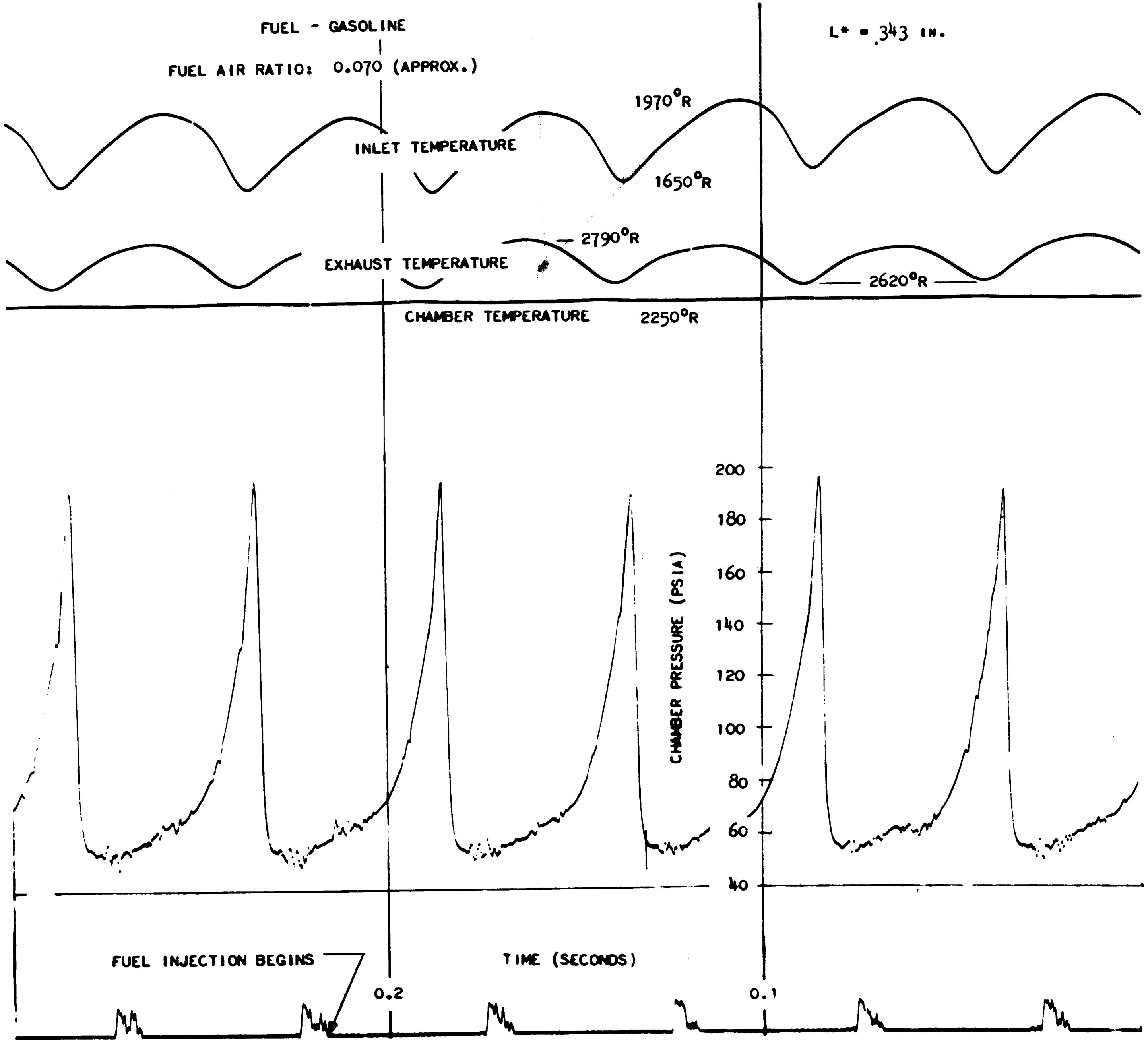


FIG. 17. EXPLOSION CYCLE TRACES FOR THE A.P.L CHAMBER (P_{c_n} = 55 P.S.I.A.)

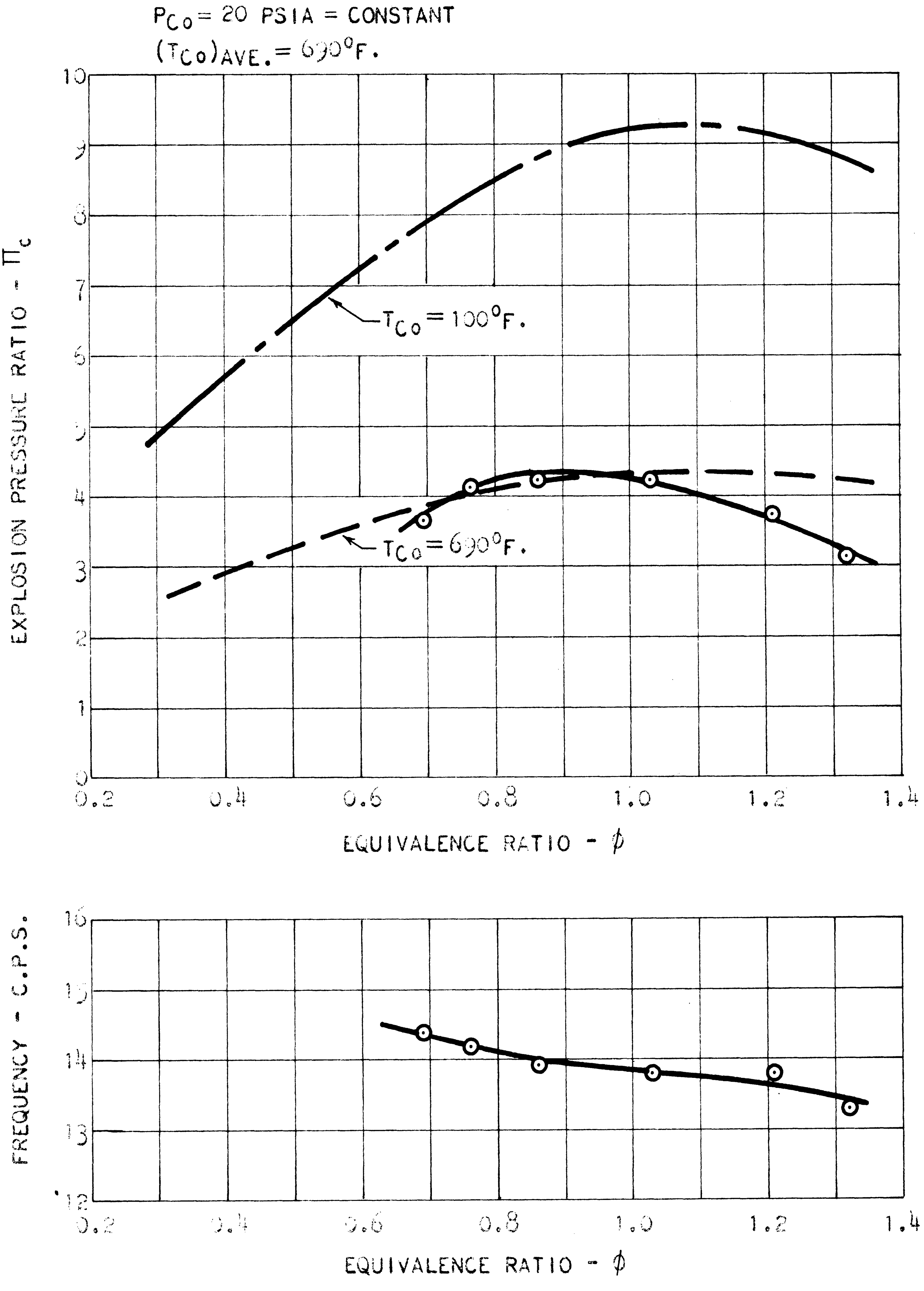
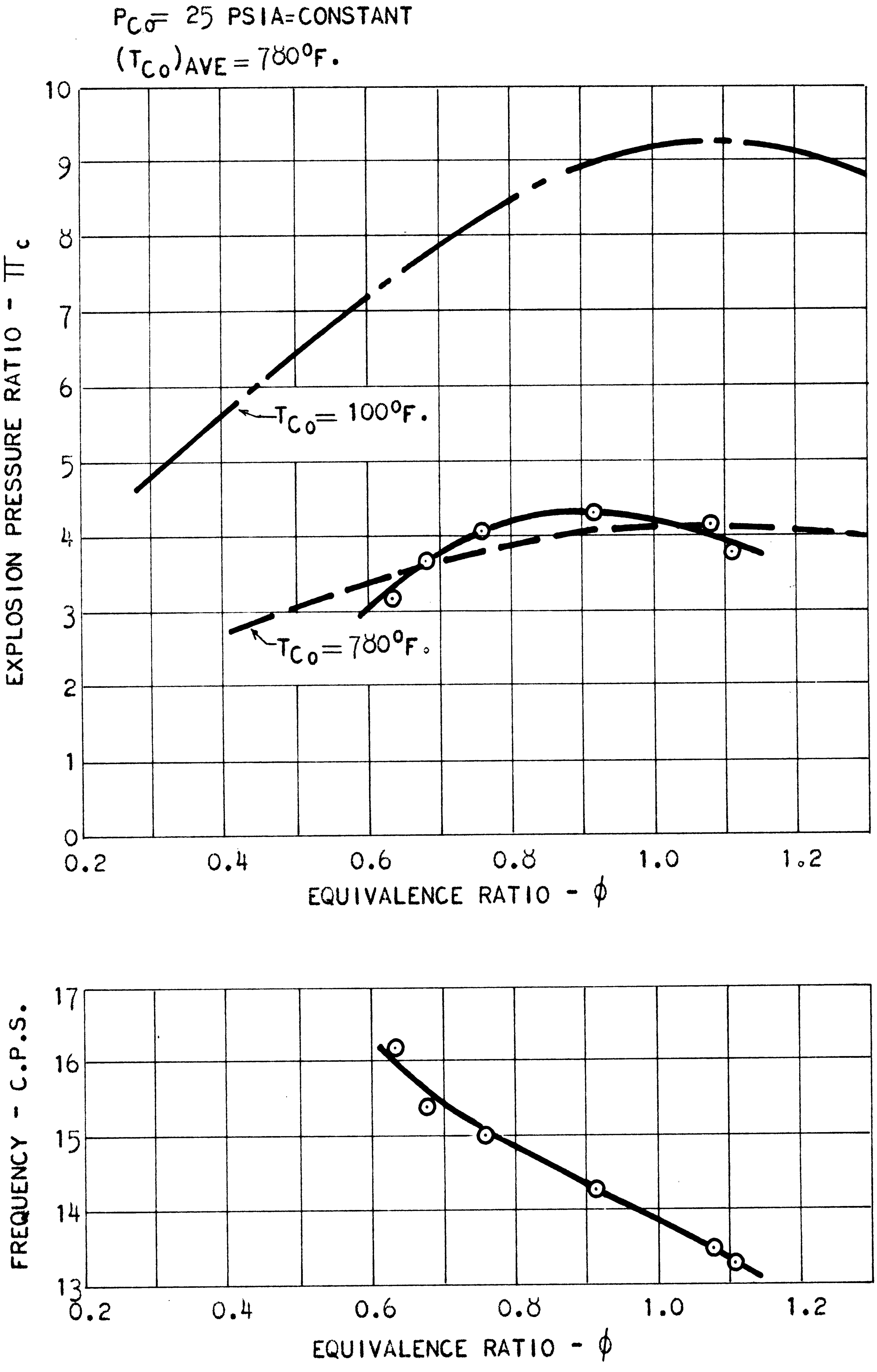
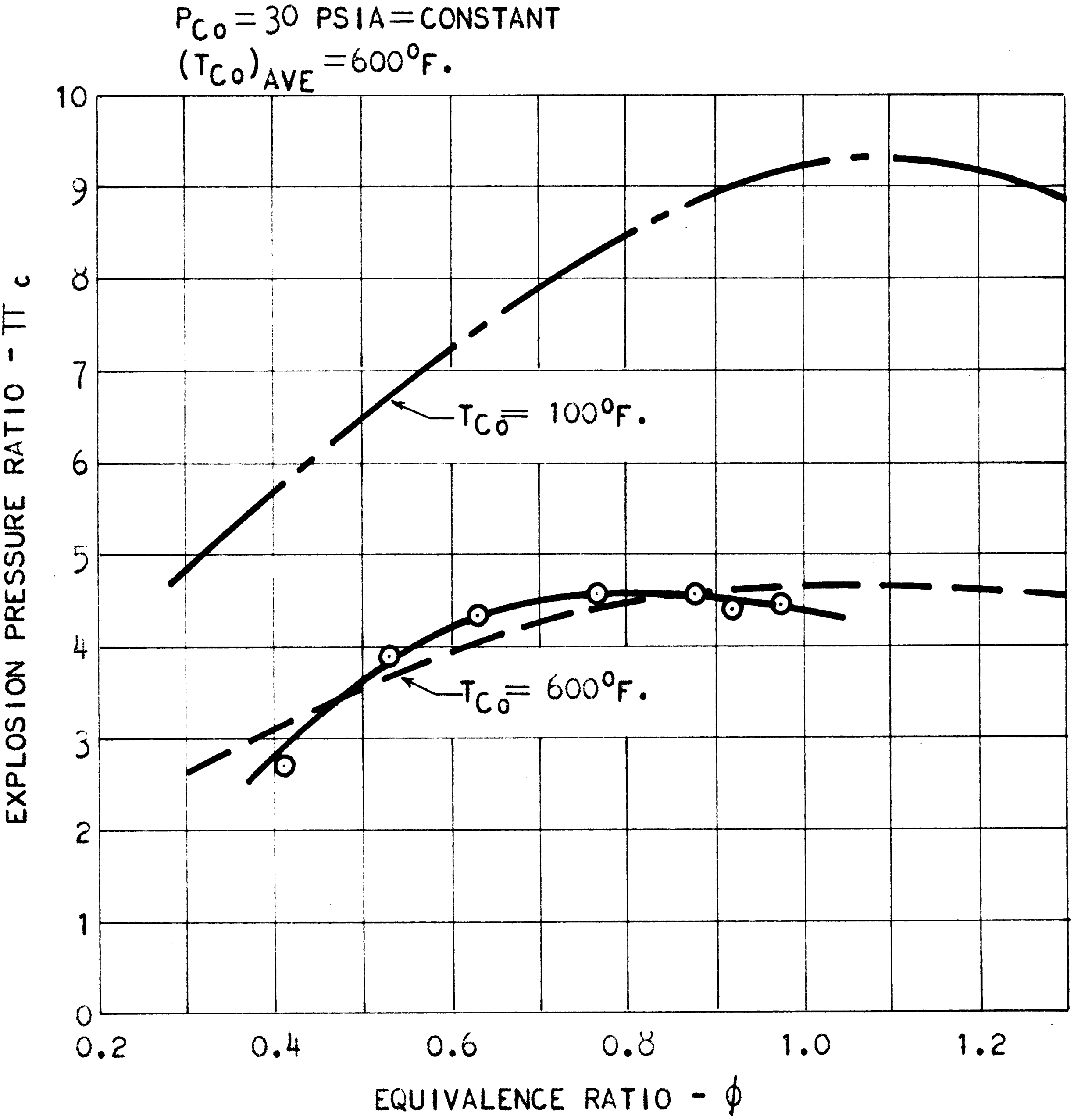

P_Co = 20 PSIA = CONSTANT
(T_Co)AVE. = 690°F.
EXPLOSION PRESSURE RATIO - π_c
0
1
2
3
4
5
6
7
8
9
10
T_Co = 100°F.
T_Co = 690°F.
0.2
0.4
0.6
0.8
1.0
1.2
1.4
EQUIVALENCE RATIO - φ
FREQUENCY - C.P.S.
12
13
14
15
16
0.2
0.4
0.6
0.8
1.0
1.2
1.4
EQUIVALENCE RATIO - φ

FIGURE - 18

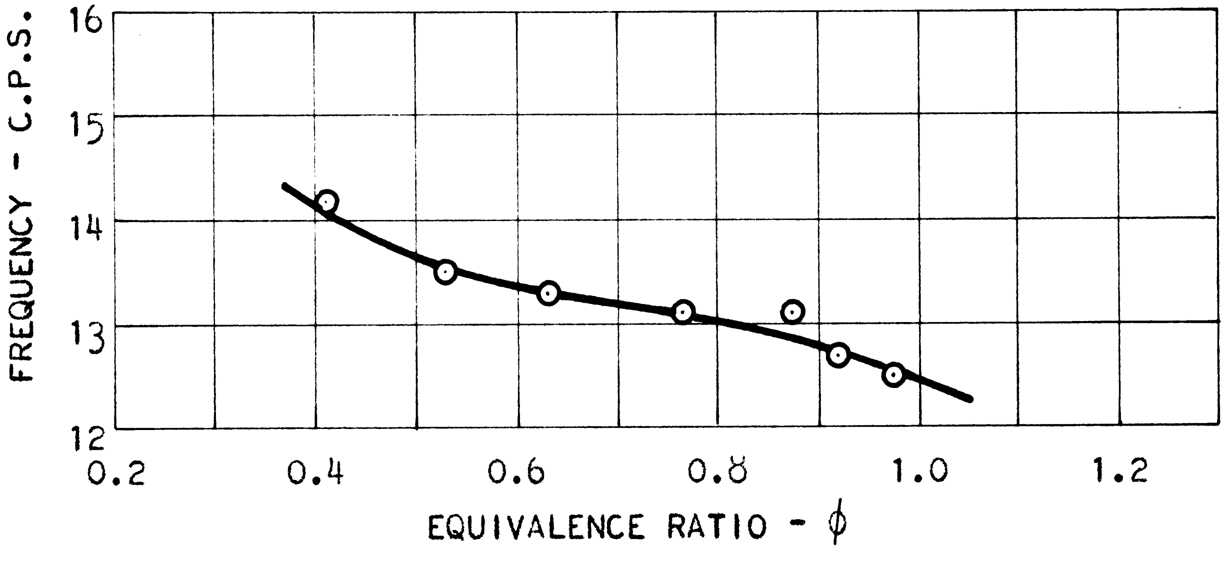


P_Co = 25 PSIA = CONSTANT
(T_Co)AVE = 780°F.
EXPLOSION PRESSURE RATIO - Π_c
0
1
2
3
4
5
6
7
8
9
10
T_Co = 100°F.
T_Co = 780°F.
0.2
0.4
0.6
0.8
1.0
1.2
EQUIVALENCE RATIO - φ
FREQUENCY - C.P.S.
13
14
15
16
17
0.2
0.4
0.6
0.8
1.0
1.2
EQUIVALENCE RATIO - φ

FIGURE - 19



$P_{Co} = 30$ PSIA = CONSTANT
$(T_{Co})_{AVE} = 600°F.$
EXPLOSION PRESSURE RATIO - π_c
0
1
2
3
4
5
6
7
8
9
10
0.2
0.4
0.6
0.8
1.0
1.2
$T_{Co} = 100°F.$
$T_{Co} = 600°F.$
EQUIVALENCE RATIO - ϕ



FREQUENCY - C.P.S.
12
13
14
15
16
0.2
0.4
0.6
0.8
1.0
1.2
EQUIVALENCE RATIO - ϕ

FIGURE - 20

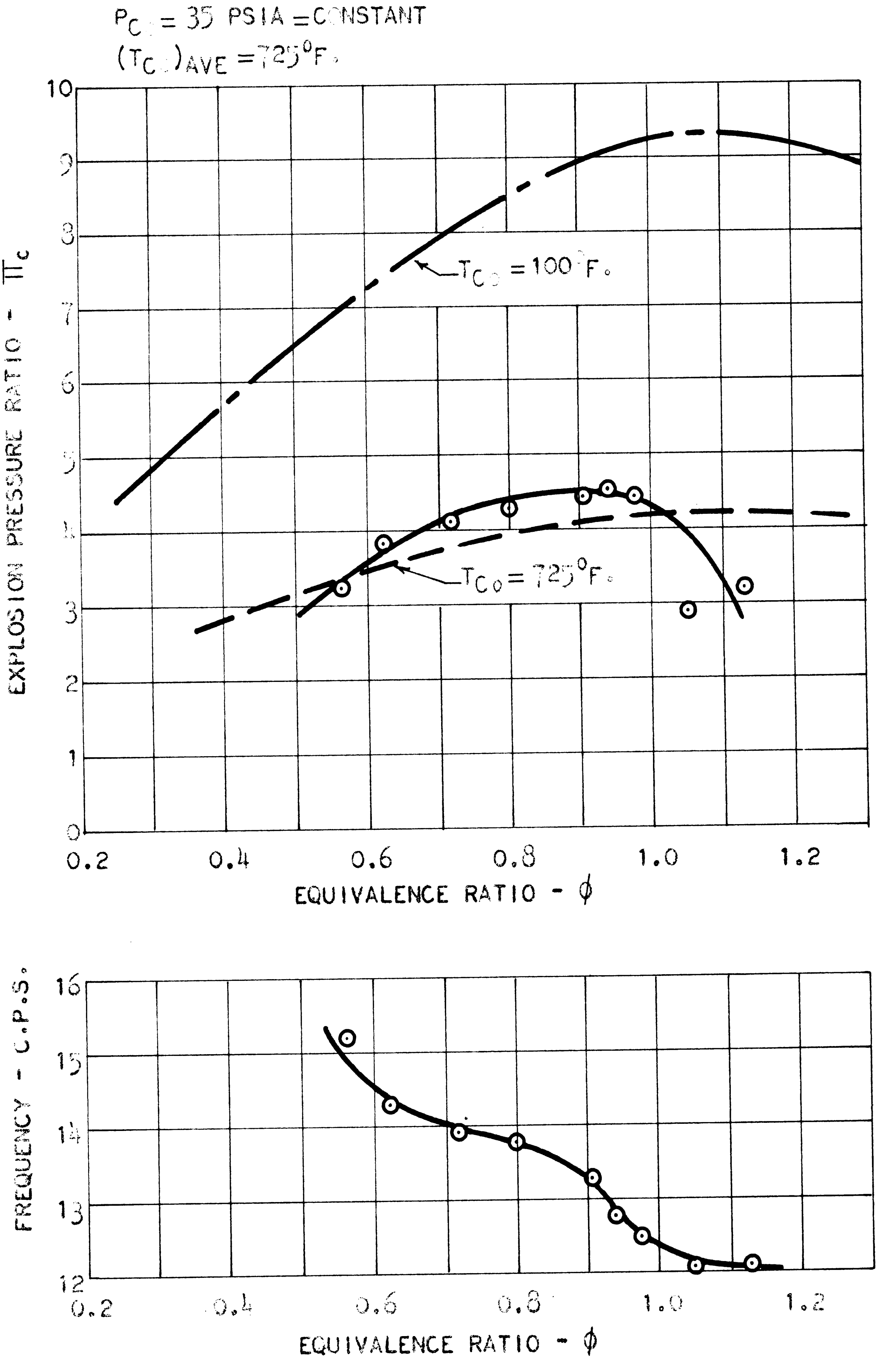

P_C = 35 PSIA = CONSTANT
(T_C)_AVE = 725°F.
T_C0 = 100°F.
T_C0 = 725°F.
EXPLOSION PRESSURE RATIO - π_c
0
1
2
3
4
5
6
7
8
9
10
0.2
0.4
0.6
0.8
1.0
1.2
EQUIVALENCE RATIO - φ
FREQUENCY - C.P.S.
12
13
14
15
16
0.2
0.4
0.6
0.8
1.0
1.2
EQUIVALENCE RATIO - φ

FIGURE - 21

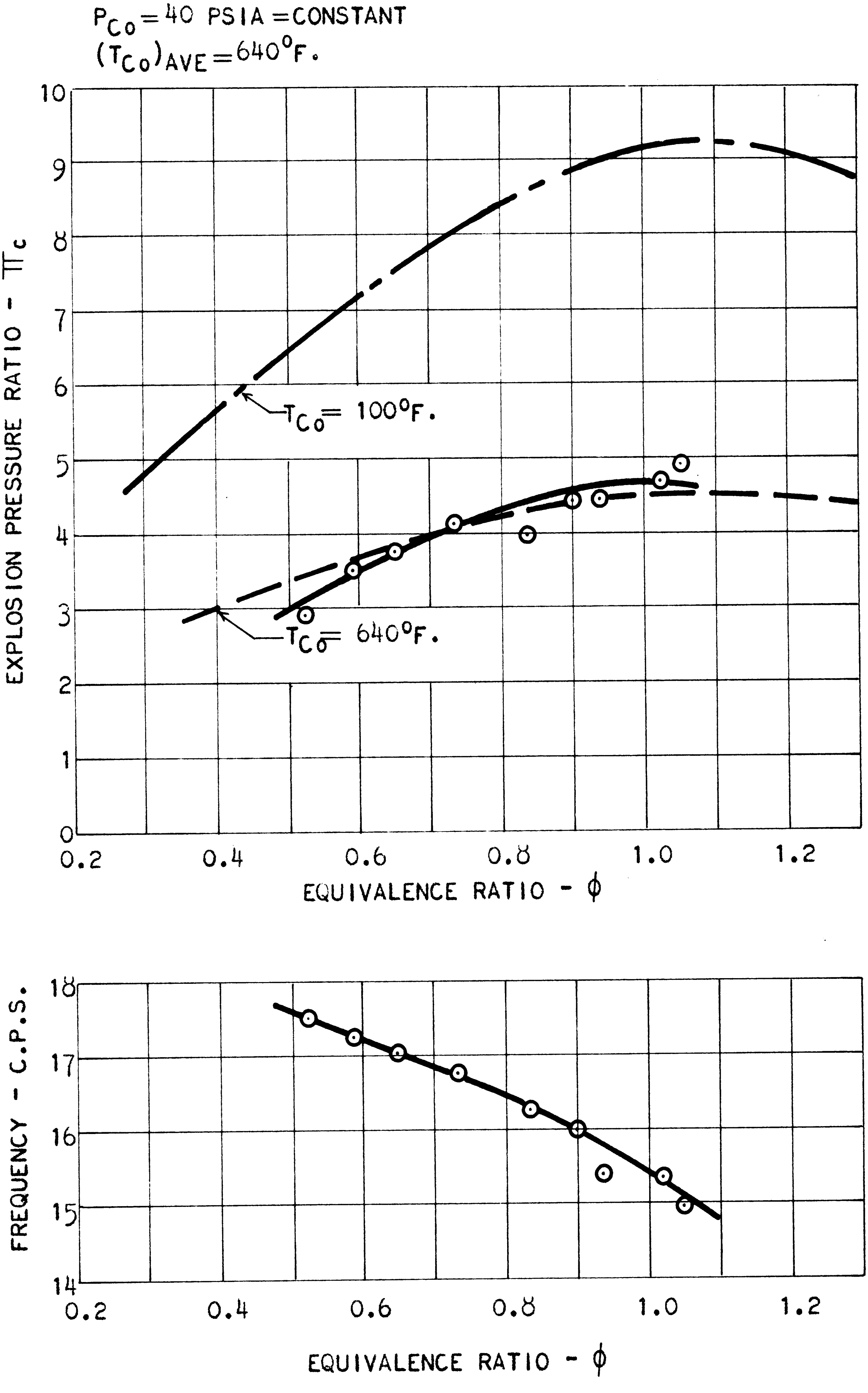

P_{Co} = 40 PSIA = CONSTANT
$(T_{Co})_{AVE}$ = 640°F.
EXPLOSION PRESSURE RATIO - π_c
10
9
8
7
6
5
4
3
2
1
0
0.2
0.4
0.6
0.8
1.0
1.2
EQUIVALENCE RATIO - ϕ
T_{Co} = 100°F.
T_{Co} = 640°F.
FREQUENCY - C.P.S.
18
17
16
15
14
0.2
0.4
0.6
0.8
1.0
1.2
EQUIVALENCE RATIO - ϕ

FIGURE - 22

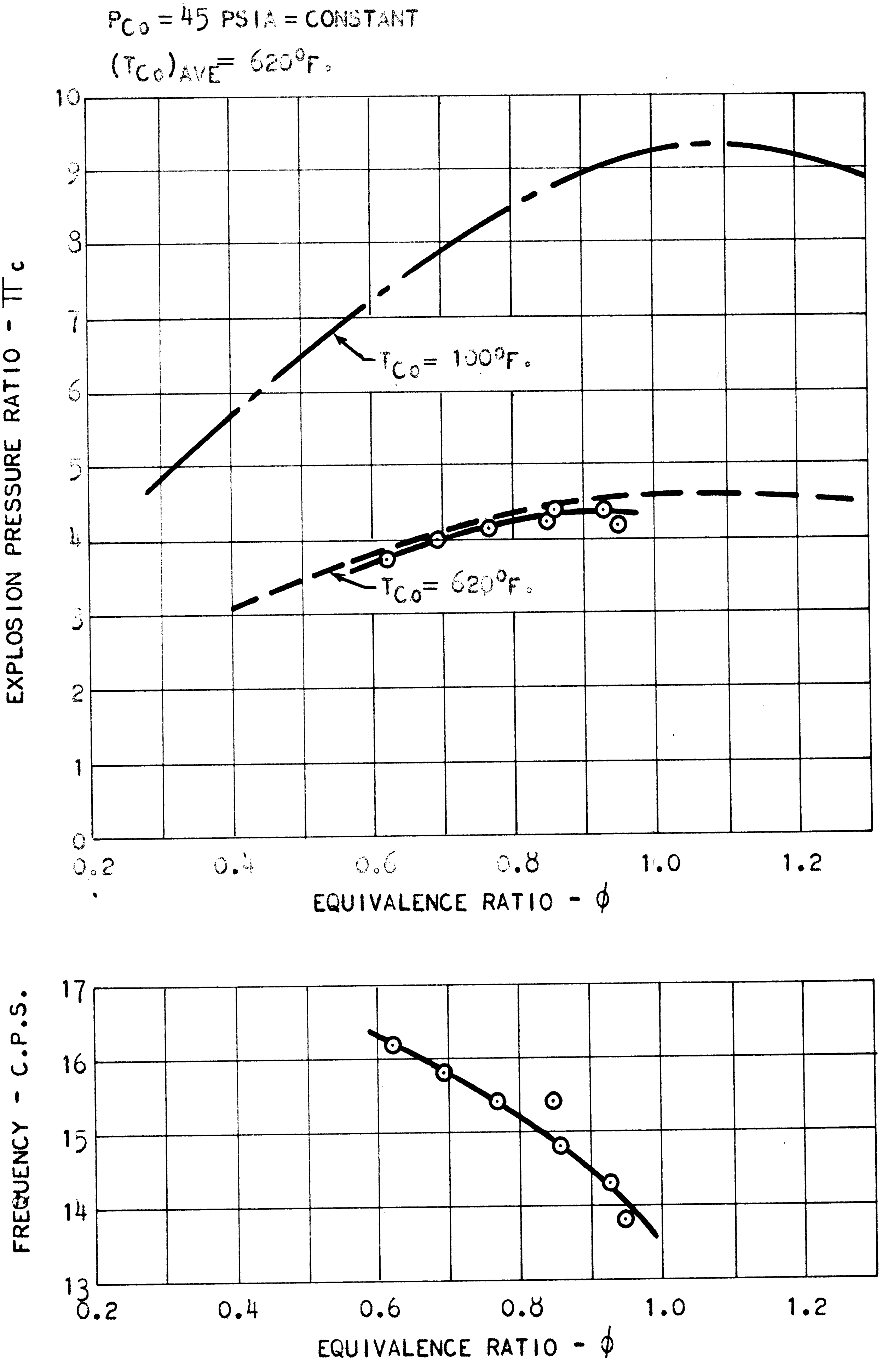

$P_{C_0} = 45$ PSIA = CONSTANT
$(T_{C_0})_{AVE} = 620°F.$
EXPLOSION PRESSURE RATIO - π_c
10
9
8
7
6
5
4
3
2
1
0
0.2
0.4
0.6
0.8
1.0
1.2
EQUIVALENCE RATIO - ϕ
$T_{C_0} = 100°F.$
$T_{C_0} = 620°F.$
FREQUENCY - C.P.S.
17
16
15
14
13
0.2
0.4
0.6
0.8
1.0
1.2
EQUIVALENCE RATIO - ϕ

FIGURE - 23

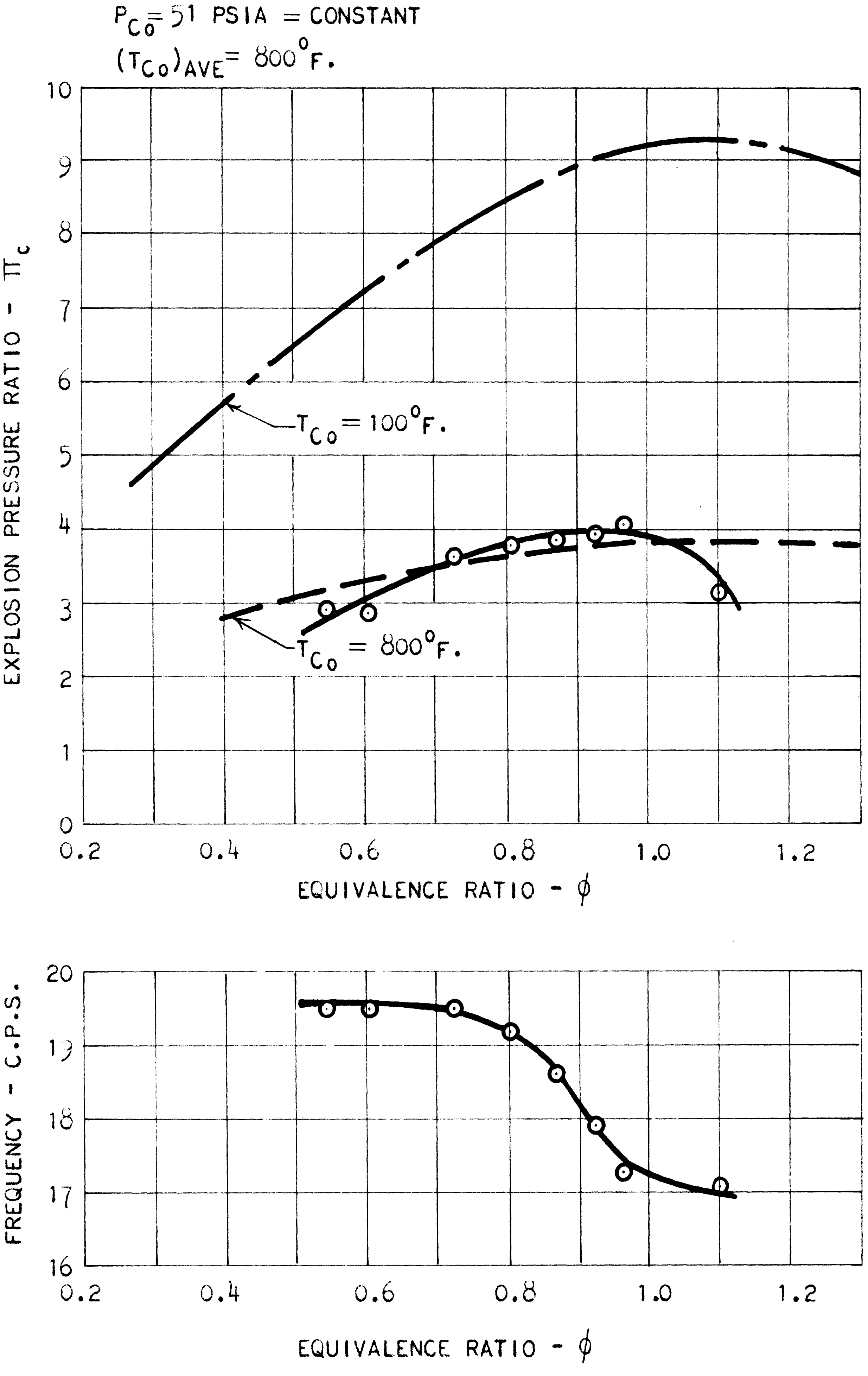

$P_{Co} = 51$ PSIA = CONSTANT
$(T_{Co})_{AVE} = 800°F.$
EXPLOSION PRESSURE RATIO - Π_c
10
9
8
7
6
5
4
3
2
1
0
0.2
0.4
0.6
0.8
1.0
1.2
$T_{Co} = 100°F.$
$T_{Co} = 800°F.$
EQUIVALENCE RATIO - ϕ
FREQUENCY - C.P.S.
20
19
18
17
16
0.2
0.4
0.6
0.8
1.0
1.2
EQUIVALENCE RATIO - ϕ

FIGURE - 24

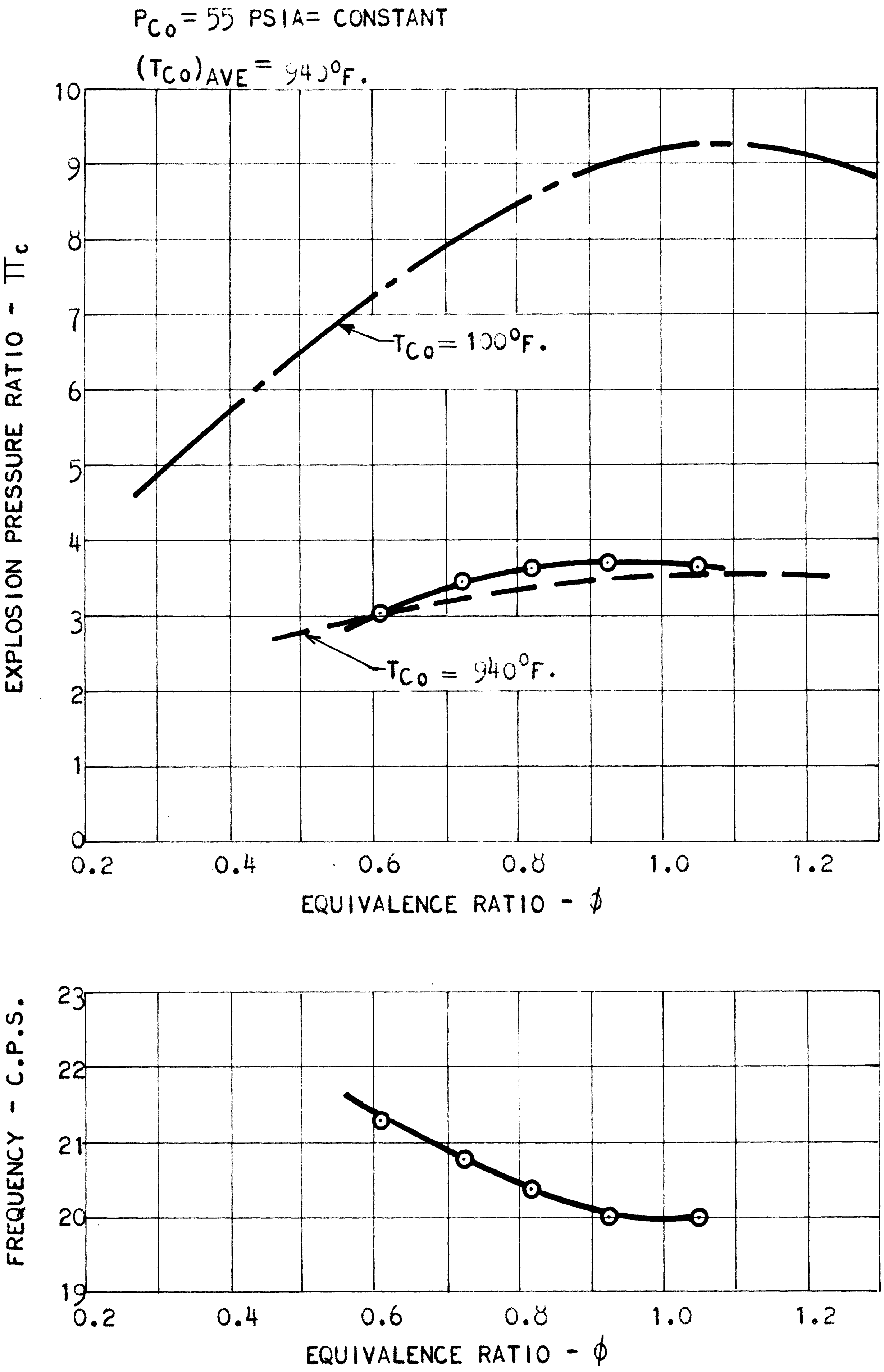

P_{Co} = 55 PSIA = CONSTANT
$(T_{Co})_{AVE}$ = 940°F.
EXPLOSION PRESSURE RATIO - Π_c
0
1
2
3
4
5
6
7
8
9
10
T_{Co} = 100°F.
T_{Co} = 940°F.
0.2
0.4
0.6
0.8
1.0
1.2
EQUIVALENCE RATIO - ϕ
FREQUENCY - C.P.S.
19
20
21
22
23
0.2
0.4
0.6
0.8
1.0
1.2
EQUIVALENCE RATIO - ϕ

FIGURE - 25

REPRESENTATIVE VALUES OF THE COMBUSTION TIME - t_c

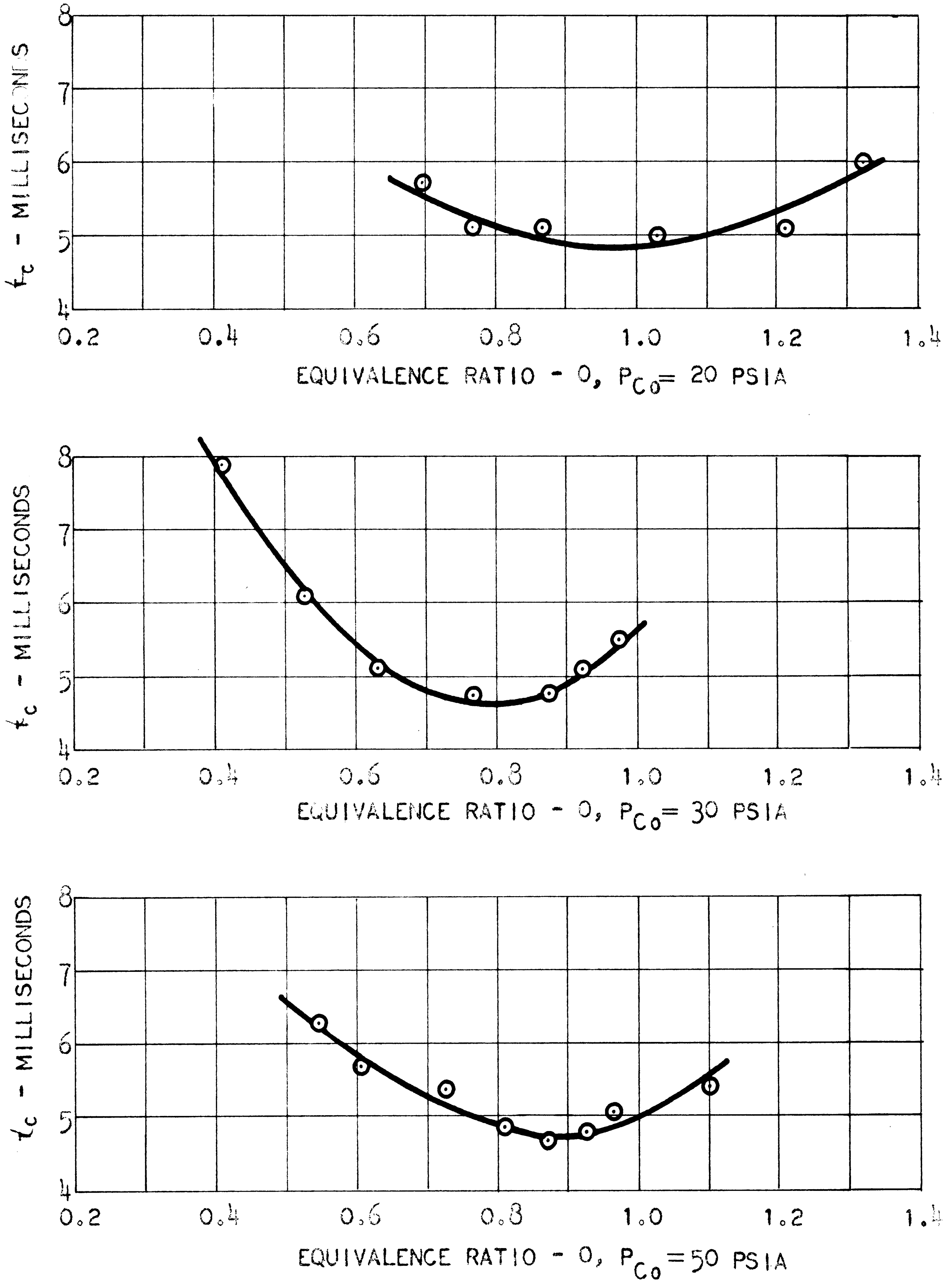
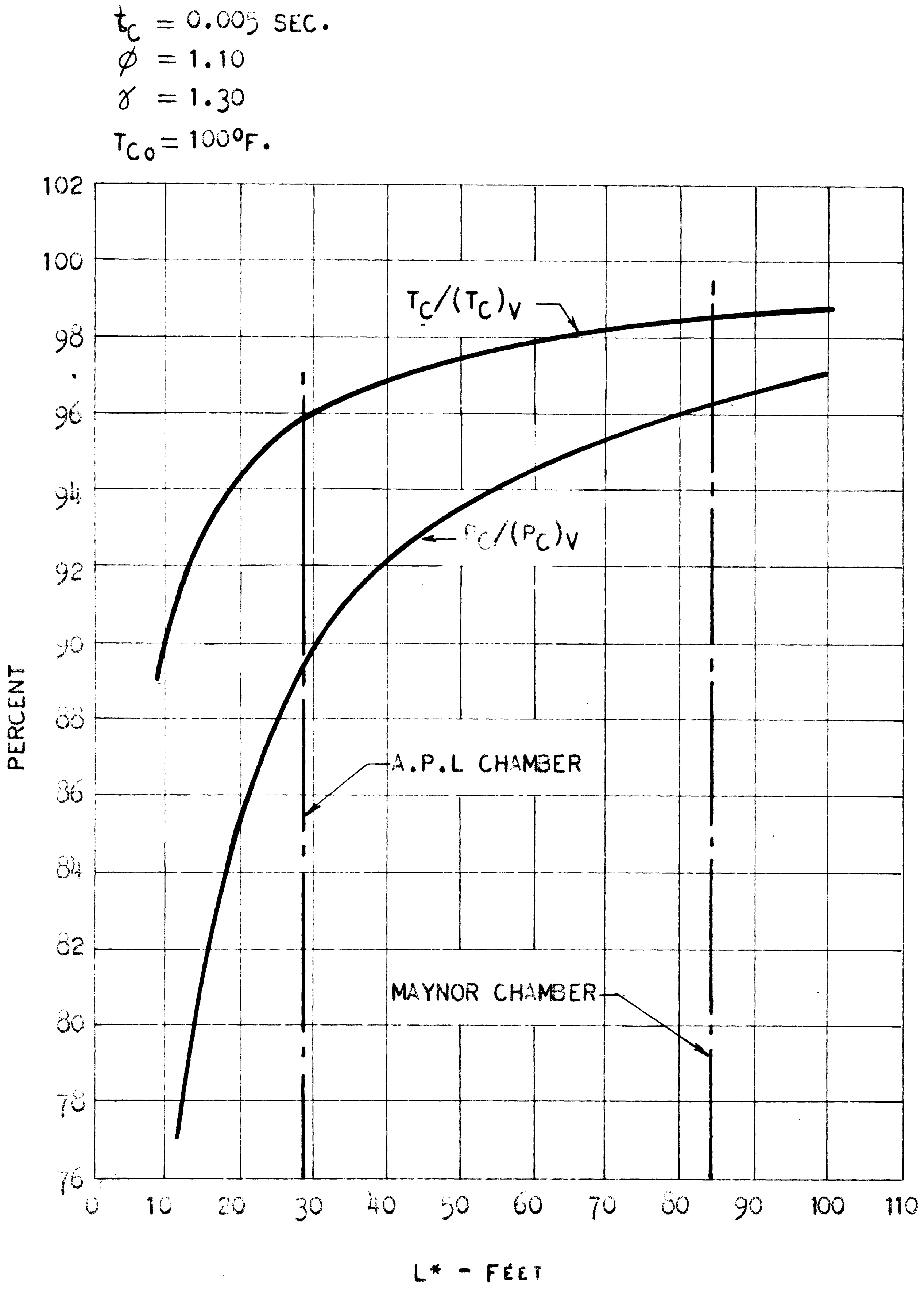


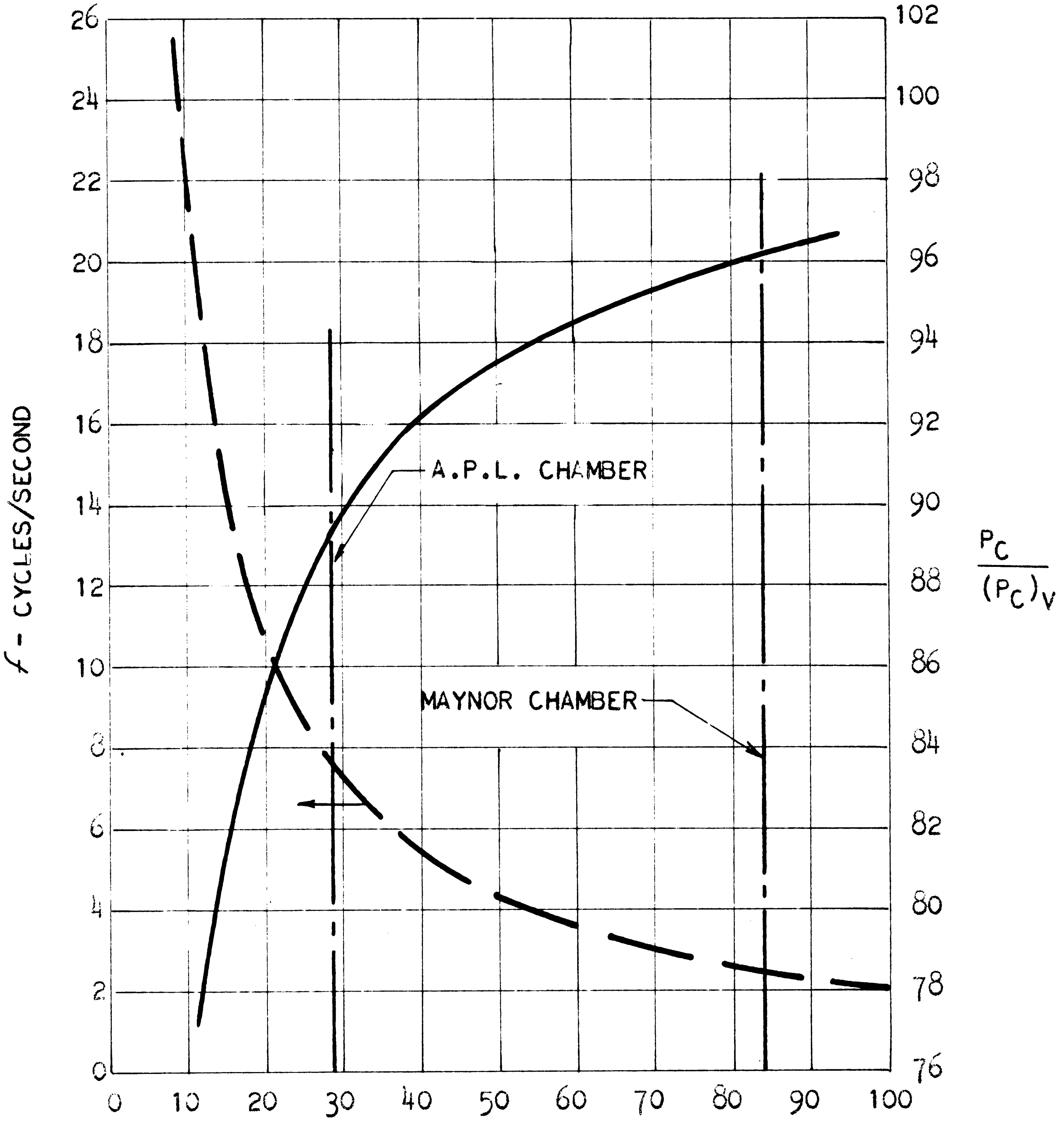
FIGURE 26



EFFECT OF COMBUSTION CHAMBER L* ON EXPLOSION PRESSURE AND TEMPERATURE

FIGURE - 27

$t_C = 0.005$ SEC.
$\phi = 1.10$
$\gamma = 1.30$
$T_{C_0} = 100^\circ$F.



EFFECT OF COMBUSTION CHAMBER L* ON

CYCLING RATE AND EXPLOSION PRESSURE

FIGURE - 28