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RESEARCH MEMORANDUM

STARTING OF ROCKET ENGINE AT CONDITIONS OF SIMULATED ALTITUDE USING CRUDE MONOETHYLANILINE AND OTHER FUELS WITH MIXED ACID

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SUMMARY

Experiments were conducted at sea level and at a pressure altitude of approximately 55,000 feet at various temperatures in order to determine the starting characteristics of a commercial 220-pound-thrust rocket engine using crude monoethylaniline and other fuels with mixed acid.

With crude monoethylaniline and mixed acid, ignition difficulties were encountered at sea level and at a pressure altitude of 55,000 feet at temperatures below about 20° F. With fuels (a) mixed butyl mercaptans, (b) clear water-white turpentine, and (c) α-pinene, with mixed acid, no starting difficulties attributable to the propellants were experienced at sea level and at pressure altitudes of 48,000 to 60,000 feet for temperatures as low as -74° F. The turpentine and α-pinene, however, sometimes left deposits on the injector face. With fuel blends,(a) 70-percent furfuryl alcohol and 30-percent crude monoethylaniline by volume, (b) 70-percent furfuryl alcohol and 30-percent xylene by volume, and (c) 90-percent crude monoethylaniline and 10-percent aviation gasoline by volume, with mixed acid, difficulties were experienced either with appreciable deposits or with starting. With any propellent combination at low temperature, the possibility exists that ice from condensed moisture may obstruct or partly obstruct the propellant injection holes and cause ignition failure.

INTRODUCTION

The consideration of rocket-engine applications requiring starting at high altitude has focused attention on the possibility that rocket propellants that ignite spontaneously at sea level and normal temperatures may not ignite at low-pressure, low-temperature conditions encountered at high altitudes.

As part of a general investigation of the ignition characteristics of several rocket-propellant systems conducted at the NACA Lewis laboratory, starting tests of a commercial 220-pound-thrust rocket engine were conducted at sea level and at a pressure altitude of approximately 55,000 feet at various temperatures using crude monoethylaniline and mixed acid. Additional experiments were performed with six other fuels. The research, conducted from June 1949 to February 1950, was first directed to isolating any starting difficulties attributable to low pressures, low temperatures, or the combination of both, using crude monoethylaniline and mixed acid. Subsequently, the research was directed to investigating other fuels that might provide satisfactory starting with mixed acid at low temperatures and low pressures. The results of these experiments, and a few auxiliary experiments conducted in attempts to explain the results obtained, are presented herein.

The purpose of the investigation was to define the altitude ignition problem and to arrive at some simple solution that quantitatively defines the ignition characteristics of several propellants in a particular engine.

APPARATUS

The apparatus consisted of an altitude tank (providing pressure altitude only) with means for evacuating and purging the tank, and the rocket engine mounted to exhaust into the tank. The rocket engine, propellant valves, and small propellant tanks were immersed in a coolant bath in order to simulate the low temperatures encountered at altitude. Photographs of the equipment are shown in figure 1.

Equipment for simulating altitude. - The layout of the altitude tank and auxiliary equipment is shown in figure 2. The tank was 8 feet in diameter and 29 feet long, and was provided with two 20-inch flanges at one end, a 10-inch flange at the opposite end, a 6-inch connection to the vacuum pump, and a water inlet and outlet. The rocket engine was mounted on one 20-inch flange and the other 20-inch flange contained a blow-out disk (fig. 1(a)). A gate valve was mounted on the 10-inch flange as an exhaust outlet. The vacuum pump could be isolated from the tank by means of a 6-inch vacuum-type valve (fig. 1(c)). A tee was placed in the line from the tank to the vacuum-break valve. A centrifugal blower was connected by a 6-inch line to the vacuum-break valve and was used to ventilate the tank after rocket operation. For most of the runs, the bottom of the tank contained water to dilute and to render harmless any propellants that failed to ignite.

In order to provide low temperatures, the entire engine assembly and the propellant tanks were immersed in a coolant bath (figs. 1(a) and 1(b)). During the course of the experiments, the method of cooling was varied. In all cases, the engine assembly and the tanks were immersed in a coolant (either methyl alcohol or a mixture of carbon tetrachloride and chloroform) during the cooling period. For the initial runs (through run 19), the coolant was drained to a level below the unit before operation (for safety reasons). Because draining produced uneven temperatures of engine parts and tanks, the remaining runs were made with the engine assembly and the tanks immersed during the cooling period and during operation.

Rocket engine. - A diagrammatic sketch of the 220-pound-thrust rocket engine, the propellant-valve assembly, and the blower system used with it is shown in figure 3. A regulated supply of helium was used to force the propellants into the rocket engine and to force the hydraulic fluid into the propellant-valve actuating system. The pressurization of the propellant tanks and the hydraulic-fluid accumulator of the propellant-valve actuating system was accomplished by means of helium-operated three-way valves, which were controlled by solenoids. When the solenoids were deenergized, the propellant tanks and accumulator were vented to the atmosphere.

The propellant tanks were made of Inconel and had a capacity of about 1.3 gallons. The filter-caps of the tanks contained safety blow-out disks. Caps were provided on the tanks for measurement of pressure and temperature and for draining the propellants. A pressure tap was placed on each propellant line to the injector and a pressure tube was connected to the combustion chamber.

Instrumentation. - The following measurements were made:

(1) Combustion-chamber pressure

(2) Oxidant-injection pressure

(3) Fuel-injection pressure

(4) Propellant-tank pressure

(5) Propellant-valve position

(6) Temperature of fuel, oxidant, and engine parts

(7) Exhaust temperature at nozzle exit

(8) Altitude-tank pressure

Time-synchronized records were made of items (1) to (5) for all runs. Pressures were measured by Bourdon-tube-type recorders. For some of the runs, the combustion-chamber and injection pressures were also measured by strain-gage cells and a multichannel oscillograph. The lines for the measurement of combustion-chamber and injection pressures were kept short for most of the runs in order to reduce the time lag of response. The position of the propellant valves was measured by means of a resistance-type position transmitter, the output of which was recorded on a self-balancing recording potentiometer. The transmitter was linked to the propellant valves by means of a rack-and-pinion arrangement. The rack was mounted on an I-shaped bar that was bolted to the yoke of the propellant valves. Propellant temperatures were measured by copper-constantan thermocouples installed in the propellant tanks. Copper-constantan thermocouples were placed on the surfaces of the engine jacket, propellant valves, and propellant lines. A chromel-alumel thermocouple was installed at the rocket-nozzle exit in order to obtain a qualitative indication of ignition. The outputs of the copper-constantan thermocouples were measured by a manual-balance potentiometer for the initial runs and by recording potentiometers for the remainder of the runs. For the initial runs, the output for the thermocouple in the rocket exhaust was measured by a microammeter, and for the remainder of the runs, the output was measured by a recording potentiometer.

Propellants. - The propellants specified for the engine were used for the initial part of the investigation. The fuel was crude monoethylaniline and the oxidant was mixed acid. Specifications and analyses of these propellants are shown in table I. Some physical properties of these propellants are shown in table II.

During the second phase of the work, when other fuels were sought to eliminate ignition difficulties, the following fuels were used: (1) a blend of 90-percent crude monoethylaniline and 10-percent aviation-grade gasoline (specification AN-F-48b, Amendment-1), by volume; (2) a blend of 70-percent furfuryl alcohol and 30-percent crude monoethylaniline, by volume; (3) a blend of 70-percent furfuryl alcohol and 30-percent xylene, by volume; (4) commercial gum turpentine; (5) α-pinene; and (6) mixed butyl mercaptans of the following composition: sec-butyl mercaptan, 37 percent; n-propyl- and tert-butyl mercaptans, 23 percent; amyl mercaptans, 21 percent; n-butyl mercaptan, 11 percent; isobutyl mercaptan, 7 percent; and isopropyl mercaptan, 1 percent.

PROCEDURE

Engine operation. - The quantities of propellants supplied to the fuel and oxidant tanks were made small in order to minimize hazards from ignition failures. Approximately 4.5 pounds of fuel and 16 pounds of mixed acid were used for most of the runs. Although the design oxidant- to fuel-weight ratio for crude monoethylaniline and mixed acid is from 3.15 to 3.45, an excess of acid was supplied to insure that the cooling jacket on the combustion chamber would remain filled during combustion.

For low-pressure runs, the altitude tank was exhausted to the desired pressure; for low-temperature runs, the engine, the valves, and the propellant tanks were immersed in the coolant for a period of 45 minutes to several hours in order to be sure that the propellant parts and the propellants had reached the desired temperature. The thermocouples measuring the temperature at various positions were read during the cooling period and recorded just before the run. During the experiments, it was found that ice from moisture in the system sometimes jammed the injector holes or combustion-chamber pressure tap. This difficulty was eliminated by installation of helium pressure taps on the injector lines and combustion-chamber tap (installed after run 32).

At 20-minute intervals during the cooling period and just before engine operation, the oxidant- and fuel-injection holes and the combustion-chamber pressure line were checked for possible restrictions by forcing helium through them. In some of the runs, a small flow of helium was bled continuously through the combustion-chamber pressure line; this procedure did not affect the pressure measurements. After the loading of the propellant tanks and the attainment of the pressure and temperature conditions, the propellant tanks were pressurized, the instruments were started, and the firing switch that pressurized the hydraulic system actuating the propellant valves was closed. The propellant valves were held open until operating combustion-chamber pressure was attained (about 315 lb/sq in. absolute) and then were closed. The supply of the propellant was such that, if normal combustion occurred, the pressure altitude of the tank would change from an initial value of 55,000 feet to a final value of approximately 40,000 feet. After the run, air was bled into the altitude tank until atmospheric pressure was reached and the tank was then purged of exhaust fumes by a blower.

Pressure and temperature. - Runs were made for the following general conditions: (a) sea-level pressure and variable temperatures and (b) altitude pressure of approximately 55,000 feet and variable temperatures.

Propellant-valve opening time. - Early in the investigation, it was found that low temperatures increased the time for the propellant valve to move from the closed to the full-flow position, which in turn influenced the ignition results. The long valve opening time at low temperature is not surprising, inasmuch as the hydraulic fluid (specification AN-O-366) increased in viscosity by a factor of 20 for a temperature change of 70° to -40° F. Because of the excessively long valve opening time and its apparent influence on ignition, the valve opening time was varied by modifying the restrictor orifice in the hydraulic system and by using a silicone oil of high viscosity index (which had only a five-fold viscosity change from 70° to -40° F).

Definition of ignition failure. - The procedure for cases when no ignition was obtained varied slightly during the experiments. For the early runs, the propellant valves were left open until all the propellant charge was ejected through the engine. For the later runs, the propellant valves were closed before all the propellant charge was exhausted in order to get an approximate value of the mixture ratio by measurement of the remaining charge. In all cases, however, at least 2.5 pounds of fuel and 8.5 pounds of oxidant passed through the engine; this quantity would allow approximately 9 seconds of normal operation. The time for the injection of these quantities of propellants varied and depended on the propellant-valve opening time and on the temperature. The criterion of ignition failure, as defined for these experiments, is therefore whether the combustion-chamber pressure reached at least two-thirds of its normal value (315 lb/sq in. absolute) before 2.5 pounds of fuel and 8.5 pounds of oxidant were simultaneously injected into the engine.

RESULTS AND DISCUSSION

Crude Monoethylaniline and Mixed Acid

The experiments using crude monoethylaniline and mixed acid at both sea-level and altitude pressure are discussed in the following sections.

Sea-level pressure. - The results of the experiments with the engine, using crude monoethylaniline and mixed acid at sea-level pressure are shown in table III, which presents experimental measurements and indicates runs for which ignition occurred satisfactorily and those for which ignition difficulties were encountered. These runs are summarized in the following table:

Temperature (°F)	Valve opening time (sec)	Number of runs	
		Ignition	No ignition
77 ± 11	< 5	12	0
-8	16	1	0
-15 ± 2	9 ± 2	0	6
-17	16	0	1
-28	26	1	0

Twelve runs were made at normal temperatures (77 ± 11° F) and normal propellant-valve opening times of less than 5 seconds. These runs were interspersed among other runs to serve as checks on normal engine operation. A typical run in this series is shown in figure 4(a), where valve position, propellant-injection pressure, and combustion-chamber pressure are plotted as a function of time, with the initial valve movement taken as zero time. The oxidant-injection pressure rises before the fuel-injection pressure, which is an intended condition because the oxidant-propellant valve is designed to reach full-flow position before the fuel valve.

Of nine runs made at temperatures from -8° to -28° F, two started and seven failed to start. The temperature of one of the runs that started (a mean value -8° F) is somewhat uncertain, and the run also had a comparatively long valve opening time. The time variation of valve position and pressures for this run is shown in figure 4(b). The second of these low-temperature runs that started was at -28° F and had a very slow inflow of propellants because of the long valve opening time of 26 seconds. The time variation of valve position and pressures for this run is shown in figure 4(c). The ignition failures at about -15° F are characterized by a low combustion-chamber pressure of from 25 to 30 pounds per square inch absolute. Data for a typical run with no ignition are shown in figure 4(d).

Altitude pressure. - The results of starting runs at a pressure altitude of 55,000 feet at several temperatures is shown in table IV. These runs are summarized as follows:

Temperature (°F)	Approx. valve opening time (sec)	Number of runs	
		Ignition	No ignition
88 ± 3	< 4	3	0
18	< 5	3	0
14	7	1	0
10 ± 1	< 5	0	3
3 ± 2	< 5	1	3
2	12	1	0
-4	< 5	0	2
-12	12	1	0
-17 ± 2	3-8	0	4 + explosion
-28	26	1	0
-30	3	0	1
-35	43	0	1
-38	(a)	0	explosion
-47	64	0	1
-50	84	0	1

[a]Valve opening rate approximately same as for run at -35° F.

Seven runs at temperatures 14° F and above started satisfactorily. Twenty-two runs were made at temperatures from 11° to -50° F and of these, four started, sixteen failed to start, and two exploded, causing severe damage.

The time variation of valve position and pressures for a typical run with ignition at a pressure altitude of 55,000 feet and a temperature of 88° F is shown in figure 5(a). Some effect of low pressure is noted; the time for the combustion pressure to increase to its maximum is about twice as long at low pressure (for example, runs 7 and 9 of table IV) as at sea-level pressure at the same temperatures (for example, runs 27 and 61 of table III). Figure 5(b) shows the time variation of valve position and pressures for the run at 14° F (run 18).

One of the runs that started below 14° F (run 90, 5° F) was at approximately the same temperature as three runs that failed to start (runs 93, 94, and 95). Figures 5(c) and 5(d) show the time variation of valve position and pressures for the run that started and a typical run that failed to start at the same conditions, respectively.

The other three runs that started at a temperature below 14° F (at 2°, -12°, and -28° F) had comparatively long valve opening times. Figure 5(e) shows the time variations of valve position and pressures for the run at -12° F and figure 5(f) shows similar data for the run at -28° F, which had an approximate valve opening time of 26 seconds.

The operating conditions for the ignition failure at -35° F (run 15) and the explosion at -38° F (run 22) are comparable and are shown in figures 5(g) and 5(h), respectively. The explosion occurred at about 11 seconds after the initial movement of the propellant valve. A photograph of the equipment after this explosion is shown in figure 6. The explosion occurred in the combustion chamber near the injector head and was apparently caused by injection of fuel into an excess of oxidant. Another explosion occurred at -19° F (run 80) and separated the injector head from the combustion chamber; this explosion was not as destructive as the first. A time variation of the propellant-valve position and the pressures before the explosion (run 80), and for a run with no ignition at approximately the same conditions (run 88), are shown in figures 5(i) and 5(j), respectively. The runs at still lower temperatures (-47° and -50° F) had very slow valve opening times. Figure 5(k) shows data for the run at -47° F. In the run at -50° F, only a small quantity of fuel was injected during the run. In addition to the effect of high viscosity of this fuel at low temperatures on flow rate, observations subsequent to the run at -50° F indicated that condensed moisture from the tank atmosphere may have frozen and thus prevented normal fuel flow during the run. A temporary clogging of the fuel injectors by ice may have been responsible for the sudden rise in fuel-injection pressure for run 22 (fig. 5(h)) and dislodgement of the ice by the high pressure may have resulted in a sudden inrush of fuel that mixed well (because of high jet velocity) with acid already in the chamber and thereby produced the explosion. As previously mentioned, the apparatus was modified later (after run 32) by the installation of helium-pressure taps on the propellant lines to check for injector-hole clogging prior to operation.

Discussion. - The experiments summarized by tables III and IV show that ignition difficulties at sea level or pressure altitude of 55,000 feet may occur at temperatures below about 15° to 20° F. This temperature limit may be found by examining the component temperatures from which the mean temperatures were obtained. At lower temperatures, ignition may occur if the propellant valves open slowly. Explosions may occur if cold crude monoethylaniline is injected into cold mixed acid, but the exact conditions are uncertain.

Some insight into the behavior of crude monoethylaniline and mixed acid can be gained from these experiments. The differences in ignition results obtained at low temperatures are apparently caused by a combination of slower initial reaction rate and rate of flow of incoming propellants. When ignition occurred for runs at low temperatures and relatively slow valve opening times (for example, see runs 12 and 13 of table III and runs 17, 19, and 20 of table IV), the initial rate of flow of the propellants into the combustion chamber was apparently slow enough to allow the self-accelerating reaction to proceed without appreciable disturbance; whereas, in runs with no ignition and low temperatures with comparatively fast valve opening times (for example, runs 101 and 105 of table III and runs 28, 82, 86, 91, 93, 98, and 100 of table IV), the rapid flow of propellants into the combustion chamber was apparently sufficient to quench or to retard the progress of the reaction. This theory is further supported by the fact that, when the flow stopped, the chamber pressure usually rose momentarily (about 10 lb/sq in.) and flame was observed from the reaction of propellants remaining in the combustion chamber. In runs at normal temperature with relatively fast-opening valves, ignition occurred because the initial reaction rate was rapid enough that the flow of fresh propellants, although fast, could not retard or quench the reaction.

At low temperatures, a reduced rate of chemical reaction between fuel and oxidant has been mentioned. This reduction can be considered in terms of ignition delay of the propellants defined as the time interval between the initial contact of the fuel and oxidant and the first appearance of flame. Unpublished experiments conducted at the Lewis laboratory indicate that the ignition delay for the propellants used in these experiments increased from about 80 milliseconds at room temperature to about 220 milliseconds at -30° F. This increase in ignition delay at low temperature is apparently sufficient to cause ignition failure, which results in unreacted propellants flowing through the engine, or explosions resulting from an accumulation of propellants in favorable proportions in the combustion chamber.

Low temperatures increase the oxidant-to-fuel mixture ratio because of disproportionate changes in the kinematic viscosities of the propellants. For example, the kinematic viscosity of the fuel undergoes almost a forty-fold increase for a temperature change from 70° to -40° F as shown in table II; whereas the oxidant undergoes only a four-fold increase in viscosity for the same temperature change.

The determination of mixture ratios by measuring the quantities of propellant consumed was inaccurate, but results indicated that the oxidant-to-fuel ratio increased from normal values of about 3 to 3.5 to values as high as 5.

Ambient pressures below the vapor pressure of the propellants tends to break up the jets because of increased vaporization (reference 1); this vaporization, of course, decreases as temperature decreases. At the experimental conditions where vaporization was greatest - at the highest temperature (90° F) and the lowest pressures (2.71 in. Hg for pressure altitude of 55,000 ft; 1.72 in. Hg for one run at a pressure altitude of 64,500 ft) - successful ignition occurred for crude monoethylaniline and mixed acid. In the range of low temperatures and pressures, the reaction rate, the mixture ratio, and the vaporization all varied, and their separate effects were not isolated.

Results with Other Fuels

Fuel blend of 90-percent crude monoethylaniline and 10-percent aviation gasoline (AN-F-48b) by volume; oxidant, mixed acid. - The high viscosity of crude monoethylaniline at low temperature affects the mixture ratio and the mixing characteristics, as previously mentioned. The addition of a small quantity of aviation gasoline to the crude monoethylaniline reduced the viscosity as follows:

Temperature (°F)	Viscosity, centistokes	
	Crude monoethylaniline	90-percent crude monoethylaniline, 10-percent AN-F-48b
70	2.3	2.2
-40	90	33

The results of the starting experiments for this fuel blend are shown in table V. There were eight successful runs at temperatures of 74° to 86° F; five were at sea level and three were at a pressure altitude of approximately 55,000 feet. Only two runs were attempted at a pressure altitude of 55,000 feet and low temperatures (-17° and -28° F) and each resulted in an explosion. The propellant-valve opening times for all the runs were less than 4 seconds. Figure 7(a) shows a typical run at altitude and a temperature of 81° F and figure 7(b) shows the records for the explosion at -28° F. Figure 8 is a photograph of the apparatus after this destructive explosion.

Fuel blend of 70-percent furfuryl alcohol and 30-percent crude monoethylaniline by volume; oxidant, mixed acid. - Unpublished experiments conducted at the Lewis laboratory, using a blend of 70-percent furfuryl alcohol and 30-percent crude monoethylaniline by volume with mixed acid, showed an ignition delay at room temperature of about half that of crude monoethylaniline with mixed acid, and further, the delay interval was not increased at low temperature (-33° F). These experiments were confirmed by the rocket-starting experiments, as shown in table VI. Six runs at sea-level pressure and normal temperature indicated satisfactory starting, although one run (run 58) had a low combustion-chamber pressure; two runs at a pressure altitude of approximately 55,000 feet and temperatures of -20° and -25° F also showed satisfactory starting, although run 59 had a low combustion-chamber pressure. Valve opening times were 5 seconds or less for all runs. Figure 9 shows data for two runs with this fuel at normal temperatures. Table VI also shows one run with a fuel blend of 70-percent furfuryl alcohol and 30-percent xylene by volume at sea level and 77° F. Although starting with the furfuryl-alcohol blends was satisfactory for all conditions tested, its use introduced another problem, that of severe clogging of the combustion chamber with solid products of reaction. These products are furfuryl-alcohol polymers produced by the presence of sulfuric acid in the mixed acid. The solid products would undoubtedly cause trouble if repeated runs or long-duration runs were desired.

Turpentine and mixed acid. - Ignition-delay experiments conducted at the Lewis laboratory (not reported) showed that turpentine with mixed acid also has a low delay interval at room temperature and the delay is not increased appreciably at low temperatures. These results were confirmed by rocket-starting experiments as shown in table VII. Data for the one run made at sea level and normal temperature are shown in figure 10(a). Eighteen runs were made at a pressure altitude of approximately 55,000 feet and temperatures from -22° to -74° F, and of these runs, fifteen started and three failed to start. One of the three failures was caused by clogging of the fuel-injector holes by ice in the turpentine; the other two runs that failed were at -72° and -73° F and were believed to have been caused by partical clogging of the injector holes by deposits from two previous runs inadvertently made with turpentine containing a considerable amount of rosin and rosin-oil impurities, as indicated by its yellow color. Runs made with clear water-white gum turpentine at temperatures above -57° F showed no deposits, but some deposits on the injector face were found after runs at other temperatures in the region of -70° F. Figures 10(b) and 10(c) show data for runs at -57° and -70° F, respectively.

Two successful starts with α-pinene (main constituent of turpentine) and mixed acid at a pressure altitude of approximately

55,000 feet and temperatures of -71° and -72° F are also shown in table VII. Deposits were observed on the injector face for one of the runs, but not for the other. The experiments with turpentine and α-pinene indicate that the usefulness of these two fuels may be hampered by objectionable deposits.

Mixed butyl mercaptans and mixed acid. - A mixture of mercaptans (designated herein mixed butyl mercaptans) has been proposed as a rocket fuel by the California Research Corporation. Unreported experiments conducted at the Lewis laboratory indicate ignition delays for mixed butyl mercaptans with mixed acid to be lower than for crude monoethylaniline with mixed acid and, further, the delay interval is not appreciably affected by temperatures as low as -55° F. These results have been confirmed by rocket-starting experiments, as shown in table VIII. Three runs made at sea level and a temperature of 75°, -12°, and -31° F started satisfactorily. Twenty-one runs were made at a pressure altitude of approximately 50,000 feet at temperatures from -27° to -73° F and all started satisfactorily. The 11 successful runs at 50,000 feet and a temperature of approximately -70° F clearly demonstrate the reliability of the starting characteristics of this propellant combination. Data from one of these runs are shown in figure 11 (run 127). The engine was very clean after repeated runs with mixed butyl mercaptans and mixed acid. Mixed butyl mercaptans have a very objectionable odor and this may restrict their use.

High-speed photographs and explosion experiments. - Several supplementary experiments were conducted in an effort to determine the reasons for the explosions that occurred. In one series of experiments, high-speed motion pictures were taken of the combustion process in a modified engine in which the conventional combustion chamber and nozzle were replaced by a transparent-sided combustion chamber of equal volume and a simple convergent nozzle. The results are shown in table IX. No successful ignition was obtained for five attempted runs at sea-level pressure and temperatures from 15° to -26° F, and one attempted run at a pressure altitude of 56,000 feet and a temperature of 3° F. These results agree with those found with the commercial engine. With a blend of 70-percent furfuryl alcohol and 30-percent crude monoethylaniline by volume with mixed acid, successful ignition occurred for two runs at sea-level pressure and temperatures of -14° and -31° F and three runs at a pressure altitude of approximately 55,000 feet and temperatures of from -25° to -36° F. With crude monoethylaniline and mixed acid at about 80° F, ignition delays of 0.99 and 1.39 seconds were measured from the photographs for sea level and a pressure altitude of 42,800 feet, respectively. At low temperatures, fogging of the transparent plates made the determination of ignition delays uncertain. The motion pictures of combustion that were obtained clearly show the oxidant entering the combustion chamber ahead of the fuel, as was expected because of the propellant-valve design.

Several experiments were conducted to determine if there is any significance, on the basis of the explosive hazard, in having an excess of one propellant or the other in the combustion chamber. For this purpose, simple combustion chambers were constructed of pipe with a hole in one end of the same diameter as the rocket-engine throat. The propellants were the same as those specified for the commercial rocket: crude monoethylaniline and mixed acid. For some of the runs, the application of pressure to force one propellant into a pool of the other was applied momentarily. The results are shown in table X.

These qualitative results show that, at low temperature, three runs in which the oxidant was injected into a pool of fuel in the combustion chamber produced only sluggish reactions and burning; whereas in three out of four runs in which fuel was injected into a pool of the oxidant in the combustion chamber violent explosions occurred. These destructive explosions occurred with quantities of propellant that correspond to the quantities injected into the conventional rocket engine in about 1/2 second of full flow without combustion.

In ignition-delay experiments conducted at the Lewis laboratory, glass ampoules containing 1 milliliter of crude monoethylaniline were broken in a test tube containing 3 milliliters of mixed acid at low temperatures (ranging from -25° to -50° F) without producing violent explosions. The difference in results between these experiments and those summarized in table X indicates that the quantity of propellants, the mixture ratio, the method of mixing, and a confined volume, as well as low temperatures, are contributing factors in producing explosions. Although the results of the experiments to explain the explosions are incomplete and inconclusive, they indicate that the accumulation of mixed acid in the combustion chamber prior to the entry of the crude monoethylaniline produced the explosions at low temperatures. Additional experiments are necessary to determine more definitely the conditions that produce explosions.

SUMMARY OF RESULTS

Experiments were made to determine the starting characteristics of a commercial 220-pound-thrust rocket engine at conditions simulating high altitude, using crude monoethylaniline and mixed acid as propellants; additional experiments of a similar nature were made with the same engine and several other fuels. The propellant valve opening time was varied during the experiments. The results are summarized as follows:

1. With crude monoethylaniline and mixed acid, 12 satisfactory starts occurred at sea level and normal temperatures. Of nine runs in the temperature range of -8° to -28° F, two started and seven failed to start. The two runs that started were apparently the result of a slow inflow of propellant from a long propellant-valve opening time.

2. With crude monoethylaniline and mixed acid, satisfactory starts occurred for seven runs at a pressure altitude of 55,000 feet and temperatures from 14° to 90° F. Twenty-two runs were made at temperatures from 11° to -50° F, of which four started, sixteen failed to start, and two exploded, causing considerable damage. Three of those runs that started satisfactorily had comparatively long valve opening times.

3. With a blend of 90-percent crude monoethylaniline, 10-percent aviation gasoline (by volume), and mixed acid, five starts were made at sea-level pressure and temperatures from 74° to 86° F and three starts were made at 55,000 feet and temperatures from 81° to 84° F. Two attempted runs at a pressure altitude of 55,000 feet and temperatures of -17° and -28° F resulted in explosions.

4. With a blend of 70-percent furfuryl alcohol and 30-percent crude monoethylaniline (by volume) and mixed acid, six runs at sea-level pressure and normal temperatures showed satisfactory starting. Two runs at a pressure altitude of 55,000 feet and temperatures of -20° and -25° F also showed satisfactory starting. This propellant combination, however, left objectionable deposits in the combustion chamber.

5. With a blend of 70-percent furfuryl alcohol and 30-percent xylene (by volume) and mixed acid, a satisfactory start was made at sea-level pressure and normal temperatures, but this propellant combination also left an objectionable deposit in the combustion chamber.

6. With turpentine and mixed acid, a satisfactory start was made at sea-level pressure and normal temperatures. Of eighteen runs made at a pressure altitude of 55,000 feet and temperatures from -22° to -74° F, fifteen started and three failed to start. One of the three failures was caused by ice in the turpentine plugging the fuel-injection holes. The other two failures are believed to have been caused by partial clogging of the injection holes by deposits from impure turpentine used in two previous runs.

7. With α-pinene (main constituent of turpentine) and mixed acid, two starts were made at a pressure altitude of 55,000 feet and temperatures of about -70° F.

8. With mixed butyl mercaptans and mixed acid, all runs resulted in satisfactory starting. The runs included three at sea-level pressure and temperatures of 75°, -12°, and -31° F, and 21 runs at a pressure altitude of 50,000 feet and temperatures from -27° to -73° F.

9. In all runs at low temperatures, the possibility exists that moisture may condense and freeze in restricted passages such as the injector holes and thus cause starting failures.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

REFERENCE

1. Schmidt, Jacob M.: An Experimental Study of the Behavior of Liquid Streams Injected into a Low-Pressure Chamber. Prog. Rep. No. 4-94, Jet Prop. Lab., C.I.T., April 22, 1949. (Powerplant Lab. Proj. No. MX801 and MX527 (Air Materiel Command), and ORDCIT Proj. Contract No. W-04-200-ORD-455.)

TABLE I - ANALYSES OF CRUDE MONOETHYLANILINE AND MIXED ACID

Component	Specification	Runs 1-69[a]	Runs 70-73	Runs 79-101
Crude monoethylaniline, percent by weight				
N-ethylaniline	62-66	61.8	59.8	60.9
Aniline	24-28	25.0	25.5	26.7
N,N-diethylaniline	8-12	12.4	11.6	8.6
Water	---------	.29	.25	.21

Component	Specification	Runs 2-27	Runs 1,70, 72-77	Runs 79-118	Runs 119-149
Mixed acid, percent by weight					
Nitric acid	81-85	80.9	80.95	78.8	79.2
Sulfuric acid	14-17	16.1	15.45	17.9	17.1
Water, max.	4	3.0	3.6	3.3	3.7
Nitrosyl sulfuric acid, max.	1	----	-----	------	-------
Water + nitrosyl sulfuric acid, max.	4.5	----	-----	------	-------
Ammonium nitrate	--------	----	-----	------	0.6[b]

[a]Used as fuel blend for some runs.

[b]Analyzed as ammonia.

Note: Acid used for runs 28-69, 71, and 78 not analyzed; fuel used for runs 74-78 was mixed butyl mercaptans

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TABLE II - PHYSICAL PROPERTIES OF CRUDE MONOETHYLANILINE AND MIXED ACID

Physical properties		Crude monoethylaniline	Mixed acid
Density, g/ml		0.967 at 89.6° F .990 at 36.5° F	1.548 at 84° F 1.604 at 14° F 1.657 at -50° F
Freezing point, °F		[a]Very thick at -80° F	[b]-81
Viscosity, centistokes at	70° F	[c]2.3	1.4
	32	[c]4.8	2.0
	10	8.5	2.6
	-20	30	4.0
	-40	90	6.0
	-60	390	9.6

[a]Cloudiness appeared at -40° F.
[b]Crystal formation started at -47° F.
[c]Extrapolated value.

TABLE III - SUMMARY OF DATA FOR CRUDE

[Sea-level pressure;

Run (a)	Pressure altitude (ft)	Mean temperature of propellants and engine (°F) (b)	Ignition	Maximum combustion-chamber pressure (lb/sq in. absolute)	Time to attain maximum combustion-chamber pressure (sec)	Time for propellant valves to open 75 percent of full travel (sec)	Fuel temperature (°F)
61	0	88	Yes	250	3.0	[c]2.4	88
27	0	88	Yes	[g]260	3.9	3.5	88
26	0	87	Yes	[j]250	3.6	3.8	87
11	0	85	Yes	330	2.8	[c]3.0	[k]85
25	0	85	Yes	265	6.5	4.0	85
5	0	82	Yes	315	3.5	3.5	[k]82
6	0	82	Yes	315	3.5	3.7	[k]82
84	0	79	Yes	305	3.7	4.0	79
29	0	76	Yes	300	5.0	2.0	76
81	0	72	Yes	275	3.7	3.3	72
87	0	72	Yes	[n]315	----------	3.5	72
79	0	66	Yes	305	1.9	----------	66
13	0	[o,p]-8	Yes	300	12.2	[c]16	[k]-16
103	0	[q]-13	No	25	----------	11	-12
101	0	[q]-14	No	27	----------	7.5	-14
104	0	[q]-15	No	30	----------	8	-14
105	0	[q]-15	No	28	----------	8.5	-14
102	0	[q]-15	No	30	----------	9	-12
107	0	[q]-15	No	27	----------	11	-16
106	0	[q]-17	No	29	----------	16	-13
12	0	[o,p]-28	Yes	280	13.7	[c]26	[k]-27

[a]Runs arranged in order of decreasing temperature in tables III to VIII.

[b]Mean temperature is average of fuel, oxidant, and engine temperature. Engine temperature is average of four temperatures.

[c]Extrapolated value.

[g]Combustion-chamber pressure tap burned out before actual maximum pressure possible could be attained.

[j]Ran out of propellants before actual maximum pressure possible could be attained.

[k]Thermocouple in crude monoethylaniline tank not immersed in fuel for quantity used during run.

[n]Visual reading of combustion-pressure gage.

[o]Mean temperature taken as mean of temperatures of engine jacket and interior of fuel tank just before run.

[p]Coolant drained from low-temperature bath to level just below valves approximately 2 to 5 min before operation.

[q]Engine, valves, and tank assembly completely immersed in coolant up to and during rocket operation.

NACA

MONOETHYLANILINE AND MIXED ACID

variable temperature]

Oxidant temperature (°F)	Engine temperatures (°F)				Hydraulic fluid	Hydraulic-accumulator-orifice diam. (in.)	Engine fuel-line-orifice diam. (in.)
	Engine jacket	Fuel line	Oxidant line	Hydraulic cylinder			
88	88	88	88	88	Silicone[d]	[e]0.016	[f]0.166
88	88	88	88	88	Silicone	Standard[h]	Standard[i]
87	87	87	87	87	Silicone	Standard	Standard
85	85	85	85	85	Standard[l]	Standard	Standard
85	85	85	85	85	Silicone	Standard	Standard
82	82	82	82	82	Standard	Standard	Standard
82	82	82	82	82	Standard	Standard	Standard
79	79	79	79	79	Silicone	Special standard[m]	Standard
76	76	76	76	76	Silicone	0.018	Standard
72	72	72	72	72	Silicone	Special standard	Standard
72	72	72	72	72	Silicone	Special standard	Standard
66	66	66	66	66	Silicone	Special standard	Standard
--------	1	----	-------	---------	Standard	Standard	Standard
-16	-11	-9	-9	---------	Standard	Standard	Standard
-14	-12	-14	-12	-13	Standard	Standard	Standard
-20	-14	----	-9	-11	Standard	Standard	Standard
-15	-17	----	-15	-16	Standard	Standard	Standard
-16	-20	-16	-18	---------	Standard	Standard	Standard
-17	-13	-11	-------	-12	Modified standard[r]	Standard	Standard
-14	-23	-22	-------	-24	Modified standard	Standard	Standard
--------	-29	----	-------	---------	Standard	Standard	Standard

[d]Silicone oil with viscosity of 20 centistokes at 25° C.
[e]For this orifice diam., orifice-hole length was shortened from approximately 3/16 to 3/32 in..
[f]For this orifice diam., orifice-hole length was shortened from approximately 1/4 to 1/16 in..
[h]Standard hydraulic-system-orifice diam. is approximately 0.013 in..
[i]Standard fuel-orifice diam. is approximately 0.136 in..
[l]Standard hydraulic fluid is AN-O-366.
[m]Standard hydraulic-system-orifice used in commercial 400-lb-thrust rocket engine. Orifice diam. is approximately 0.013 in..
[r]Mixture of 75-percent standard hydraulic fluid and 25-percent S.A.E. 20 motor oil by volume.

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TABLE IV - SUMMARY OF DATA FOR CRUDE

[Altitude pressure, 55,000 ft;

Run	Pressure altitude (ft)	Mean temperature of propellants and engine (°F) (a)	Ignition	Maximum combustion-chamber pressure (lb/sq in. absolute)	Time to attain maximum combustion-chamber pressure (sec)	Time for propellant valves to open 75 percent of full travel (sec)	Fuel temperature (°F)
7	54,000	90	Yes	305	7.0	3.4	[b]90
9	56,600	88	Yes	303	7.7	3.4	[b]88
10	64,500	85	Yes	[f]171	4.2	3.7	[b]85
89	56,300	18	Yes	320	3.3	3.0	21
99	56,800	18	Yes	327	4.3	3.5	20
92	54,800	18	Yes	[i]315	----------	4.0	17
18	53,000	[j,k]14	Yes	315	7.0	7.2	[b]8
97	55,600	11	No	32	----------	4.4	15
96	55,100	9	No	32	----------	4.4	11
98	54,800	9	No	35	----------	[l]4.0	12
90	54,000	5	Yes	290	3.9	4.0	8
93	54,200	3	No	[m]23	----------	4.5	2
94	56,300	3	No	35	----------	4.5	9
17	53,700	[j,k]2	Yes	300	----------	11.5	[b]1
95	55,900	1	No	[m]50	----------	4.5	-10
91	56,200	-4	No	63	----------	4.5	1
86	54,700	-4	No	39	----------	4.6	-3
19	55,300	[k,n]-12	Yes	285	12.5	11.5	[b]-7
100	54,100	-15	No	50	----------	7.0	-13
82	54,700	-17	No	27	----------	4.5	-20
85	55,400	-17	No	25	----------	[o]8	-19
80	54,600	-19	Explosion	----------	----------	2.8	-18
88	54,800	-19	No	45	----------	4.5	-19
20	52,900	[n]-28	Yes	285	18	[l]26	[b]-18
28	55,600	-30	No	----------	----------	2.8	-30
15	54,900	[j,k]-35	No	----------	----------	[l]43	[b]-31
22	55,700	[n]-38	Explosion	----------	----------	----------[p]	[b]-30
21	54,900	[n]-47	No	----------	----------	[l]64	[b]-29
16	54,500	[j,k]-50	No[q]	----------	----------	84	[b]-36

[a]Mean temperature is average of fuel, oxidant, and engine temperature. Engine temperature is usually average of four temperatures.

[b]Thermocouple in crude monoethylaniline tank not immersed in fuel for quantity used during run.

[f]Combustion-chamber pressure tap burned out before actual maximum pressure possible could be attained.

[i]Visual reading of combustion-pressure gage.

[j]Mean temperature taken as mean of temperatures of engine jacket and interior of fuel tank just before run.

[k]Coolant drained from low-temperature bath to a level just below the valves approximately 2 to 5 min before operation.

[l]Extrapolated value.

[m]Explosion in combustion-chamber pressure tap line about 5.5 sec after valves moved. Indicated pressure maintained before and after explosion.

[n]Mean temperature taken as mean of oxidant and engine-jacket temperature.

[o]Momentary restriction in accumulator orifice increased time from probable 5.5 sec.

[p]Explosion about 11 sec after valves moved. Valve-opening rate approximately same as for run 15.

[q]All acid (16 lb) discharged. Only 1.4 lb of fuel of the 4.5-lb total discharged in over 100 sec.

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MONOETHYLANILINE AND MIXED ACID

variable temperature]

Oxidant temperature (°F)	Engine temperatures (°F)				Hydraulic fluid	Hydraulic-accumulator-orifice diam. (in.)	Engine fuel-line-orifice diam. (in.)
	Engine jacket	Fuel line	Oxidant line	Hydraulic cylinder			
90	90	90	90	90	Standard[c]	Standard[d]	Standard[e]
88	88	88	88	88	Standard	Standard	Standard
85	85	85	65	85	Standard	Standard	Standard
17	------	16	18	13	Silicone[g]	Special standard[h]	Standard
15	18	19	20	17	Silicone	Special standard	Standard
16	------	21	20	18	Silicone	Special standard	Standard
--------	19	----	-------	---------	Standard	Standard	Standard
12	------	7	5	5	Silicone	Special standard	Standard
7	------	9	8	7	Silicone	Special standard	Standard
9	7	8	8	6	Silicone	Special standard	Standard
5	------	----	5	-1	Silicone	Special standard	Standard
2	------	7	6	5	Silicone	Special standard	Standard
6	------	-6	-5	-8	Silicone	Special standard	Standard
--------	4	----	-------	---------	Standard	Standard	Standard
-3	------	9	8	6	Silicone	Special standard	Standard
-3	------	-9	-7	-15	Silicone	Special standard	Standard
-2	------	-8	-3	-11	Silicone	Special standard	Standard
-18	-5	----	-------	---------	Standard	Standard	Standard
-16	-9	-8	-9	-9	Standard	Standard	Standard
--------	------	----	-------	-14	Silicone	Special standard	Standard
-23	------	-9	-6	-13	Silicone	Special standard	Standard
-23	------	-16	-------	-15	Silicone	Special standard	Standard
-23	------	-13	-15	-16	Silicone	Special standard	Standard
-29	-28	----	-------	---------	Standard	Standard	Standard
--------	------	----	-------	---------	Silicone	0.018	Standard
--------	-39	----	-------	---------	Standard	Standard	Standard
-32	-43	----	-------	---------	Standard	Standard	Standard
-46	-49	----	-------	---------	Standard	Standard	Standard
--------	-64	----	-------	---------	Standard	Standard	Standard

[c]Standard hydraulic fluid is AN-0-366.
[d]Standard hydraulic-system-orifice diam. is approximately 0.013 in.
[e]Standard fuel-orifice diam. is approximately 0.136 in.
[g]Silicone oil with viscosity of 20 centistokes at 25° C.
[h]Standard hydraulic-system-orifice used in commercial 400-lb-thrust rocket engine. Orifice diam. is approximately 0.013 in.

TABLE V - SUMMARY OF DATA FOR 90-PERCENT (BY VOLUME) CRUDE MONOETHYLANILINE AND 10-PERCENT (BY VOLUME) AVIATION GASOLINE (AN-F-48b, AMENDMENT-1) AND MIXED ACID

[Sea-level pressure; altitude pressure, 55,000 ft; variable temperature]

Run	Pressure altitude (ft)	Mean temperature of propellants and engine (°F) (a)	Ignition	Maximum combustion-chamber pressure (lb/sq in. absolute)	Time to attain maximum combustion-chamber pressure (sec)	Time for propellant valves to open 75 percent of full travel (sec)	Fuel temperature (°F)	Oxidant temperature (°F)	Engine temperatures (°F)				Hydraulic fluid	Hydraulic-accumulator-orifice diam. (in.)	Engine fuel-line-orifice diam. (in.)
									Engine jacket	Fuel line	Oxidant line	Hydraulic cylinder			
35	0	86	Yes	320	2.0	2.1	86	86	86	86	86	86	Silicone[b]	Standard[c]	Standard[d]
36	54,800	84	Yes	320	2.0	----------	84	84	84	84	84	84	Silicone	[e]0.016	[f]0.166
33	0	84	Yes	325	2.4	----------	84	84	84	84	84	84	Silicone	Standard	Standard
34	0	83	Yes	325	2.0	2.3	83	83	83	83	83	83	Silicone	Standard	Standard
37	55,600	83	Yes	320	2.4	2.3	83	83	83	83	83	83	Silicone	0.016	0.166
38	55,500	81	Yes	312	2.1	2.4	81	81	81	81	81	81	Silicone	.016	.166
30	0	75	Yes	300	4.0	1.7	75	75	75	75	75	75	Silicone	.018	Standard
32	0	74	Yes	323	3.7	----------	74	74	74	74	74	74	Standard[g]	Standard	Standard
39	54,600	-17	Explosion	----------	----------	----------	-18	-17	------	-17	-16	-16	Silicone	0.016	0.166
31	54,200	-28	Explosion	----------	----------	----------	-32	-23	-28	-32	-31	-26	Silicone	.018	Standard

[a]Mean temperature is average of fuel, oxidant, and engine temperatures. Engine temperature is average of four temperatures.
[b]Silicone oil with viscosity of 20 centistokes at 25° C.
[c]Standard hydraulic-system-orifice diam. is approximately 0.013 in.
[d]Standard fuel-orifice diam. is approximately 0.136 in.
[e]For this orifice diam., orifice-hole length was shortened from approximately 3/16 to 3/32 in.
[f]For this orifice diam., orifice-hole length was shortened from approximately 1/4 to 1/16 in.
[g]Standard hydraulic fluid is AN-O-366.

TABLE VI - SUMMARY OF DATA FOR 70-PERCENT (BY VOLUME) FURFURYL ALCOHOL AND 30-PERCENT (BY VOLUME) CRUDE MONOETHYLANILINE WITH MIXED ACID AND FOR 70-PERCENT (BY VOLUME) FURFURYL ALCOHOL AND 30-PERCENT (BY VOLUME) XYLENE WITH MIXED ACID

[Sea-level pressure; altitude pressure, 55,000 ft; variable temperature]

Run	Pressure altitude (ft)	Mean temperature of propellants and engine (°F) (a)	Ignition	Maximum combustion-chamber pressure (lb/sq in. absolute)	Time to attain maximum combustion-chamber pressure (sec)	Time for propellant valves to open 75 percent of full travel (sec)	Fuel temperature (°F)	Oxidant temperature (°F)	Engine temperatures (°F)				Hydraulic fluid	Hydraulic-accumulator-orifice diam. (in.)	Engine fuel-line-orifice diam. (in.)
									Engine jacket	Fuel line	Oxidant line	Hydraulic cylinder			
70-percent (by volume) furfuryl alcohol, 30-percent (by volume) crude monoethylaniline with mixed acid															
62	0	84	Yes	250	2.5	2.3	84	84	84	84	84	84	Silicone[b]	[c]0.016	[d]0.166
65	0	84	Yes	255	3.0	2.3	84	84	84	84	84	84	Silicone	.016	Standard[e]
64	0	83	Yes	290	1.2	.4	83	83	83	83	83	83	None	None	Standard
63	0	81	Yes	270	1.4	.4	81	81	81	81	81	81	None	None	0.166
60	0	80	Yes	215	2.5	2.2	80	80	80	80	80	80	Silicone	.016	.166
58	0	73	Yes	165	1.6	2.2	73	73	73	73	73	73	Silicone	.016	.166
59	54,700	-20	Yes	[f]165	----------	3.2	-21	-17	-20	-25	-24	-25	Silicone	.016	.166
66	55,000	-25	Yes	250	[g]4.5	----------	-22	-24	-18	-35	-28	-37	None	None	Standard
70-percent (by volume) furfuryl alcohol, 30-percent (by volume) xylene with mixed acid															
67	0	77	Yes	248	1.5	0.4	77	77	77	77	77	77	None	None	Standard

[a]Mean temperature is average of fuel, oxidant, and engine temperatures. Engine temperature is average of four temperatures.
[b]Silicone oil with viscosity of 20 centistokes at 25° C.
[c]For this orifice diam., orifice-hole length was shortened from approximately 3/16 to 3/32 in.
[d]For this orifice diam., orifice-hole length was shortened from approximately 1/4 to 1/16 in.
[e]Standard fuel-orifice diam. is approximately 0.136 in.
[f]Visual reading of combustion-pressure gage.
[g]Combustion pressure rose to 215 lb/sq in. in 0.6 sec ; climbed slowly to 250 lb/sq in. by 4.5 sec.

TABLE VII - SUMMARY OF DATA FOR GUM TURPENTINE WITH

[Sea-level pressure; altitude pressure,

Run	Pressure altitude (ft)	Mean temperature of propellants and engine (°F) (a)	Ignition	Maximum combustion-chamber pressure (lb/sq in. absolute)	Time to attain maximum combustion-chamber pressure (sec)	Time for propellant valves to open 75 percent of full travel (sec)	Fuel temperature (°F)
							Gum turpentine
74	0	80	Yes	302	1.7	0.4	80
75	56,300	-22	Yes	315	-----------	.4	-15
76	55,300	-44	No[c]	-----------	-----------	.4	-39
77	54,700	-52	Yes	[c]55	-----------	.4	-51
78	55,300	-57	Yes	300	1.3	.3	-57
148	55,400	-57	Yes	300	1.3	.3	-60
143	57,800	-70	Yes	315	1.7	.3	-70
133	47,200	-70	Yes	320	8.6	7.5	-73
138	54,900	-70	Yes	319	7.3	7.6	-69
140	53,700	-70	Yes	318	12.7	6.0	-72
149	57,200	-71	Yes	305	2.4	.3	-73
134	49,600	-71	Yes	320	7.3	9.0	-68
145	55,100	-72	Yes	273	.4	.3	-74
147	55,600	-72	Yes	300	2.3	.3	-73
135	54,500	-72	No	26	-----------	8.8	-71
146	57,200	-73	Yes	328	1.4	.3	-73
136	55,600	-73	No	23	-----------	8.4	-73
139	55,200	-74	Yes	320	6.5	7.2	-74
141	60,200	-74	Yes	321	7.1	[f]7.4	-70
							α-pinene with
142	55,400	-71	Yes	325	8.7	9.0	-68
144	57,500	-72	Yes	318	1.9	.3	-74

[a]Mean temperature is average of fuel, oxidant, and engine temperature. Engine temperature is average of four temperatures.
[b]Ice jammed fuel-injector holes.
[f]Extrapolated value.

MIXED ACID AND FOR α-PINENE WITH MIXED ACID

55,000 ft; variable temperature]

Oxidant temperature (°F)	Engine temperatures (°F)				Hydraulic fluid	Hydraulic-accumulator-orifice diam. (in.)	Engine fuel-line-orifice diam. (in.)
	Engine jacket	Fuel line	Oxidant line	Hydraulic cylinder			
with mixed acid							
80	80	80	80	80	None	None	Standard[b]
-30	-12	-27	-21	-23	None	None	Standard
-37	-46	-60	-58	-60	None	None	Standard
-47	-63	-62	-60	-62	None	None	Standard
-42	-65	-74	-74	-74	None	None	Standard
-55	-57	-57	-56	-60	None	None	Standard
-68	-73	-73	-69	-73	None	None	Standard
-70	-67	----	-68	-65	Silicone[d]	Special standard[e]	Standard
-70	-71	-71	-74	-71	Silicone	Special standard	Standard
-74	-65	-57	-71	-65	Silicone	Special standard	Standard
-71	-67	-73	-66	-74	None	None	Standard
-70	-77	-76	-79	-76	Silicone	Special standard	Standard
-73	-70	-71	-70	-73	None	None	Standard
-70	-73	-74	-70	-75	None	None	Standard
-72	-74	-71	-75	-73	Silicone	Special standard	Standard
-74	-73	-73	-73	-75	None	None	Standard
-72	-79	-77	-74	-70	Silicone	Special standard	Standard
-75	-73	-78	-75	-73	Silicone	Special standard	Standard
-72	-81	-81	-79	-77	Silicone	Special standard	Standard
mixed acid							
-70	-75	-75	-76	-75	Silicone	Special standard	Standard
-73	-69	-69	-69	-70	None	None	Standard

[b]Standard fuel-orifice diam. is approximately 0.136 in.
[d]Silicone oil with viscosity of 20 centistokes at 25° C.
[e]Standard hydraulic-system-orifice used in commercial 400-lb-thrust rocket engine. Orifice diam. is approximately 0.013 in.

TABLE VIII - SUMMARY OF DATA FOR MIXED

[Sea-level pressure; altitude pressure,

Run	Pressure altitude (ft)	Mean temperature of propellants and engine (°F) (a)	Ignition	Maximum combustion-chamber pressure (lb/sq in. absolute)	Time to attain maximum combustion-chamber pressure (sec)	Time for propellant valves to open 75 percent of full travel (sec)	Fuel temperature (°F)
108	0	75	Yes	318	3.4	3.3	75
109	0	-12	Yes	317	4.2	4.5	-15
110	0	-31	Yes	313	9.0	8.2	-30
112	49,000	-27	Yes	320	5.5	5.7	-24
111	47,900	-28	Yes	320	5.5	5.1	-33
114	48,400	-29	Yes	315	7.0	6.7	-31
113	48,400	-31	Yes	320	7.5	7.0	-32
116	48,400	-38	Yes	320	7.7	6.9	-39
117	48,400	-39	Yes	325	9.5	8.8	-41
115	48,400	-40	Yes	320	11.0	10.0	-41
118	48,400	-41	Yes	335	10.7	11.0	-41
119	50,400	-42	Yes	295	12.4	11.0	-41
120	48,100	-56	Yes	285	16.5	21.8	-61
121	48,400	-68	Yes	285	10.5	9.9	-68
130	48,500	-69	Yes	315	8.3	7.8	-70
122	49,500	-70	Yes	265	11.9	9.2	-70
126	48,400	-70	Yes	320	7.9	6.9	-71
125	50,300	-71	Yes	330	10.3	9.3	-71
129	50,100	-71	Yes	315	9.3	9.3	-71
128	48,700	-71	Yes	325	9.1	8.9	-71
131	48,400	-71	Yes	315	11.5	9.8	-71
124	48,400	-72	Yes	330	8.7	8.4	-73
127	48,400	-73	Yes	320	9.9	9.3	-70
132	52,600	-73	Yes	318	9.7	9.7	-74

[a]Mean temperature is average of fuel, oxidant, and engine temperatures. Engine temperature is average of four temperatures.

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BUTYL MERCAPTANS AND MIXED ACID

50,000 ft; variable temperature]

Oxidant temperature (°F)	Engine temperatures (°F)				Hydraulic fluid	Hydraulic-accumulator-orifice diam. (in.)	Engine fuel-line-orifice diam. (in.)
	Engine jacket	Fuel line	Oxidant line	Hydraulic cylinder			
75	75	75	75	75	Modified standard[b]	Standard[c]	Standard[d]
-14	-6	-4	-8	-6	Standard[e]	Special standard[f]	Standard
-28	-34	-33	-34	-36	Standard	Special standard	Standard
-29	-26	-31	-29	-26	Standard	Special standard	Standard
-25	-28	-25	-28	-26	Standard	Special standard	Standard
-30	-27	----	-30	-25	Standard	Special standard	Standard
-29	-32	-31	-33	-31	Standard	Special standard	Standard
-42	-34	-33	-34	-26	Standard	Special standard	Standard
-40	-39	-37	-37	-29	Standard	Special standard	Standard
-42	-34	-37	-42	-38	Standard	Special standard	Standard
-41	-40	-43	-46	-45	Standard	Special standard	Standard
-42	-41	-44	-47	-42	Standard	Special standard	Standard
-50	-54	-58	-------	-59	Standard	Special standard	Standard
-72	-65	-63	-65	-64	Silicone[g]	Special standard	Standard
-69	-67	-69	-66	-66	Silicone	Special standard	Standard
-68	-73	-70	-78	-70	Silicone	Special standard	Standard
-70	-72	-68	-72	-68	Silicone	Special standard	Standard
-69	-74	-72	-77	-74	Silicone	Special standard	Standard
-69	-73	-71	-74	-73	Silicone	Special standard	Standard
-70	-75	-71	-75	-73	Silicone	Special standard	Standard
-68	-73	-71	-75	-73	Silicone	Special standard	Standard
-70	-73	-70	-73	-70	Silicone	Special standard	Standard
-76	-74	-74	-77	-74	Silicone	Special standard	Standard
-71	-77	-77	-71	-77	Silicone	Special standard	Standard

[b]Mixture of 75-percent standard hydraulic fluid and 25-percent S.A.E. 20 motor oil by volume.

[c]Standard hydraulic-system-orifice diam. is approximately 0.013 in.

[d]Standard fuel-orifice diam. is approximately 0.136 in.

[e]Standard hydraulic fluid is AN-O-366.

[f]Standard hydraulic-system-orifice used in commercial 400-lb-thrust rocket engine. Orifice diam. is approximately 0.013 in.

[g]Silicone oil with viscosity of 20 centistokes at 25°

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TABLE IX - SUMMARY OF DATA FOR TRANSPARENT-SIDED ROCKET

Run	Pressure altitude (ft)	Mean temperature of propellants and engine (°F) (a)	Ignition
Crude monoethylaniline with mixed acid			
40	0	81	Yes
49	0	86	Yes
46	0	15	No
50	0	2	No
48	0	-7	No
43	0	-8	No
42	0	-26	No
41	42,800	83	Yes
45	56,200	3	No
70-percent (by volume) furfuryl alcohol and 30-percent (by volume) crude monoethylaniline with mixed acid			
51	0	-14	Yes
52	0	-31	Yes
55	55,400	-25	Yes
57	54,700	-34	Yes
56	49,800	-36	Yes

[a]Mean temperature is average of fuel, oxidant, and engine temperatures. Engine temperatures is usually average of engine-jacket, fuel-line, oxidant-line, and hydraulic-cylinder temperatures.

TABLE X - SUMMARY OF EXPERIMENTS ON EXPLOSIONS

Temperature (°F)		Quantity (ml)		Observations
Mixed acid	Monoethylaniline	Mixed acid	Monoethylaniline	
Mixed acid injected into crude monoethylaniline				
80	80	200	200	Rocket horizontal; ignited readily and burned
-40	-40	200	200	Rocket horizontal; surrounded by dry ice; sparks and heavy smoke; charred deposits
-35	-29	200	400	Successive applications of helium pressure caused sluggish burning without incident
-24	-45	200	400	Acid-injector line below surface of aniline for this run only. Slight explosion occurred at interface of monoethylaniline and acid; blew 1/4-in. tube apart
-24	-49	200	400	Sluggish burning
Crude monoethylaniline injected into mixed acid				
80	80	150	50	Ignition and normal burning
80	80	400	200	Ignition and normal burning
-27	-38	400	25	No flame or explosion. Helium-pressure valve stuck and helium continually flowed for over 1 min
-53	-27	400	200	First pressure application - short duration flame Second pressure application - violent explosion
-44	-58	400	200	First pressure application - nothing happened Second pressure application - nothing happened Third pressure application - puff of white smoke Fourth pressure application - burning for about 1 min Fifth pressure application - violent explosion
-76	-76	150	50	Violent explosion

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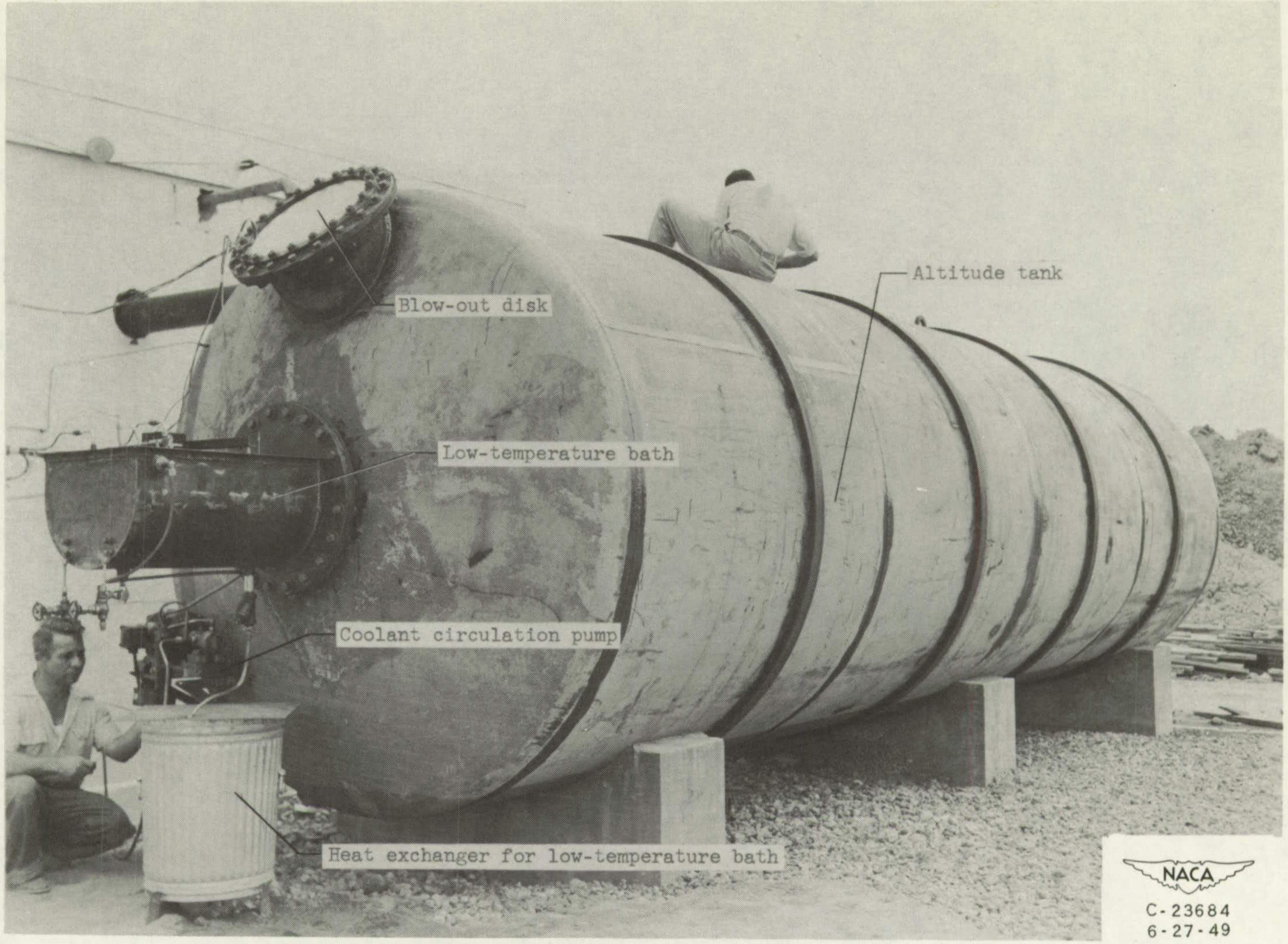

(a) Altitude tank and low-temperature bath for simulating high-altitude conditions.

Figure 1. - Altitude tank and auxiliary equipment.

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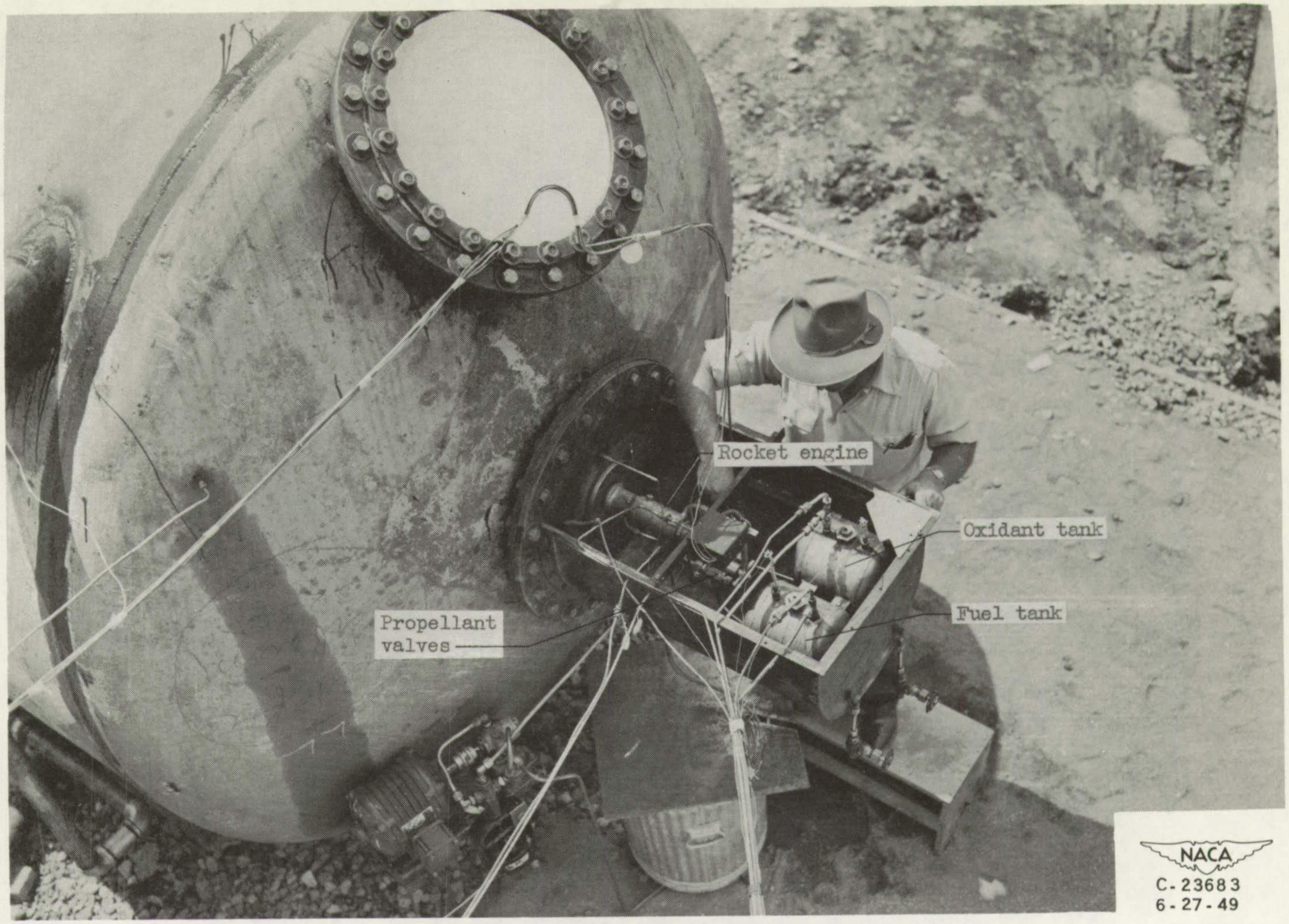

(b) Rocket engine, propellant valves, and propellant tanks mounted in low-temperature bath with engine attached to exhaust into altitude tank.

Figure 1. Continued. Altitude tank and auxiliary equipment.

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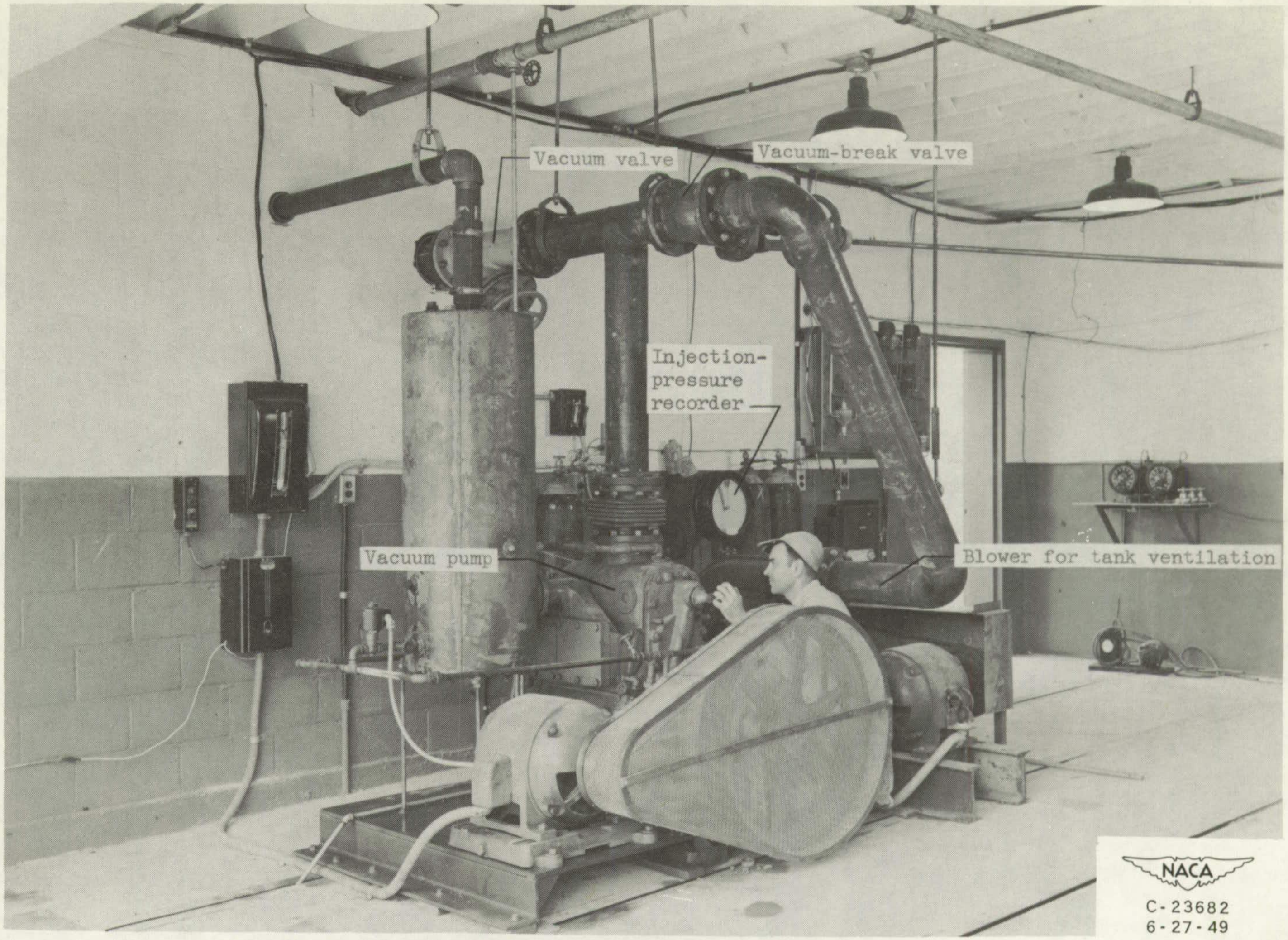

(c) Vacuum pump and tank-ventilation equipment.

Figure 1. - Concluded. Altitude tank and auxiliary equipment.

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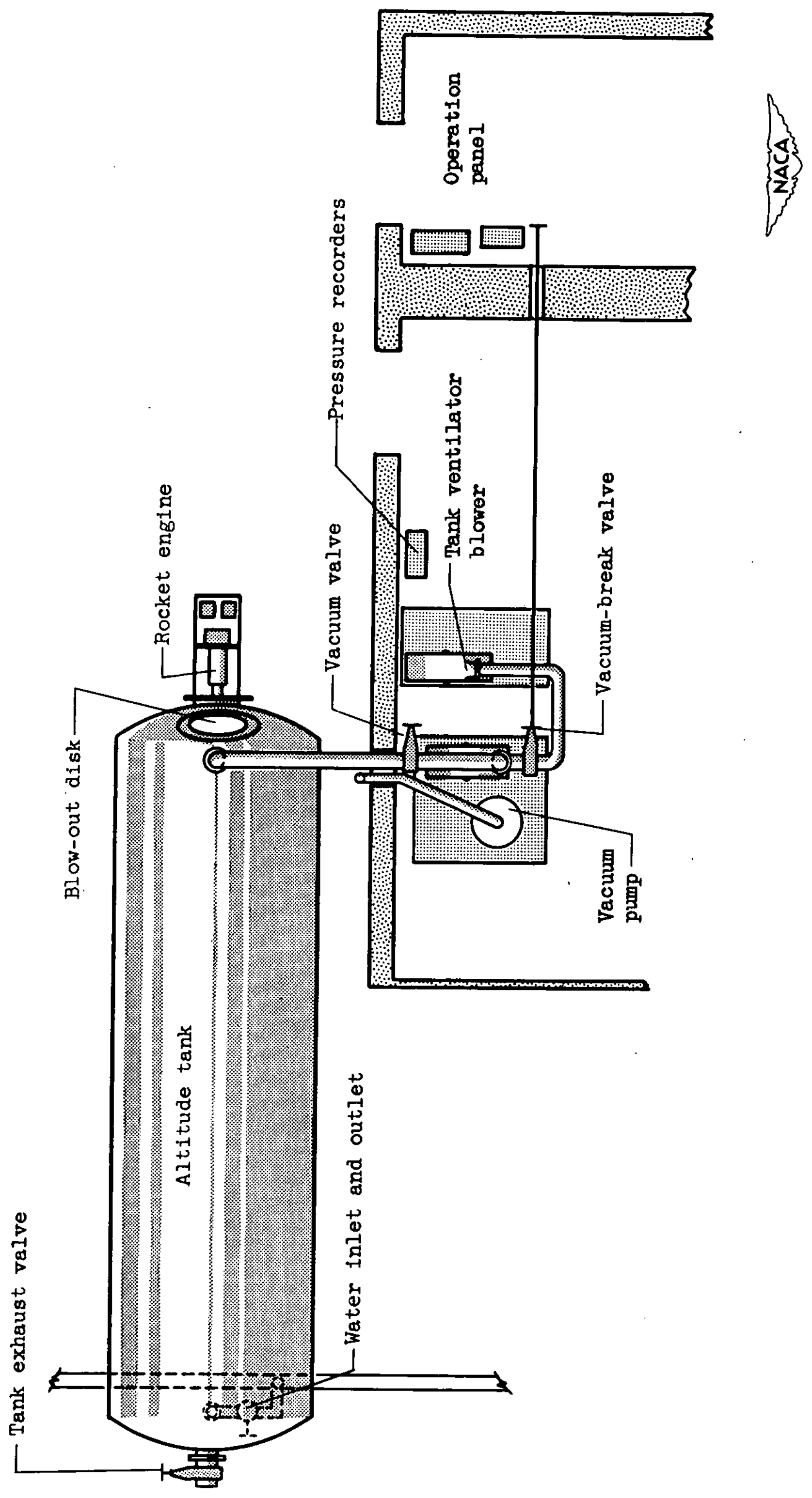


Figure 2. - Layout of altitude tank and auxiliary equipment.

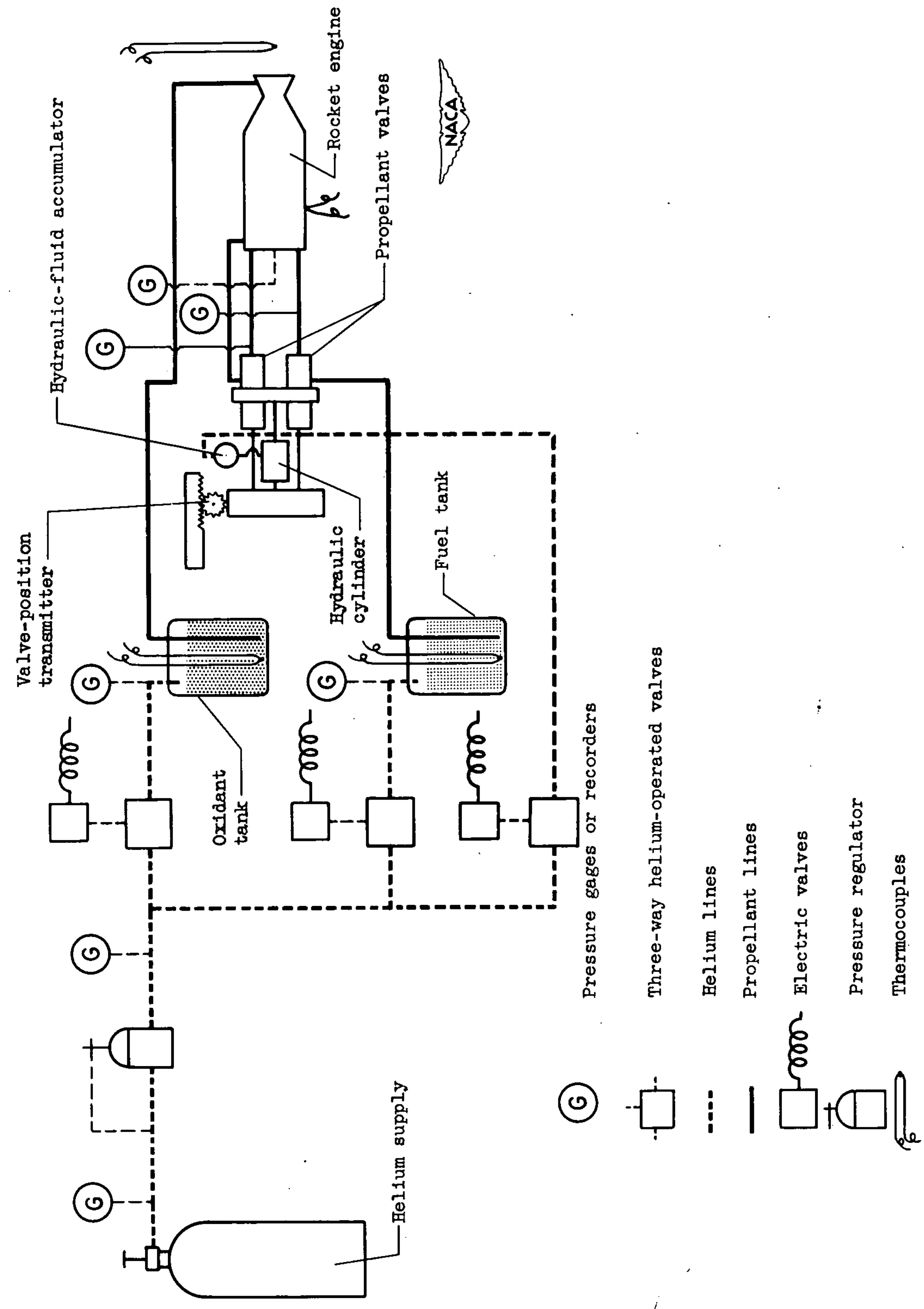
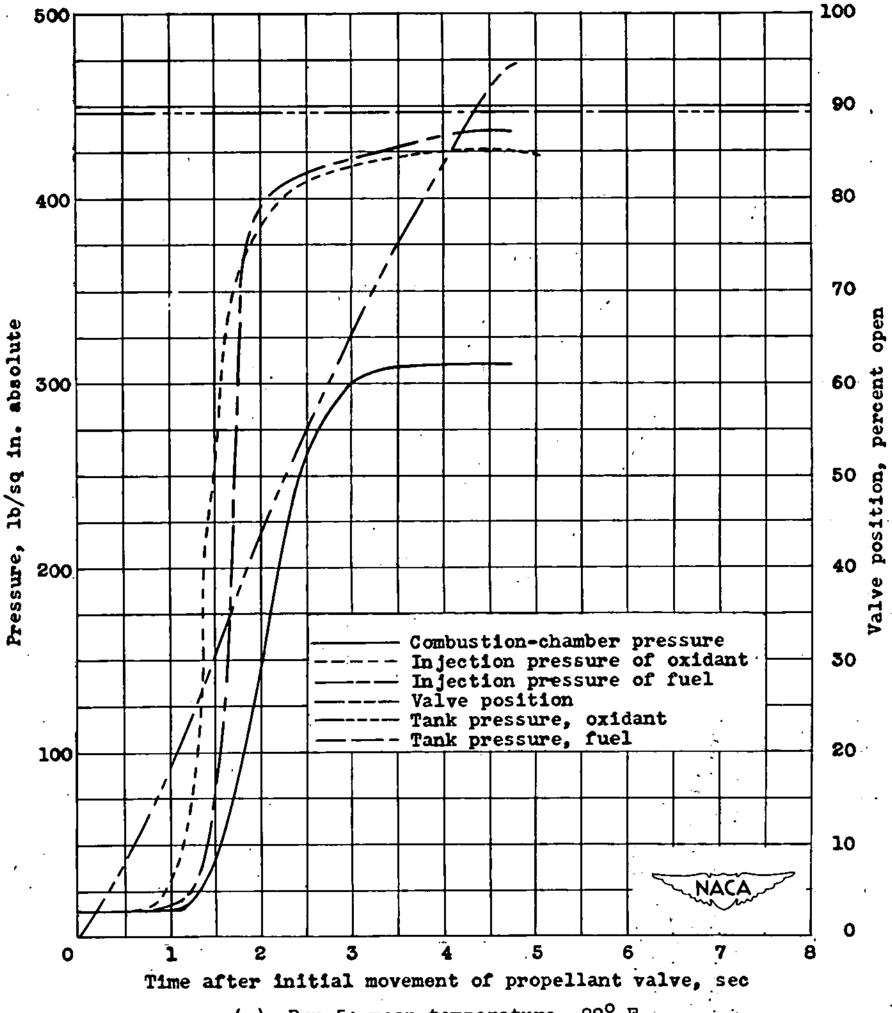
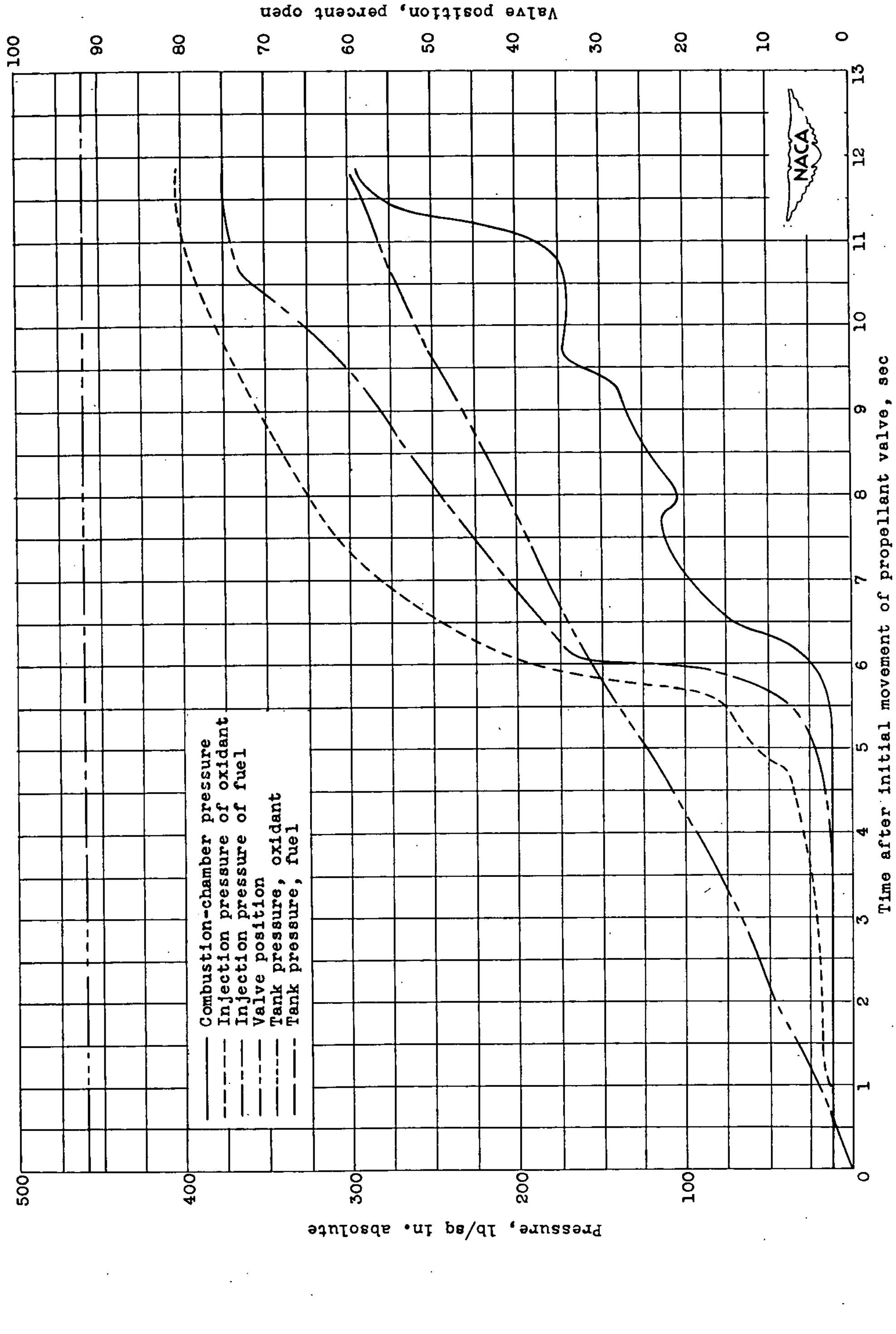


Figure 3. - Diagrammatic sketch of rocket engine and flow system.



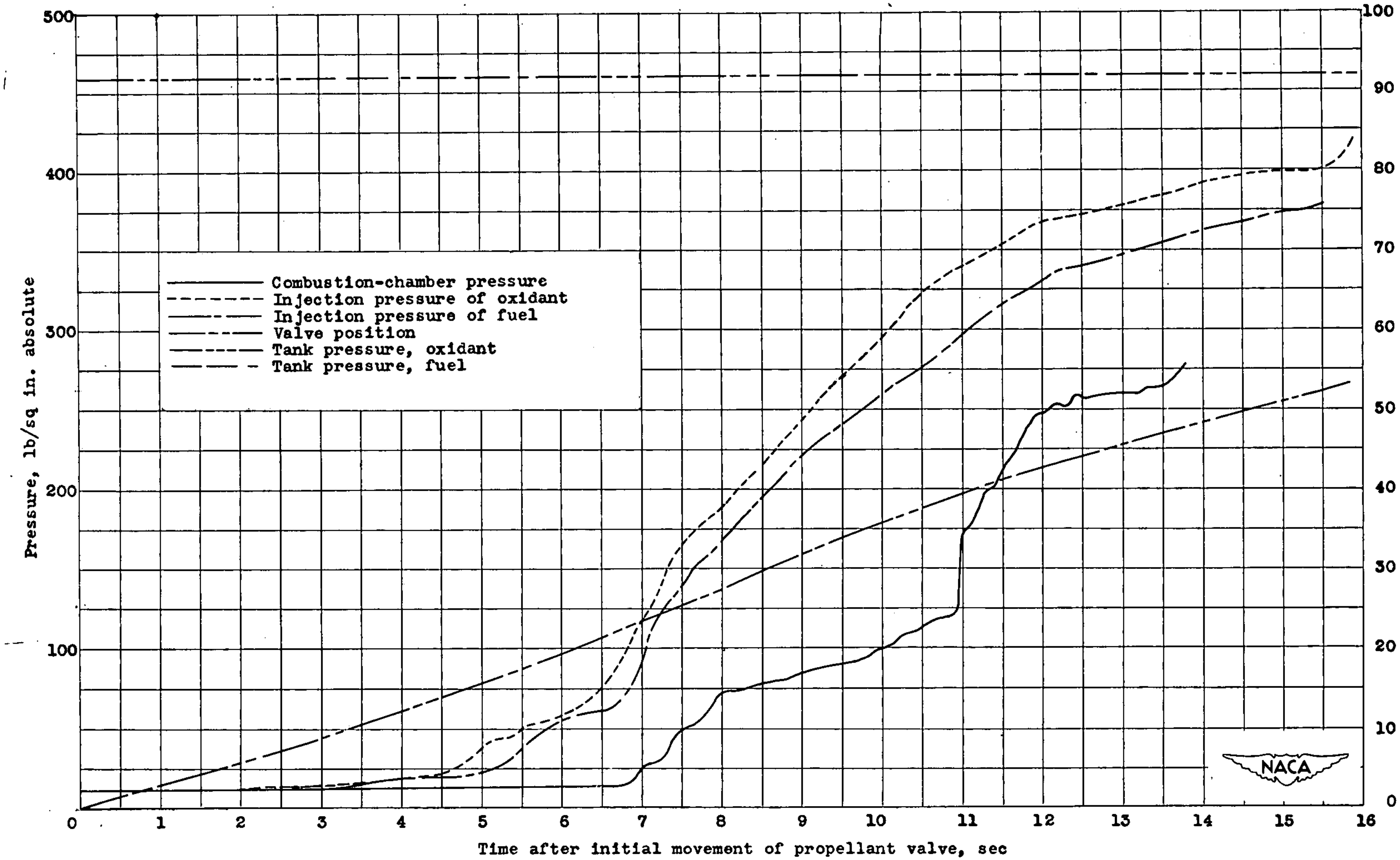
(a) Run 5; mean temperature, 82° F.

Figure 4. - Rocket starting at sea-level pressure with crude monoethylaniline and mixed acid.



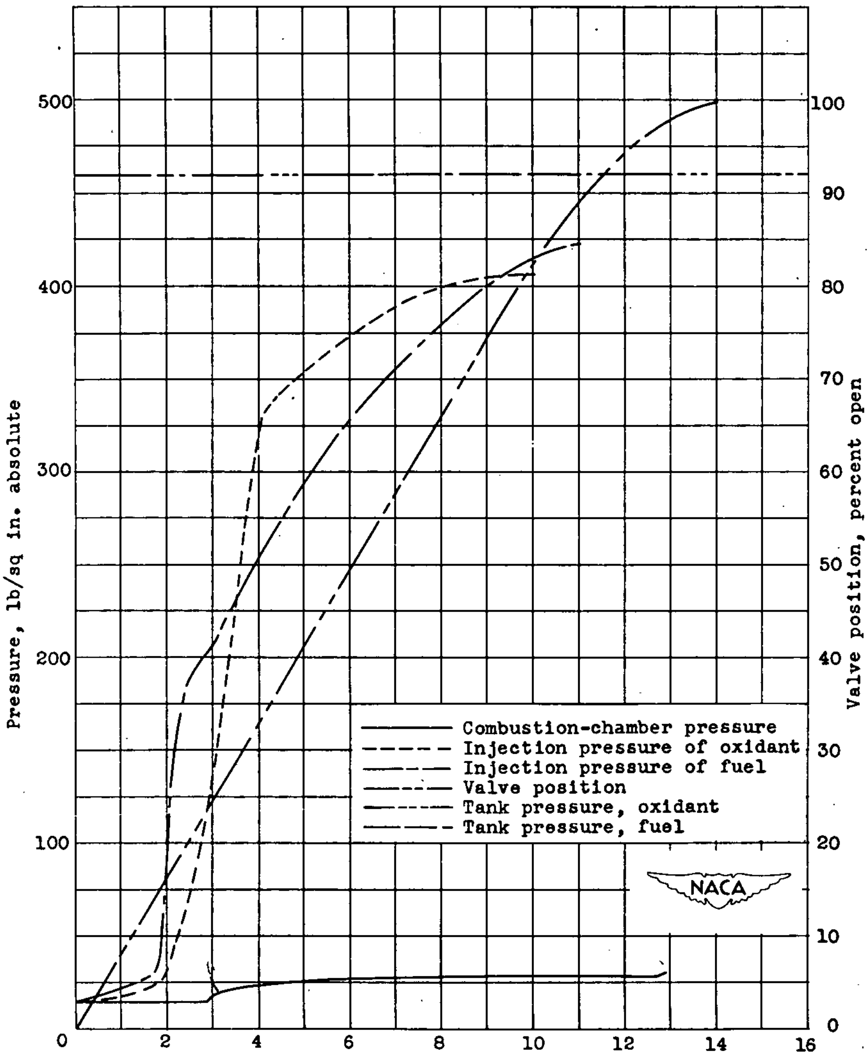
(b) Run 13; mean temperature, -8° F.

Figure 4. - Continued. Rocket starting at sea-level pressure with crude monoethylaniline and mixed acid.



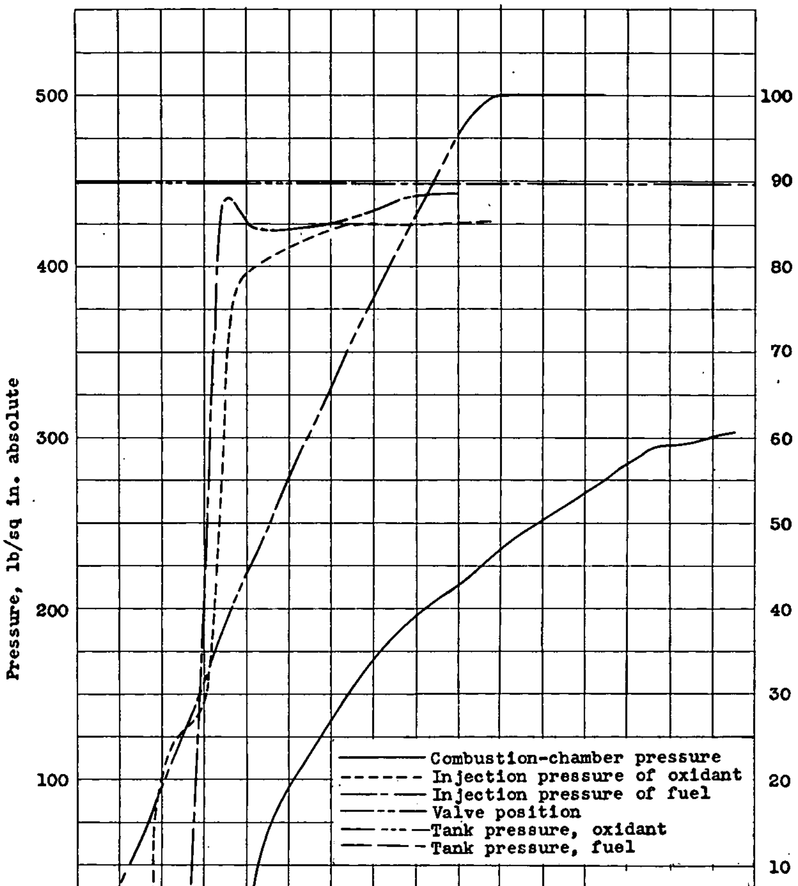
(c) Run 12; mean temperature, -28° F.

Figure 4. - Continued. Rocket starting at sea-level pressure with crude monoethylaniline and mixed acid.



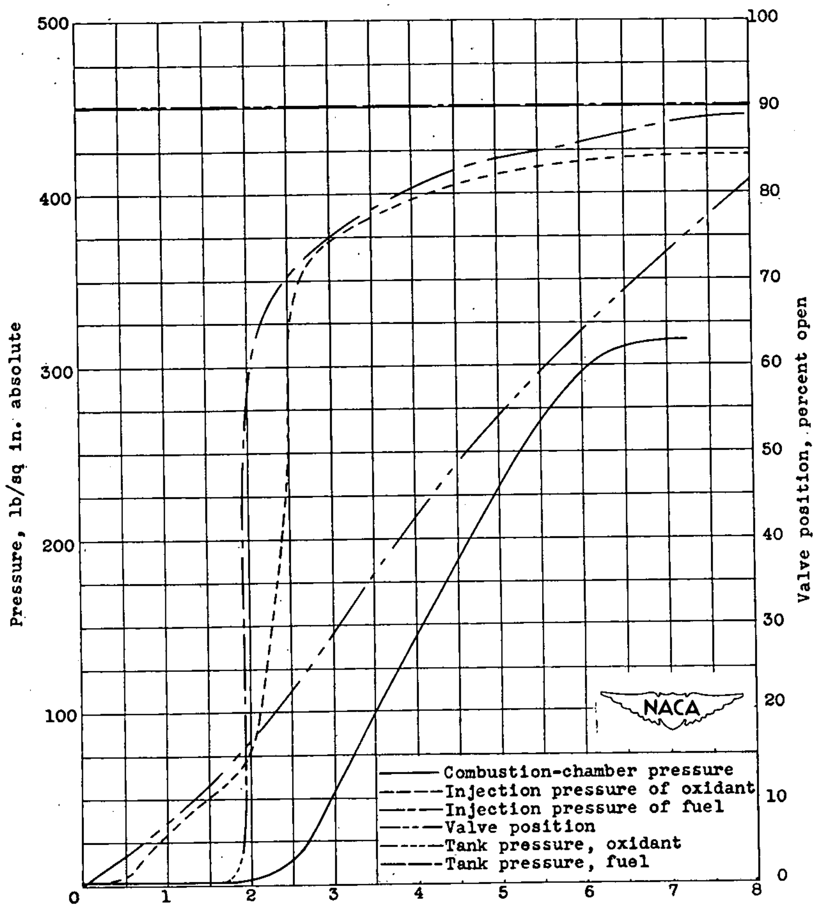
(d) Run 102; mean temperature, -15° F.

Figure 4. - Concluded. Rocket starting at sea-level pressure with crude monoethylaniline and mixed acid.



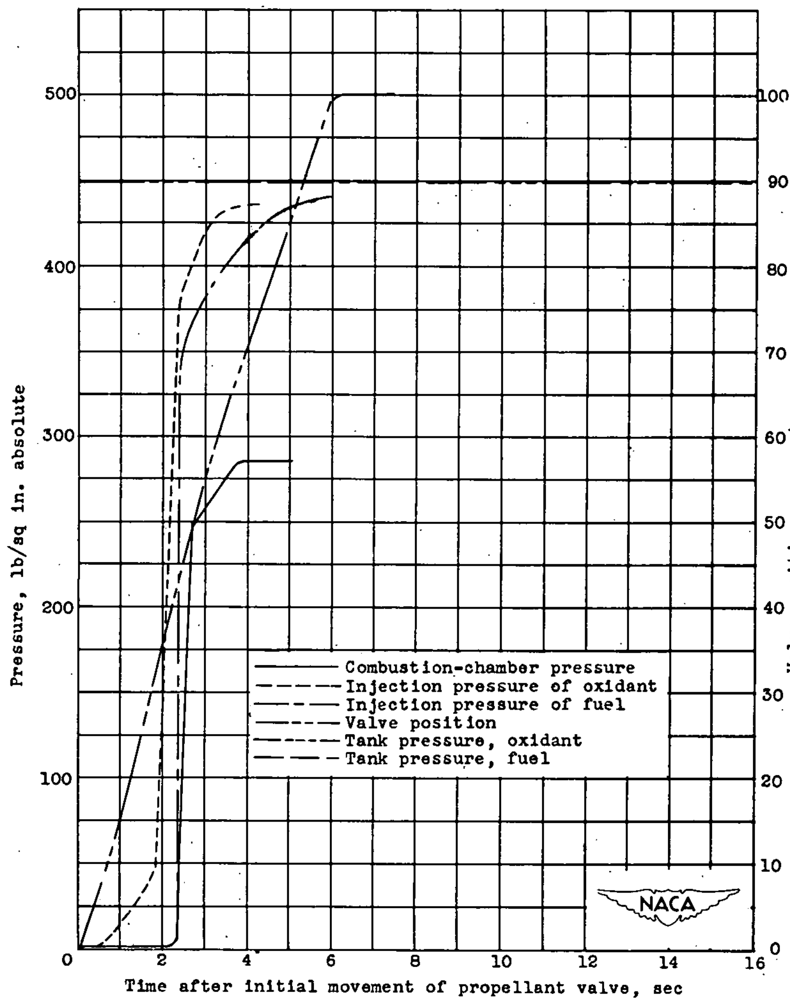
(a) Run 9; mean temperature, 88° F.

Figure 5. - Rocket starting at pressure altitude of 55,000 feet with crude monoethylaniline and mixed acid.



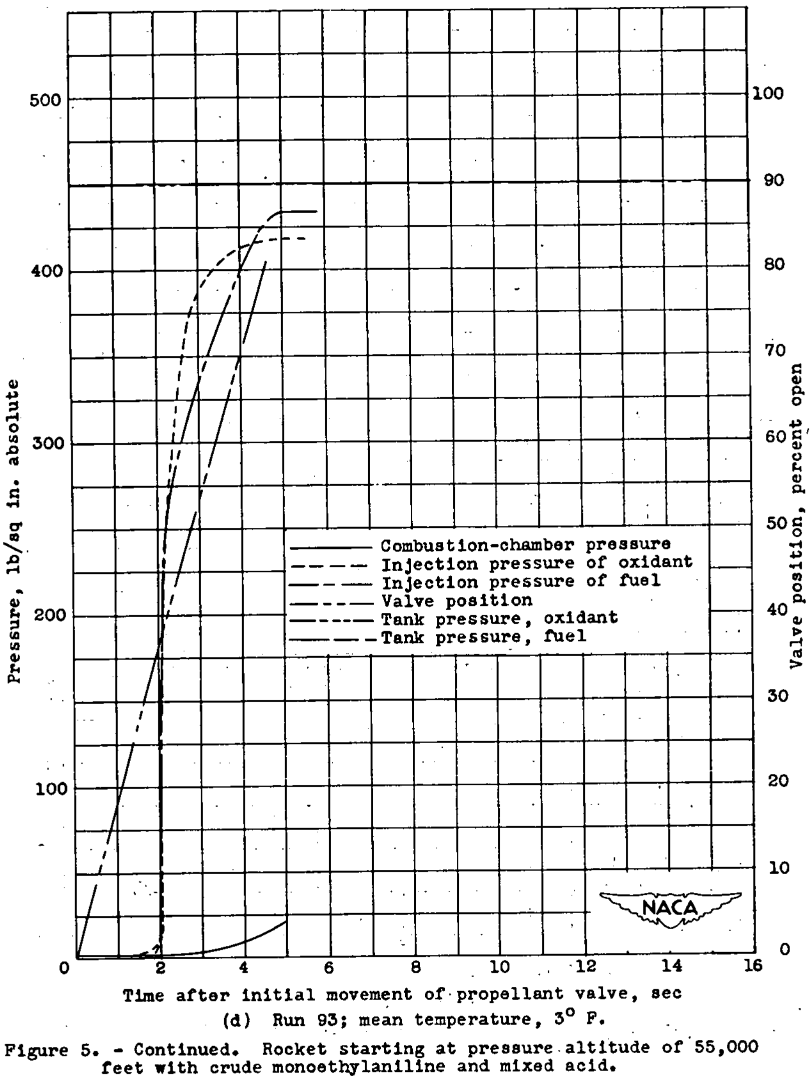
(b) Run 18; mean temperature, 14° F.

Figure 5. - Continued. Rocket starting at pressure altitude of 55,000 feet with crude monoethylaniline and mixed acid.



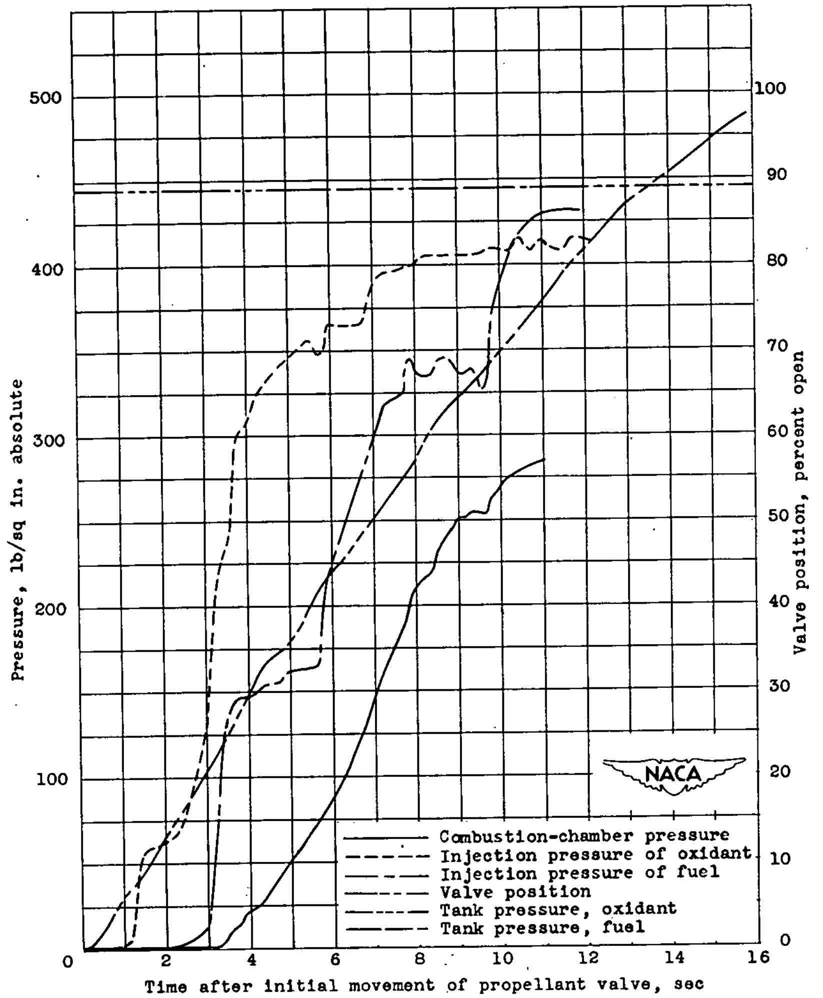
(c) Run 90; mean temperature, 5° F.

Figure 5. - Continued. Rocket starting at pressure altitude of 55,000 feet with crude monoethylaniline and mixed acid.



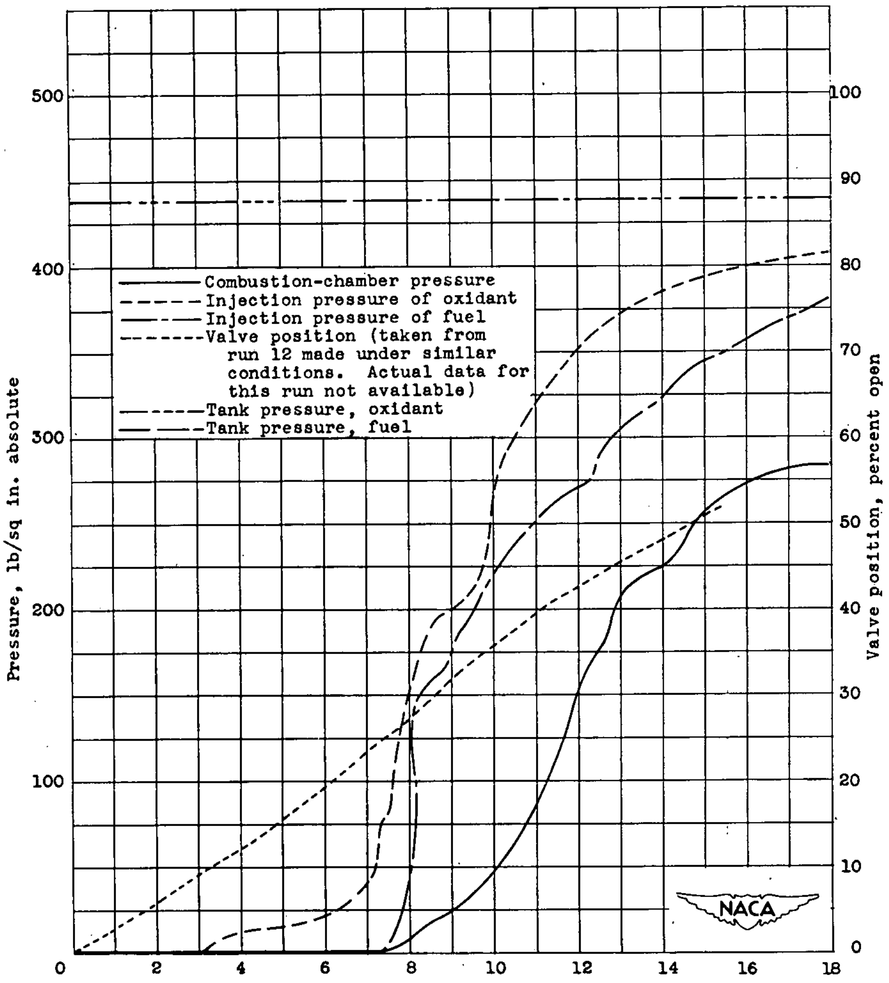
(d) Run 93; mean temperature, 3° F.

Figure 5. - Continued. Rocket starting at pressure altitude of 55,000 feet with crude monoethylaniline and mixed acid.



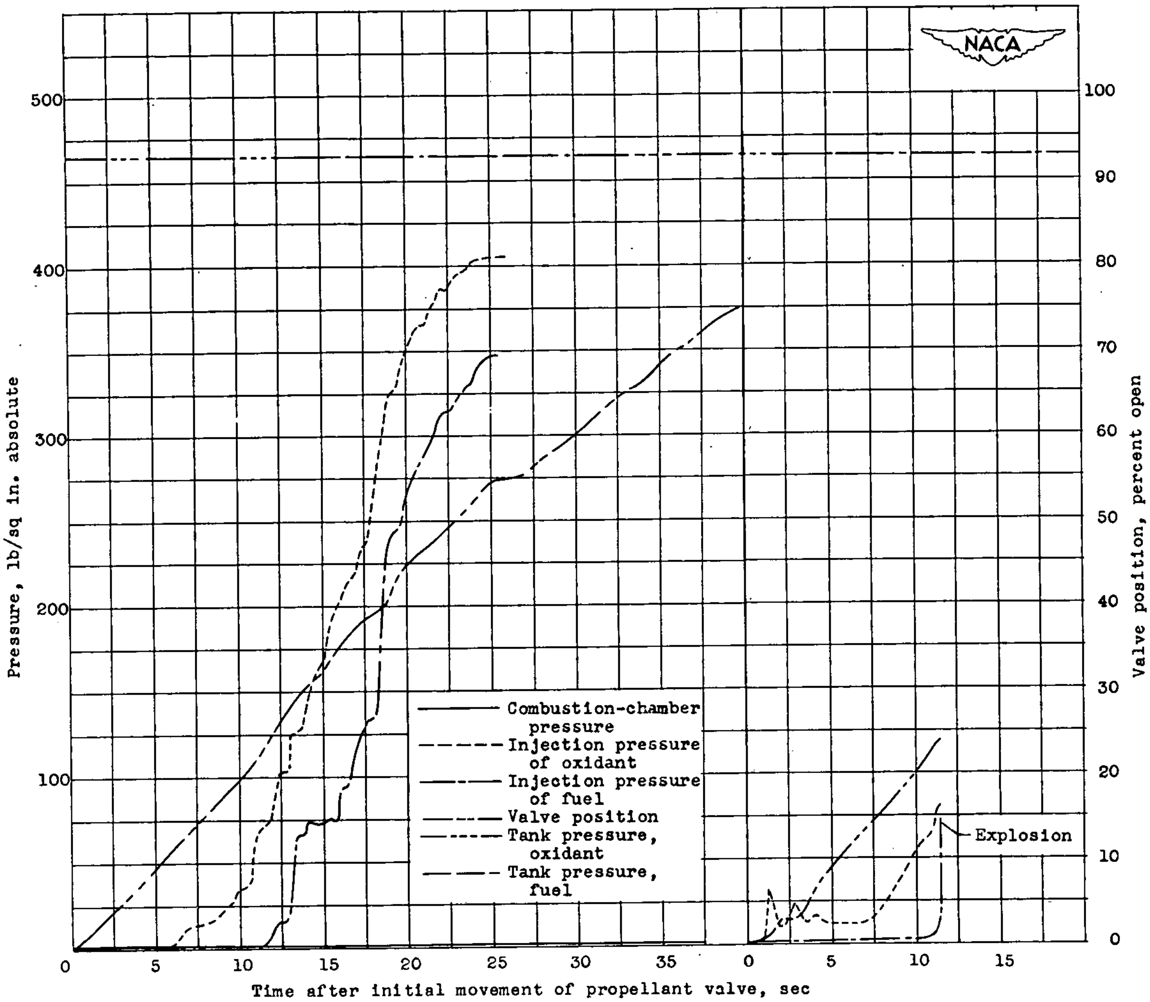
(e) Run 19; mean temperature, -12° F.

Figure 5. - Continued. Rocket starting at pressure altitude of 55,000 feet with crude monoethylaniline and mixed acid.



(f) Run 20; mean temperature, -28° F.

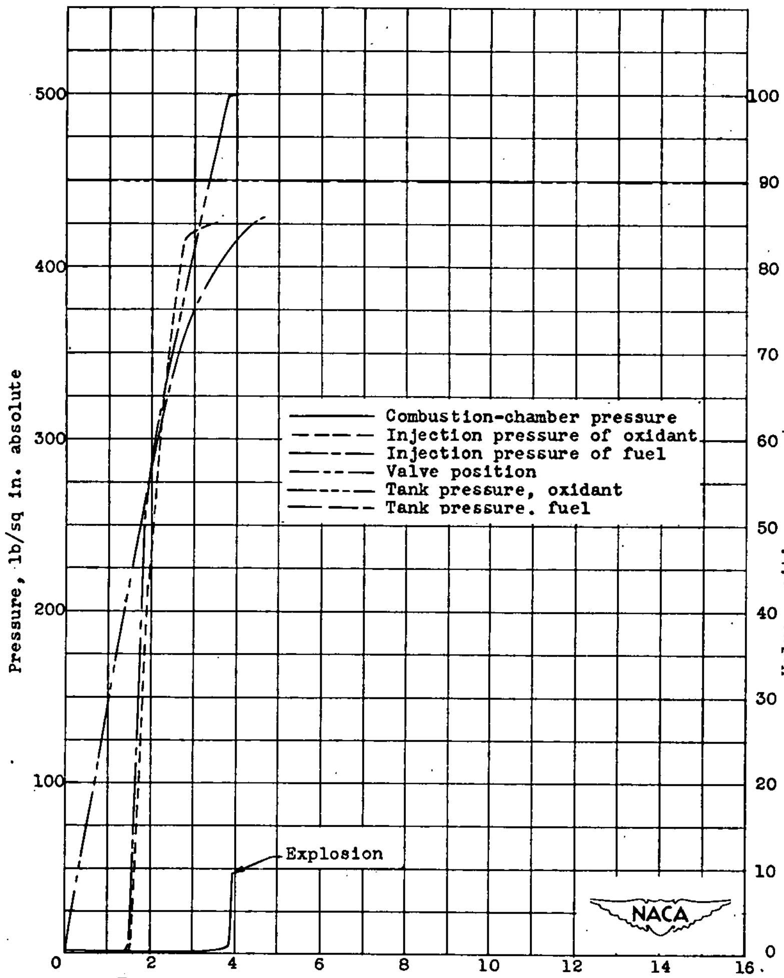
Figure 5. - Continued. Rocket starting at pressure altitude of 55,000 feet with crude monoethylaniline and mixed acid.



(g) Run 15; mean temperature, -35° F.

(h) Run 22; mean temperature, -38° F.

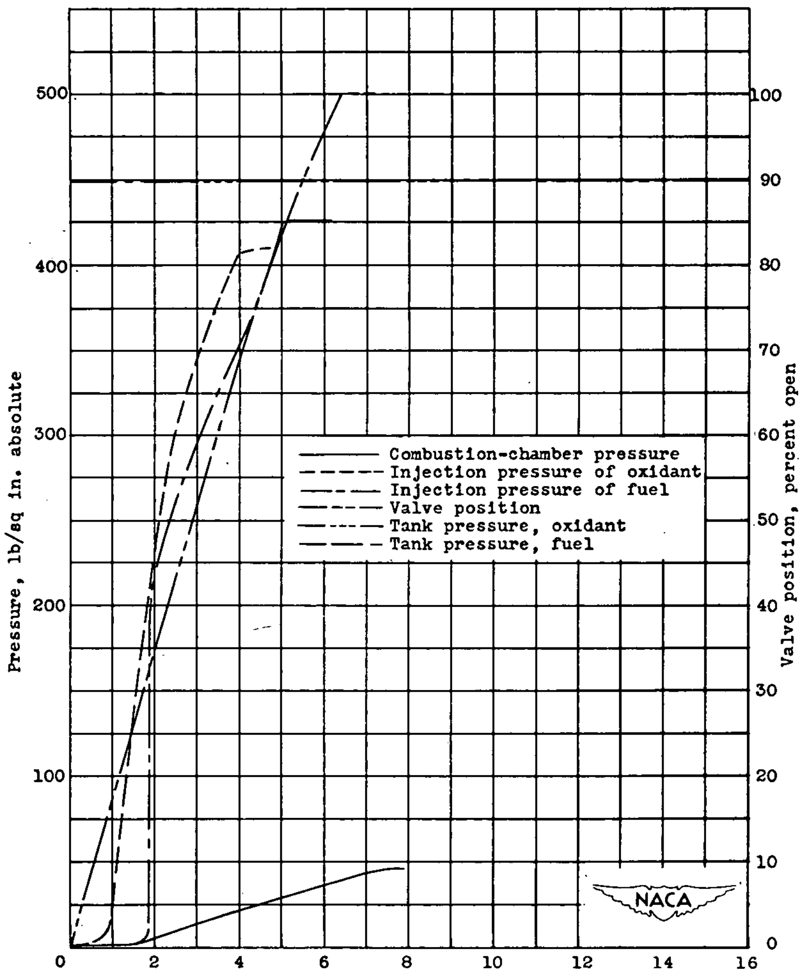
Figure 5. - Continued. Rocket starting at pressure altitude of 55,000 feet with crude monoethylaniline and mixed acid.



Time after initial movement of propellant valve, sec

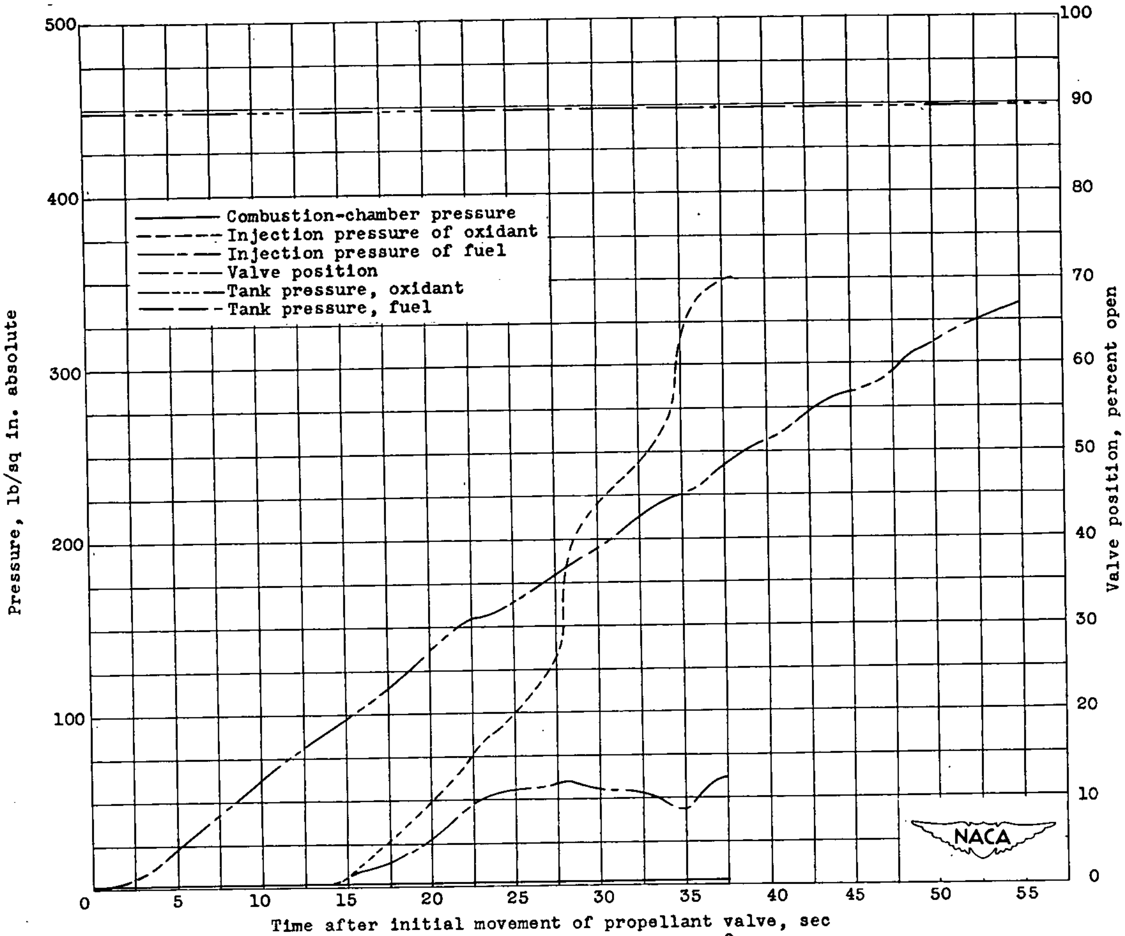
(i) Run 80; mean temperature, -19° F.

Figure 5. - Continued. Rocket starting at pressure altitude of 55,000 feet with crude monoethylaniline and mixed acid.



(j) Run 88; mean temperature, -19° F.

Figure 5. - Continued. Rocket starting at pressure altitude of 55,000 feet with crude monoethylaniline and mixed acid.



(k) Run 21; mean temperature, -47° F.

Figure 5. - Concluded. Rocket starting at pressure altitude of 55,000 feet with crude monoethylaniline and mixed acid.

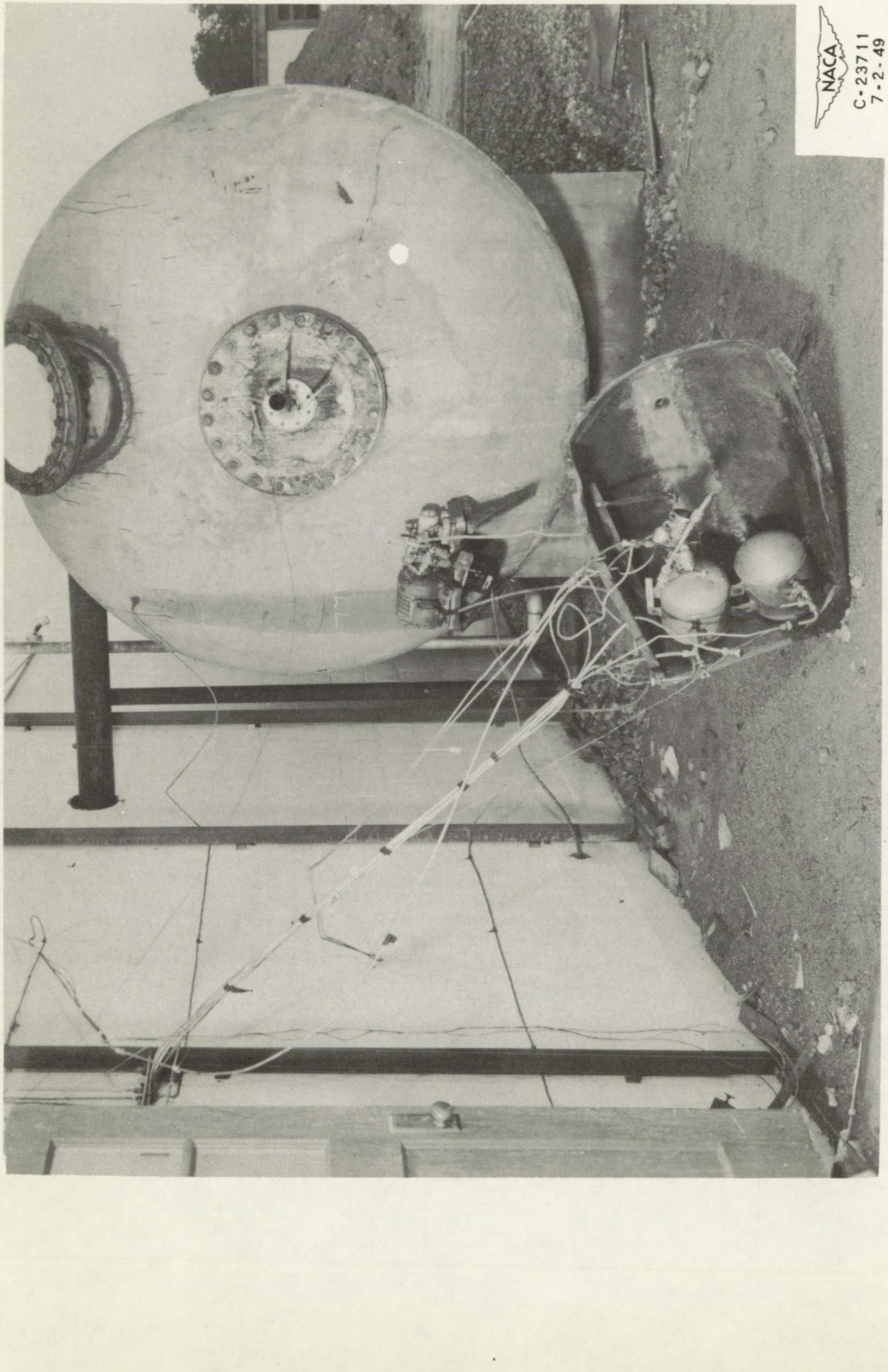


Figure 6. - Rocket engine after explosion. Run 22; pressure altitude, 55,700 feet; mean temperature, -38° F, crude monoethylaniline and mixed acid.

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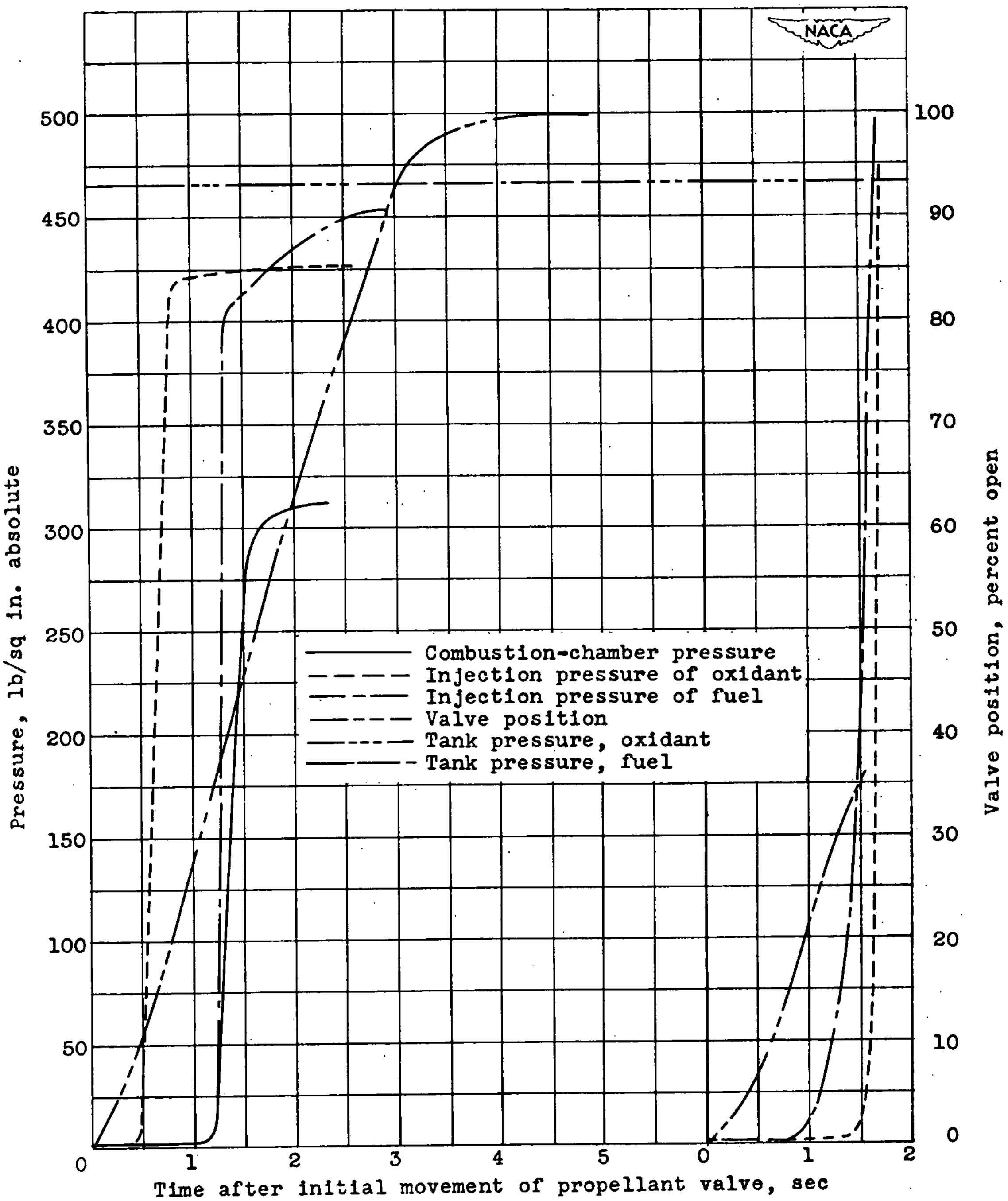

(a) Run 38; mean temperature, 81° F.

(b) Run 31; mean temperature, -28° F.

Figure 7. - Rocket starting at pressure altitude of 55,000 feet with 90-percent crude monoethylaniline and 10-percent aviation gasoline, AN-F-48 (by volume), and mixed acid.

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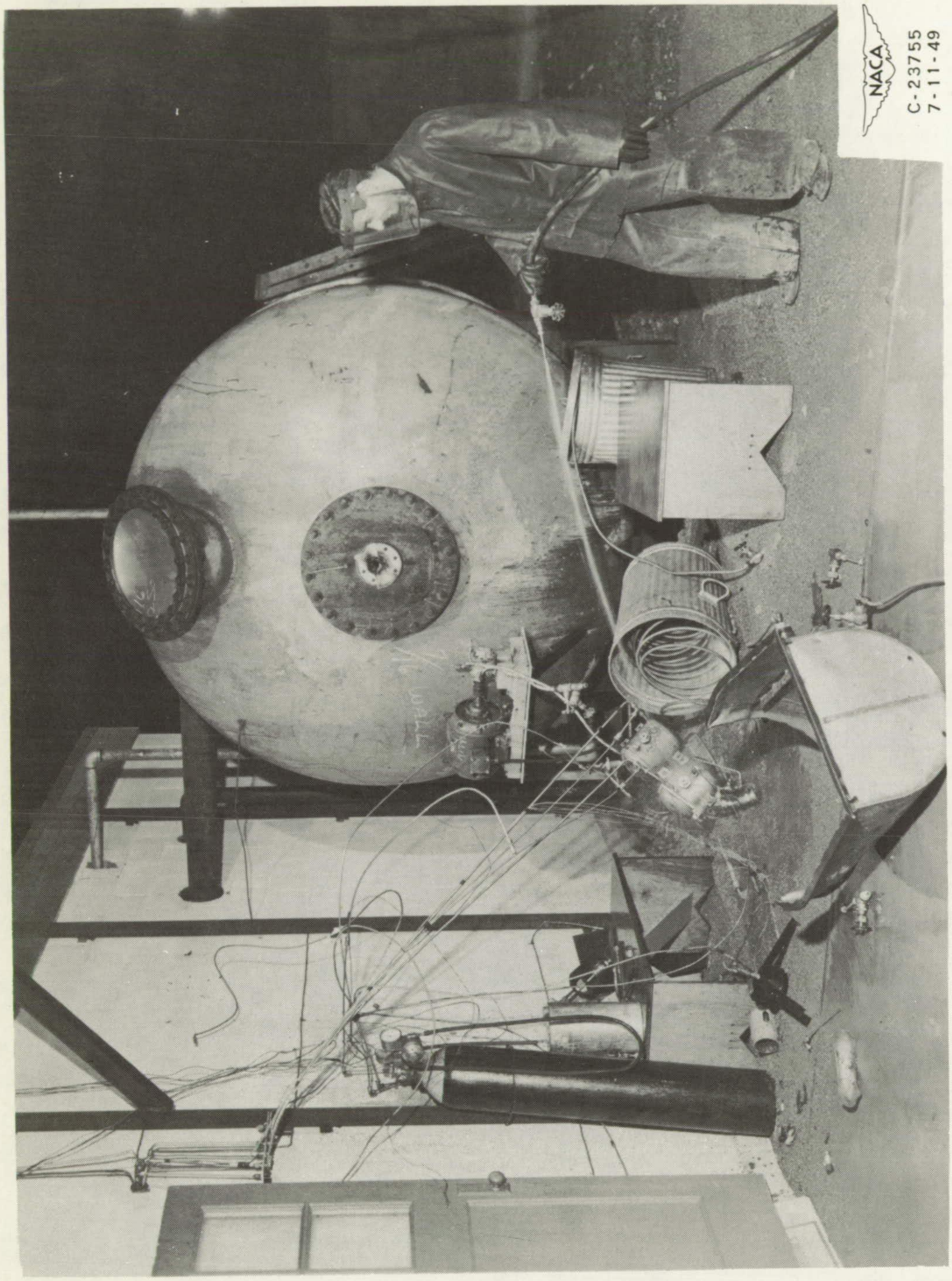

Figure 8. - Rocket engine after explosion. Run 31; pressure altitude, 54,200 feet; mean temperature, -28° F; 90-percent crude monoethylaniline, 10-percent aviation gasoline and mixed acid.

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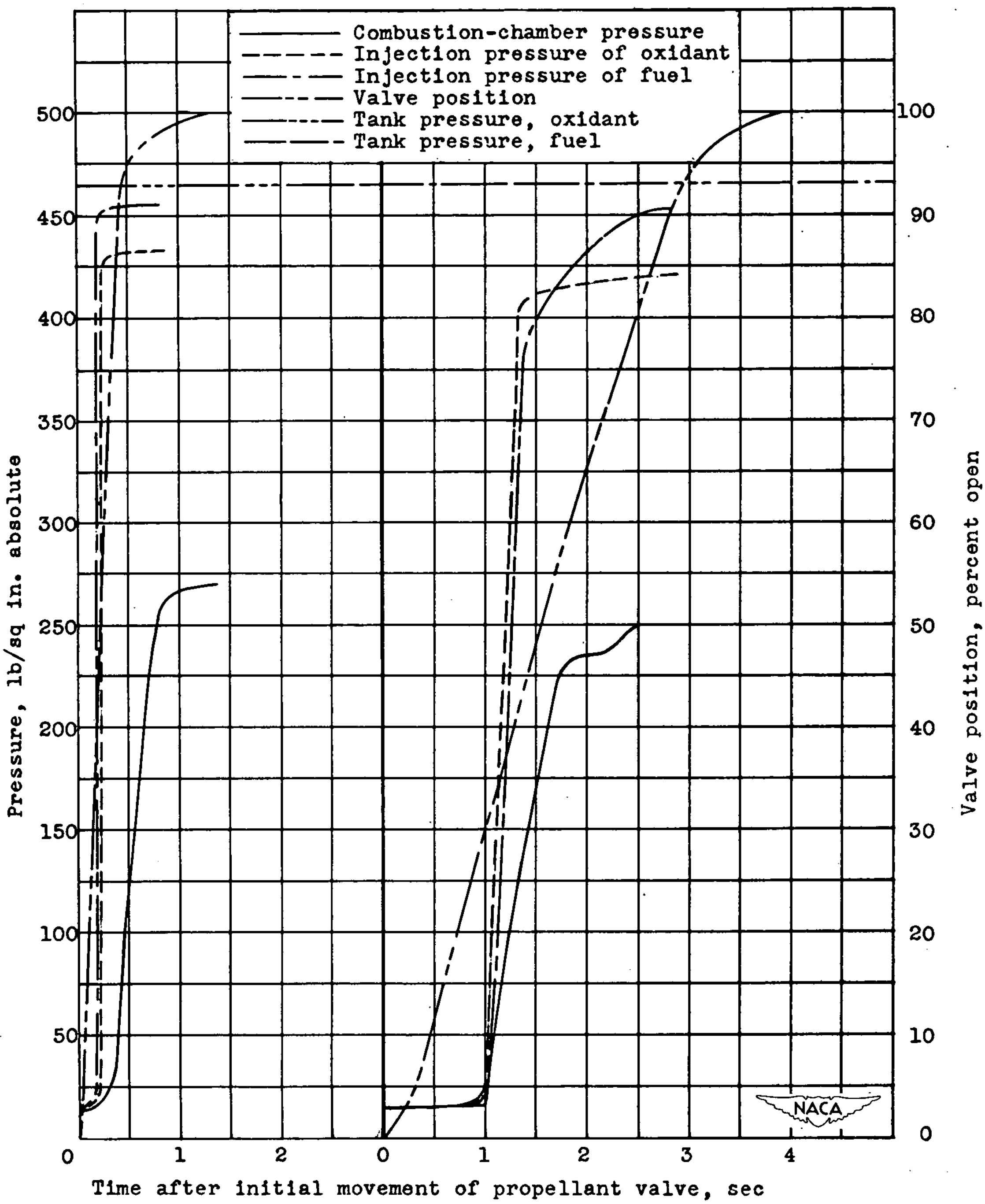
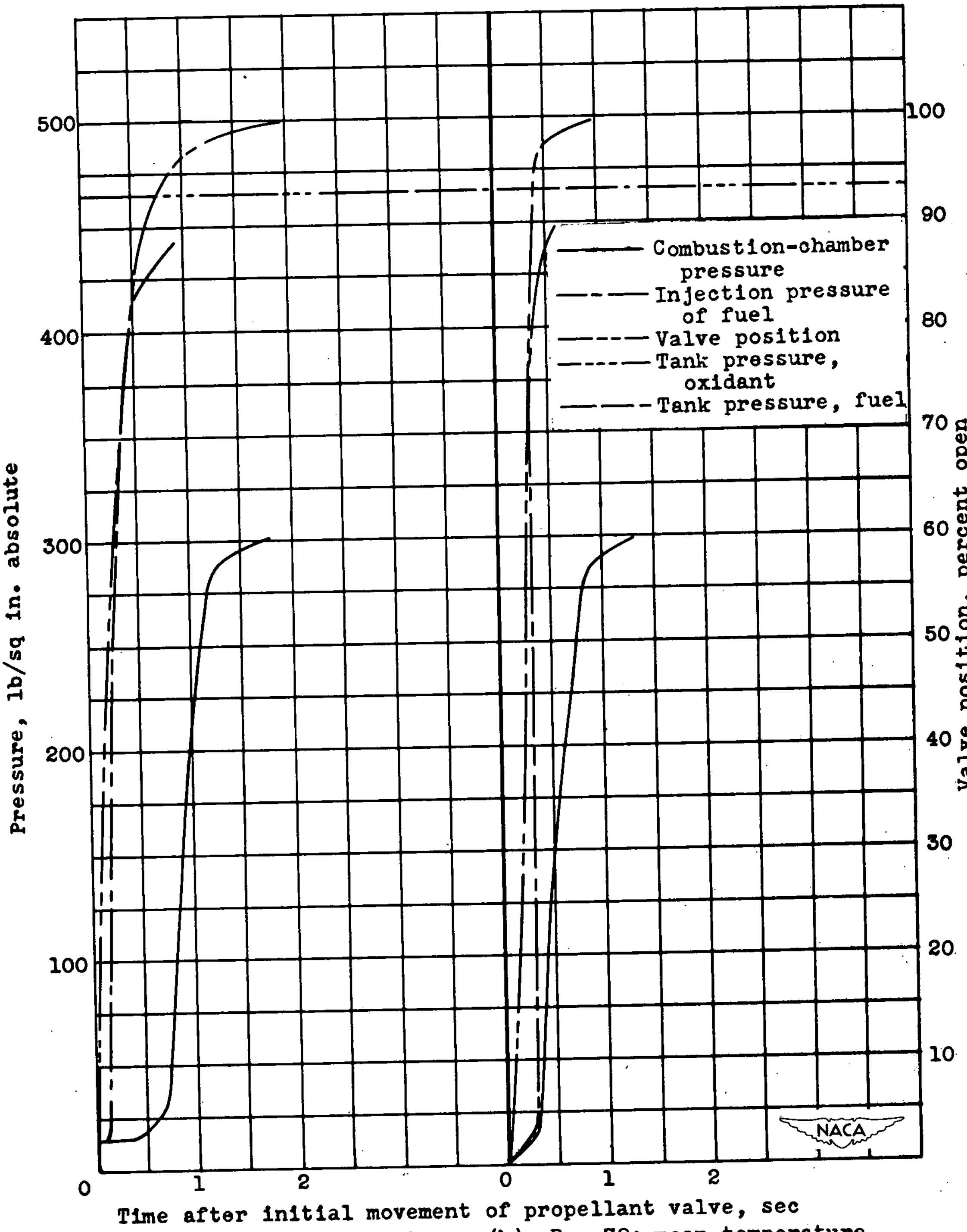


(a) Run 64; mean temperature, 83° F.

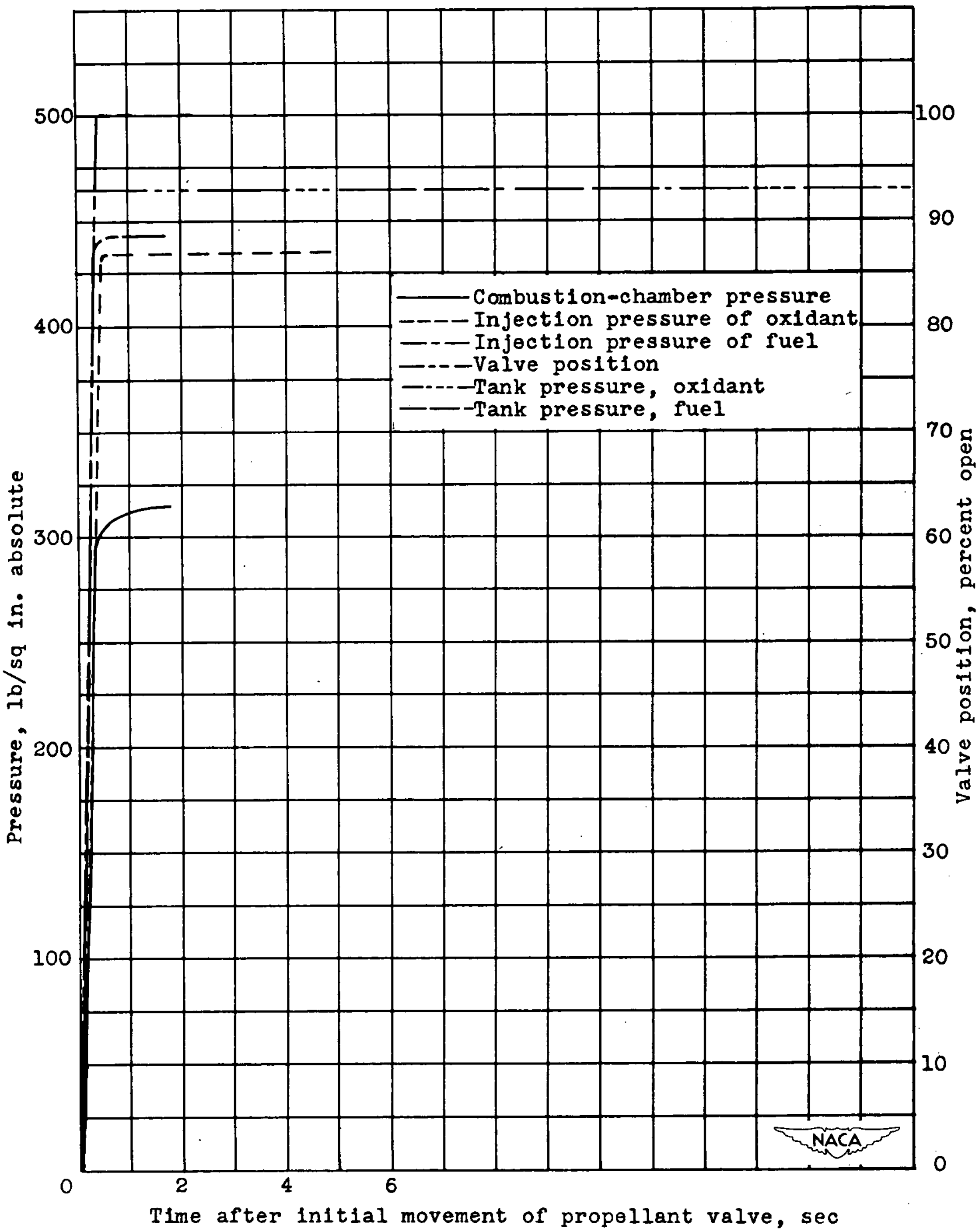
(b) Run 62; mean temperature, 84° F.

Figure 9. - Rocket starting at sea-level pressure with 70-percent furfuryl alcohol and 30-percent crude monoethylaniline (by volume), and mixed acid.



(a) Run 74; mean temperature, 80° F.
(b) Run 78; mean temperature, -57° F.

Figure 10. - Rocket starting at sea-level pressure and pressure altitude of 55,000 feet with turpentine and mixed acid.



(c) Run 143; mean temperature, -70° F.

Figure 10. - Concluded. Rocket starting at sea-level pressure and pressure altitude of 55,000 feet with turpentine and mixed acid.

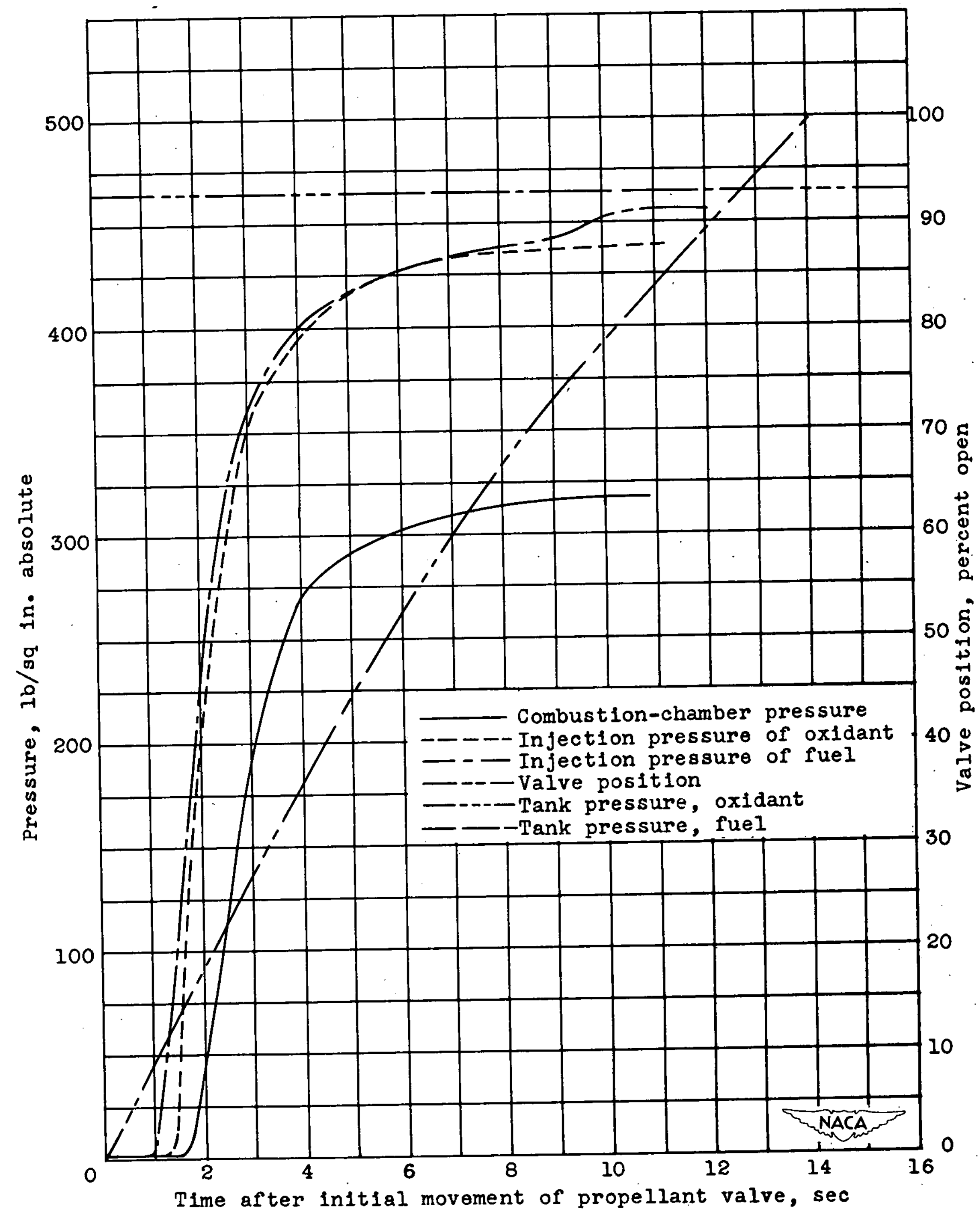


Figure 11. - Rocket starting with mixed butyl mercaptans and mixed acid. Run 127; pressure altitude, 50,000 feet; mean temperature, -73° F.