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# INVESTIGATION OF JET ENGINE COMBUSTION CHAMBER BURN-THROUGH FIRE

Thomas Rust, Jr
National Aviation Facilities Experimental Center
Atlantic City, New Jersey 08405

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FINAL REPORT

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16. Abstract

The work performed under this project was directed toward establishment of standard test conditions for testing materials which are intended for use as fire barriers for protection against a jet engine combustion chamber burn-through type of failure. The development of such a failure was accomplished on a General Electric J-47 jet engine. The resulting flame was quite severe, penetrating the present standard firewall material in 2 seconds. Studies were made of the flame impingement characteristics, including impingement temperatures and pressures; and various potential firewall materials were tested for effectiveness as fire barriers for protection against such a failure. Most materials tested in this manner failed to provide adequate protection against such an engine failure.

An investigation was conducted toward development of a means of simulating a combustion chamber burn-through failure with the ultimate goal of developing a suitable laboratory test flame for evaluating potential firewall materials. A combustion chamber simulator, which will produce a flame of similar severity to the flame produced in the J-47 engine, was developed. However, more effort is required to further develop this simulator so that exact simulation is possible.

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# INTRODUCTION

## Purpose

The purpose of this project was to develop improved standard conditions and procedures for evaluation of fireproof and fire-resistant aircraft powerplant materials under the conditions of a turbine engine combustion chamber burn-through type of failure.

## Background

The problem with which this project deals involves a failure in the combustor of an aircraft turbine engine. Known as a combustion chamber burn-through, it will be termed in this report, a "burn-through." A burn-through occurs in an engine when the hot combustion gases within a combustion chamber are deflected from their normal path and impinge on the wall of the combustion chamber thus causing a hot spot on the wall. The heat on the wall weakens it, and the high pressure in the chamber causes a bursting-type failure at this weak point. The result is a severe high-temperature, high-velocity flame escaping from the hole in the chamber. Although no serious accidents have been attributed to this type of failure to date, it is, nevertheless, a potential hazard.

A review of the Federal Aviation Administration's (FAA) Mechanical Reliability Reports (MRR) of burn-through incidents in commercial jet operations for the years of 1962 through 1969 provides the statistics shown in Table 1.

TABLE 1.--STATISTICAL SUMMARY OF REPORTED BURN-THROUGH FAILURES 1962 THROUGH 1969

| Year | 1962 | 1963 | 1964 | 1965 | 1966 | 1967 | 1968 | 1969 |
|---|---|---|---|---|---|---|---|---|
| Occurrences | 14 | 9 | 5 | 1 | 0 | 8 | 11 | 14 |

Upon inspection of Table 1, it is noted that excluding the years 1965 and 1966 an average of 10 failures occurred per year. This figure is surprisingly high, and since this type of failure is considered quite severe, the potential danger to the aircraft is worthy of research effort.

An example of a failure is the burn-through which occurred April 8, 1969, on a JT3C engine installed in a 720B airplane. The MRR description of the failure states that a hole was burned through the diffuser case of the engine at approximately the 12 o'clock position. The resulting flame caused heat damage to the engine strut, which fortunately was not weakened to the point of failure. Examination revealed that the locating lug for the combustion chamber had worn through the mating area in front of the outer case, thus allowing the combustion chamber to move away from the fuel nozzle and deflect the fuel spray pattern in such a way as to burn a hole through the outer case. This failure occurred in flight, with the pilot receiving a fire warning. The fire warning and subsequent engine shutdown resulted in minimum damage to the strut, thus preventing a possible separation of the engine from the aircraft.

The example points out an extremely important fact concerning this type of failure; namely, the pilot should be warned when a burn-through-type failure occurs as soon as possible since the spread of damage is very rapid. In the past, pilots have been warned of the failure mostly by means of the fire warning system. During the period from March 1962 through September 1968, 34 out of 49 burn-through failures gave the pilot a fire warning. This means that about 70 percent of the failures have been detected by the fire warning system. The other 30 percent of the occurrences during this period were either visually detected during flight or undetected with the fire warning system. In the latter case, the failure resulted in engine trouble which caused engine shutdown, and the failure was found during ground inspection.

MRR descriptions indicate that most burn-through failures result in a hole of about 1 inch in diameter in the combustion chamber with slightly larger holes in any material upon which it may impinge. Oil lines, hydraulic lines, structural members, fire seals, and cowling all have been damaged by burn-through flames in past occurrences. Thus, it is seen that the flame is exceptionally destructive.

Since it has been shown that burn-through failures occur at a rate of about 10 per year, and that they are quite destructive, the subject project was initiated to develop an appropriate method for simulating burn-through fires and to evaluate materials which may withstand such fires.

## DISCUSSION

### Development of a Burn-Through Failure

The project objective was initially pursued by producing a combustion chamber burn-through in a jet engine. The engine chosen as the test article was a J47-GE-25 turbojet with eight interconnected tubular stainless steel combustion chambers having Inconel alloy flame tubes. This engine was chosen because of its availability and ease of adaptability to the project. It has a 12-stage axial-flow compressor with a 5.5:1 pressure ratio and an airflow of 102 pounds per second. A single-stage axial flow turbine drives the compressor on a common shaft. The engine without cowling was mounted in a test stand as shown in Figure 1 to facilitate testing.

A burn-through failure was produced in the Number 8 burner-can of the test engine. It was produced by inserting a baffle plate between the burner-can and the flame tube or liner, thus creating a low-pressure area aft of it. The flame in the flame-tube was drawn into this area by the lower pressure and impinged on the wall of the can. A 1-inch diameter hole was made at the impingement area, thus allowing the flame to exhaust at this point. A photograph showing the modified burner-can and flame-tube is presented in Figure 2. The irregularly shaped hole in the flame-tube was made to allow the diverted flame to exit from the flame-tube more easily. A bushing or nozzle with a 1-inch-diameter hole through it was welded in position at the area of impingement on the burner-can as shown in Figure 2 to prevent excessive erosion of the can. A view of the baffle welded to the can, looking axially aft through the inside of the can, is provided in Figure 3.

During the experimentation to find the position of maximum flame impingement, a number of trial holes were made in the test can as shown in Figure 4. As may be noted in the figure, the most intense impingement occurred about 11 inches aft of the fuel nozzle.

The flame produced by incorporating these burner-can modifications is shown in Figure 5. This photograph was taken with the engine running at 80-percent power setting. At this power setting, the pressure ratio of the ambient pressure to burner-can pressure is 0.310. This pressure ratio is below the critical pressure ratio of 0.546 (Reference 1, Table 34 for $K = 1.3$), thus indicating that the flame gases are flowing at supersonic velocity. This is evident in the photograph in Figure 5 since characteristic shock diamonds are clearly visible. The flame is termed an axisymmetric, moderately underexpanded jet issuing from a convergent nozzle. A more detailed analysis of the flame will be presented later in the report.

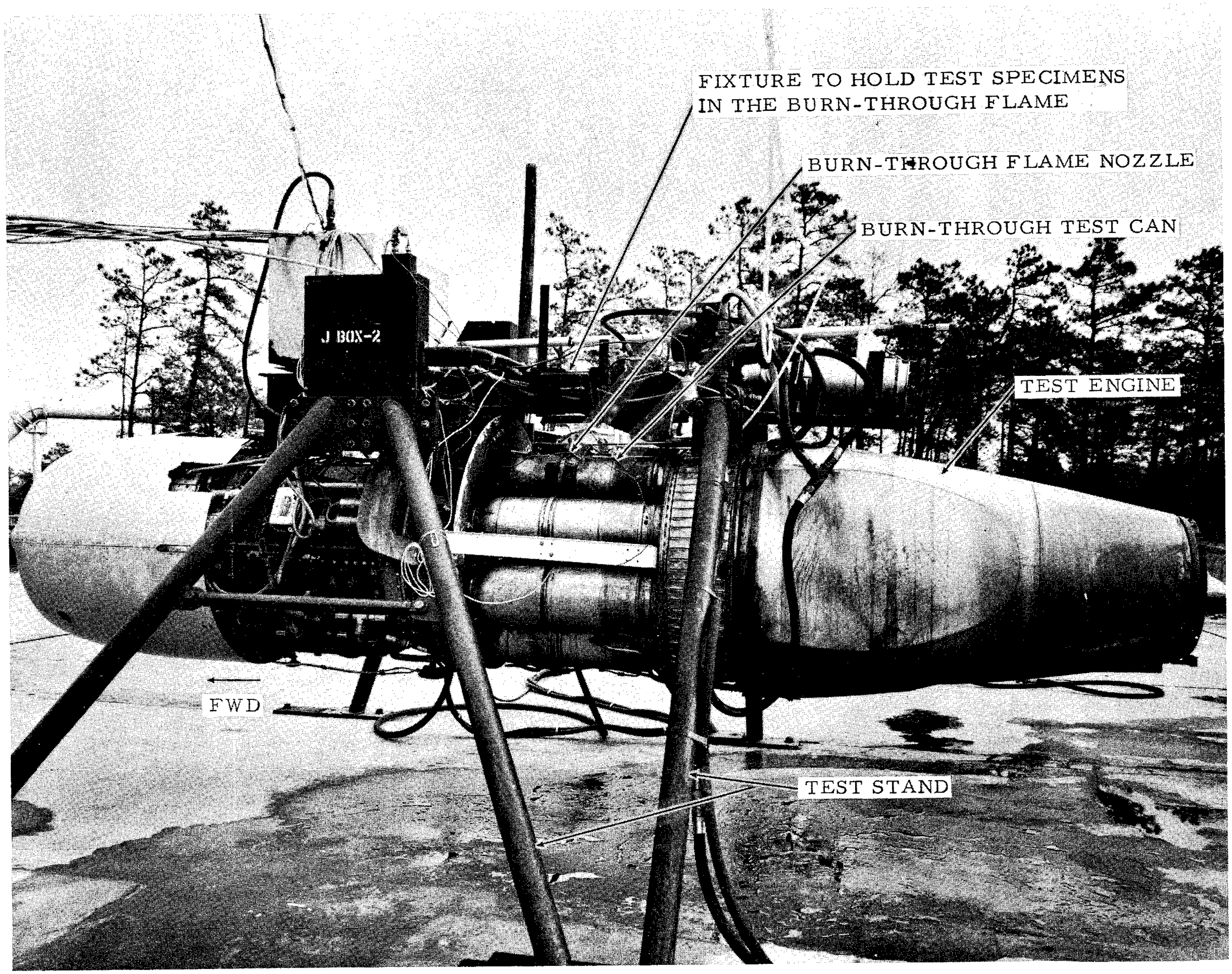


FIG. 1 OVERALL VIEW OF J-47 ENGINE AND TEST STAND

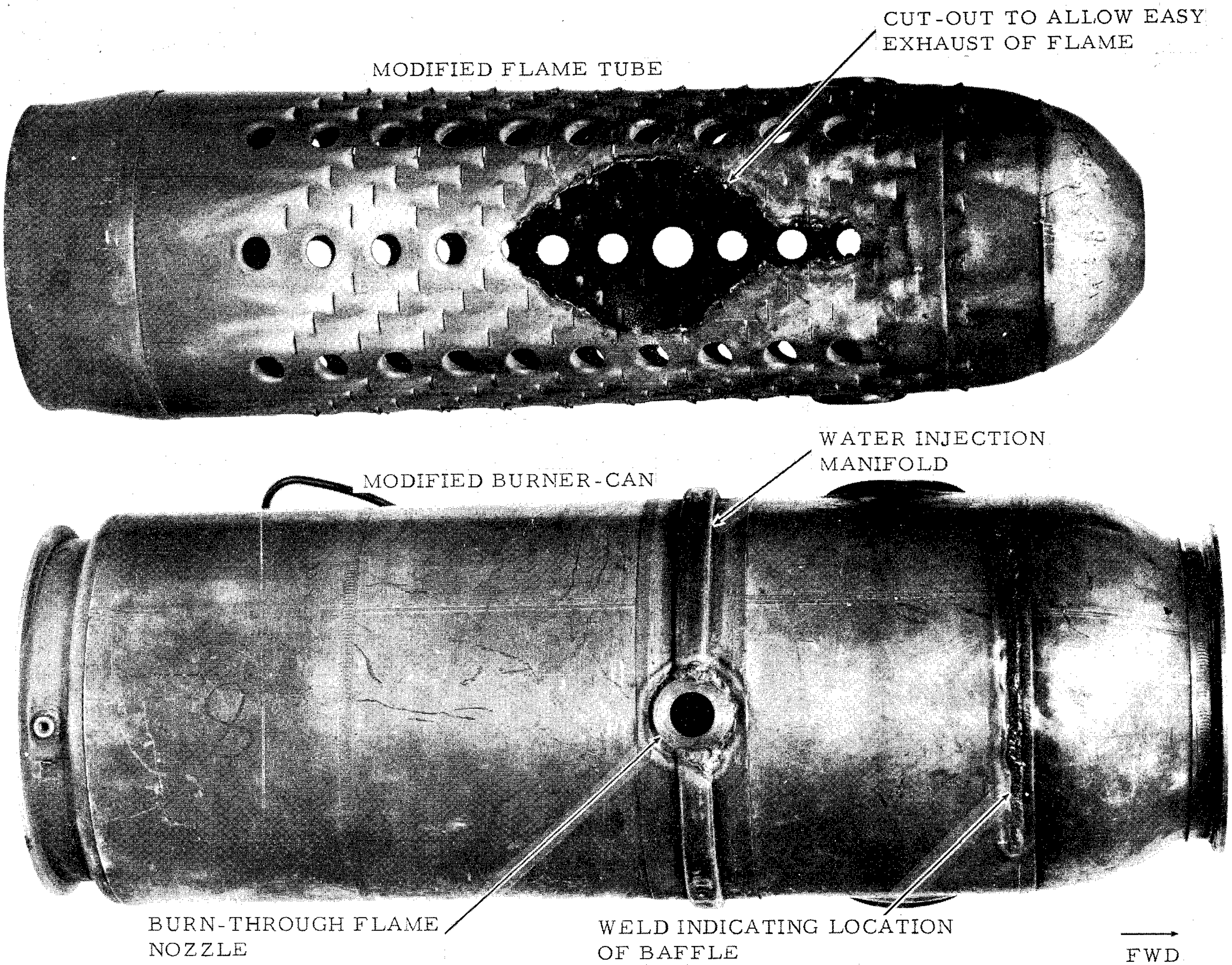


FIG. 2 MODIFIED TEST BURNER-CAN AND FLAME TUBE

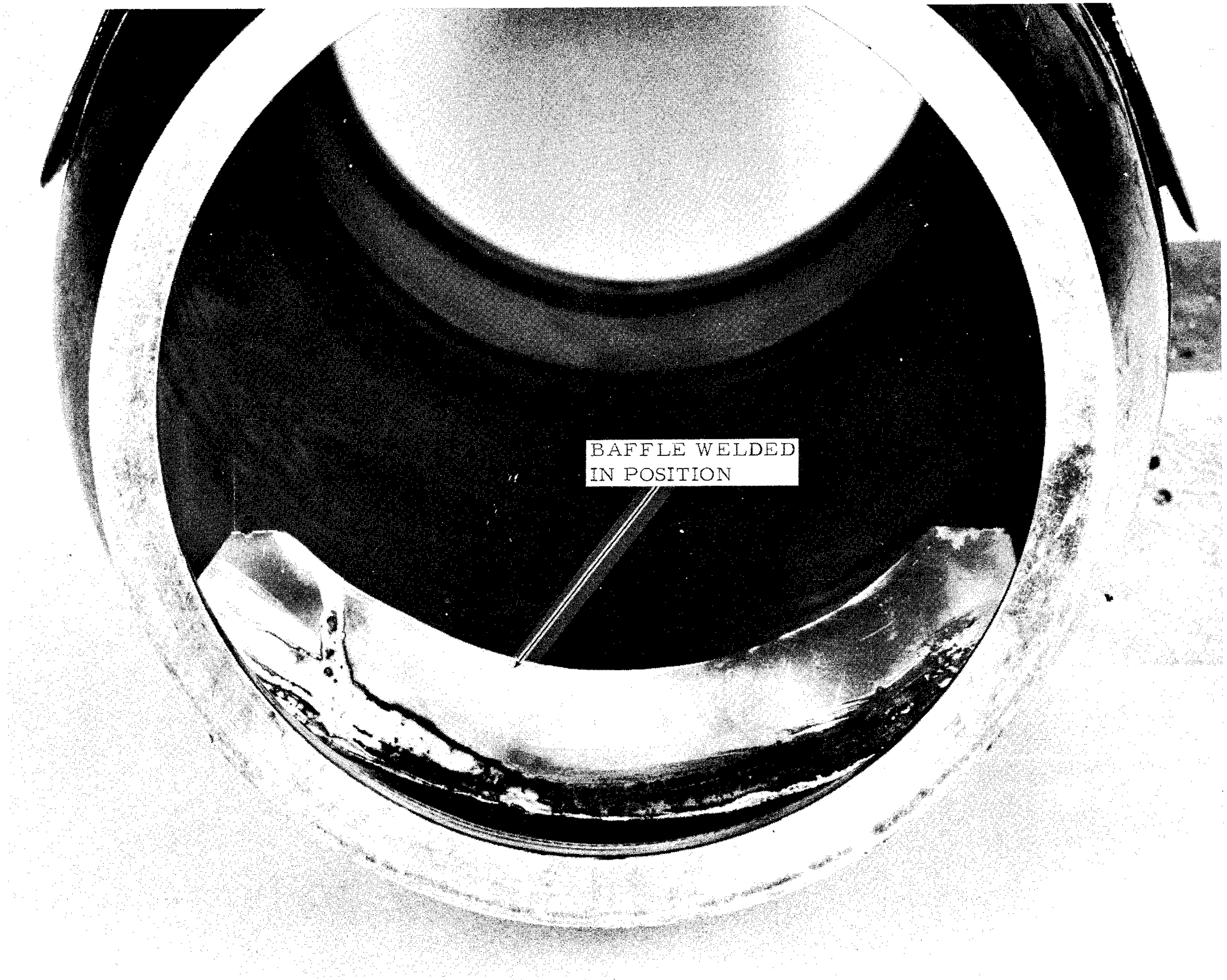


FIG. 3 VIEW OF TEST BURNER-CAN WITHOUT FLAME TUBE (LOOKING AFT)

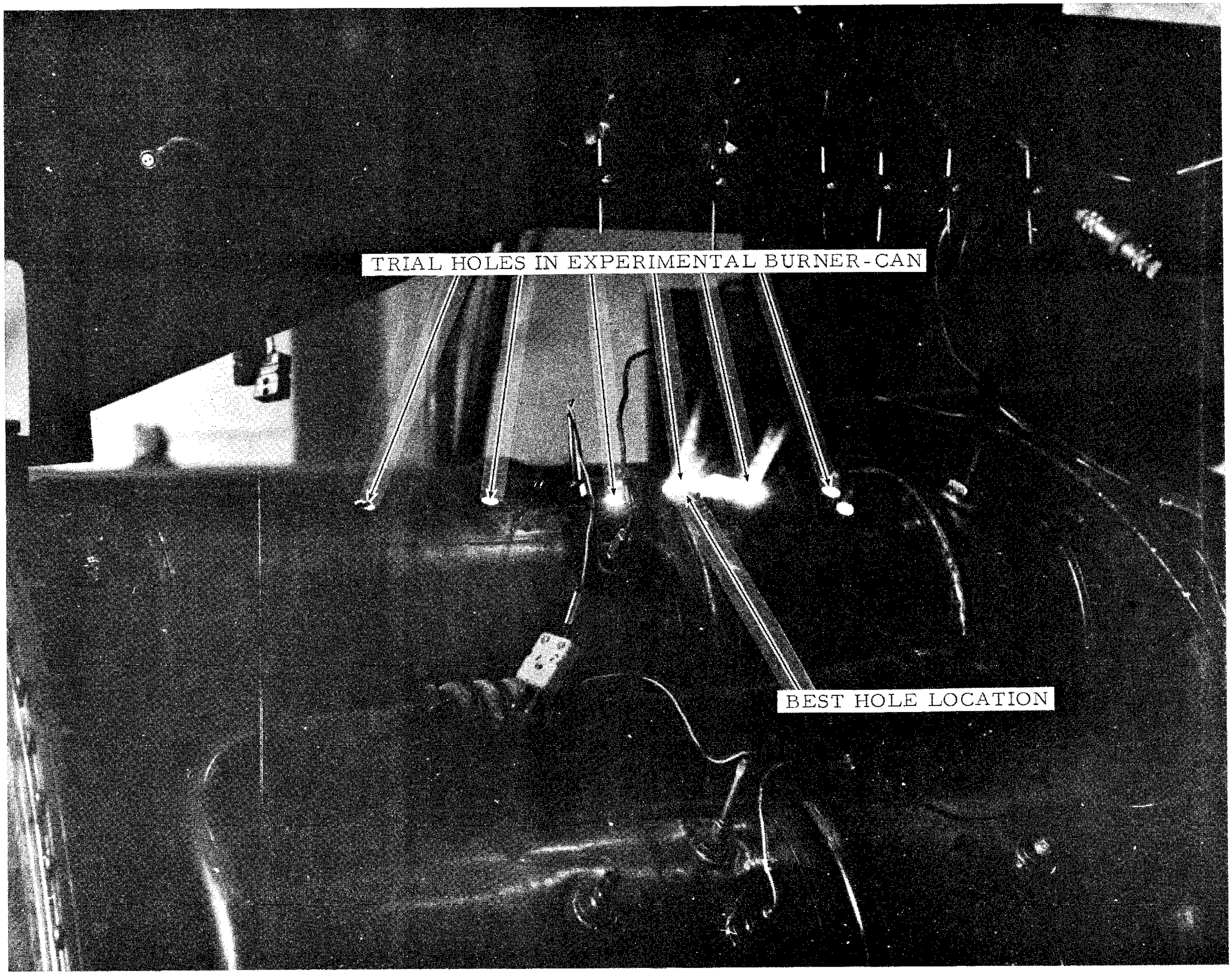


FIG. 4 EXPERIMENTAL BURNER-CAN TO DETERMINE THE BEST LOCATION OF THE FLAME NOZZLE

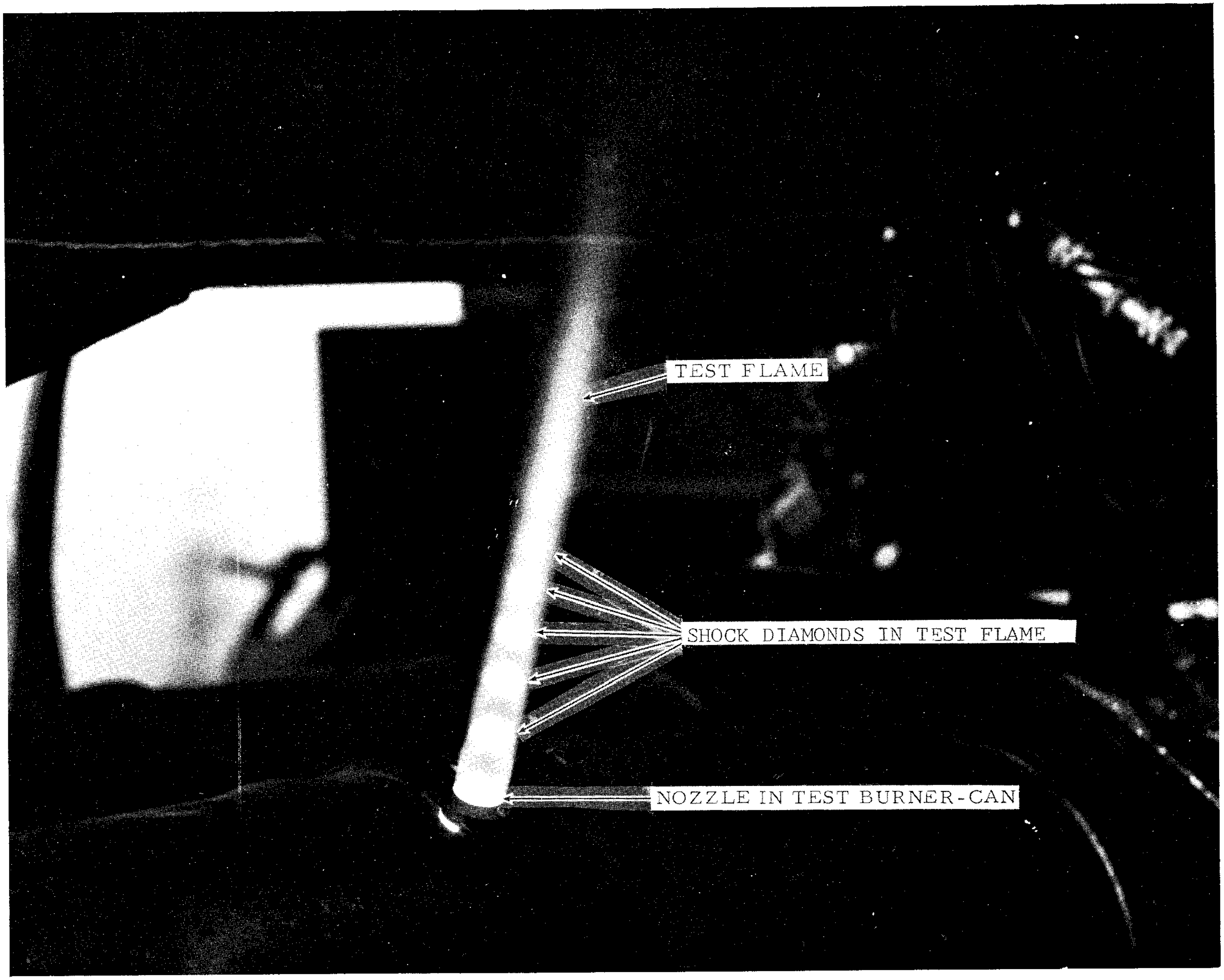


FIG. 5 BURN-THROUGH TEST FLAME AT 80% ENGINE RPM

Testing of Candidate Firewall Materials

A number of materials were exposed to the burn-through flame to determine their resistance to penetration. These materials were candidate powerplant firewall materials which could be used to protect vital aircraft components from a burn-through failure if it could be demonstrated that they would be able to withstand the test flame.

The test engine was modified to facilitate the testing of the prospective firewall materials. A fixture to hold the specimens in the test flame was fabricated and mounted on the test stand as shown in Figure 1. The fixture accepted specimens which were 8 inches square and of any thickness less than 4 inches. It could be positioned such that the specimen could be located at any distance up to 8 inches from the engine test flame exit and in such a way as to allow the test flame to impinge on the specimen exactly at the center and normal to the test surface or at angle to the material.

The test engine was also modified by the installation of an on-off solenoid in the fuel line feeding the fuel nozzle of the test can. This modification was performed in order to allow engine runup without fuel going to the test can. In this way, test engine operating conditions, i.e., pressure ratio, speed, and airflow could be attained before the test flame was produced. It should be noted, however, that heated gases passed through the burn-through nozzle whenever the engine was running. Although there was no fuel being injected into the can, these gases were relatively warm (about 1000°F at 80-percent power). This hot air flowed into the test can from the adjacent cans through the interconnecting crossover tubes. When the test engine was accelerated appreciably, some evidence of hot gases was seen exiting from the burn-through nozzle. The greater the acceleration, the more intense was the flow. Thus, if the test specimen was in position above the burn-through nozzle during engine runup, it was preheated to between 1000° and 1500°F depending on the rate of acceleration. Therefore, after a number of specimens had been tested with the fixture in a fixed position, which meant that they were preheated before the actual test was begun, an air-operated actuator was attached to the fixture. The addition of the actuator made it possible to position the specimen outside the hot-gas stream issuing from the burn-through nozzle while the engine was started and brought to the test power setting required. Then, when the test was started, the actuator was energized, positioning the specimen, and the fuel control solenoid valve was opened. The time from opening of the fuel valve to the time at which the flame burned through the specimen was recorded as the time for failure.

A listing of the candidate firewall materials which were exposed to the test flame is given in Table 2. The table indicates the materials tested, a description of each, the test conditions, and the

TABLE 2.--TESTS PERFORMED ON POTENTIAL FIREWALL MATERIALS

| Test No. | Material & Description | Thickness (inches) | Density ($lb/in^3$) | Engine Setting (% rpm) | Distance of Specimen from Burner-Can (inches) | Time to Failure (sec) | Remarks |
|---|---|---|---|---|---|---|---|
| 1 | 347 Stainless Steel | .015 | .290 | 80 | 2 | 2.0 | |
| 2 | 347 Stainless Steel | .015 | .290 | 85 | 3 | 2.0 | |
| 3 | 347 Stainless Steel | .015 | .290 | 85 | 3 | 4.0 | Flapper on test burner-can nozzle prevented preheating specimen during engine runup. |
| 4 | 347 Stainless Steel | .015 | .290 | 80 | 3 | 2.0 | |
| 5 | 347 Stainless Steel | .015 | .290 | 80 | 4 | 2.0 | |
| 6 | 347 Stainless Steel | .015 | .290 | 80 | 5 | 2.5 | |
| 7 | 347 Stainless Steel | .015 | .290 | 80 | 6 | 2.8 | |
| 8 | 347 Stainless Steel | .015 | .290 | 80 | 7 | 3.0 | |
| 9 | 347 Stainless Steel | .015 | .290 | 80 | 8 | 4.0 | |
| 10 | 347 Stainless Steel | .032 | .290 | 80 | 3 | 6.0 | |
| 11 | 347 Stainless Steel | .032 | .290 | 85 | 3 | 4.0 | |
| 12 | 347 Stainless Steel | .039 | .290 | 80 | 3 | - | No failure noted in 2-minute duration. |
| 13 | 347 Stainless Steel | .039 | .290 | 85 | 3 | 7.0 | |

TABLE 2.--TESTS PERFORMED ON POTENTIAL FIREWALL MATERIALS (Continued)

| Test No. | Material & Description | Thickness (inches) | Density ($lb/in^3$) | Engine Setting (% rpm) | Distance of Specimen from Burner-Can (inches) | Time to Failure (sec) | Remarks |
|---|---|---|---|---|---|---|---|
| 14 | 347 Stainless Steel | .050 | .290 | 80 | 3 | - | No failure noted in 2-minute duration. |
| 15 | 347 Stainless Steel | .050 | .290 | 85 | 3 | 16.0 | |
| 16 | 347 Stainless Steel | .064 | .290 | 80 | 3 | - | No failure noted in 2-minute duration. |
| 17 | 347 Stainless Steel | .064 | .290 | 85 | 3 | 16.0 | |
| 18 | 347 Stainless Steel | .032 | .290 | 85 | 3 | 10.0 | Flapper on test burner-can nozzle prevented preheating specimen during engine runup. |
| 19 | AMS 4902 Titanium | .015 | .161 | 85 | 3 | 2.0 | Failure accompanied by a shower of molten titanium. |
| 20 | AMS 4902 Titanium | .032 | .161 | 85 | 3 | 4.0 | Failure accompanied by a shower of molten titanium. |
| 21 | Hard Asbestos Fiber Material backed by .015-inch Stainless Steel | .072 | .071 | 80 | 2 | 2.5 | |
| 22 | Hard Asbestos Fiber Material unbacked | .250 | .071 | 80 | 2 | 49 | |
| 23 | Silica Glass, Phenolic Resin backed by .015-inch Stainless Steel | .076 | .051 | 80 | 2 | 3.7 | |

TABLE 2.--TESTS PERFORMED ON POTENTIAL FIREWALL MATERIALS (Continued)

| Test No. | Material & Description | Thickness (inches) | Density ($lb/in^3$) | Engine Setting (% rpm) | Distance of Specimen from Burner-Can (inches) | Time to Failure (sec) | Remarks |
|---|---|---|---|---|---|---|---|
| 24 | Hard Asbestos Fiber, Ceramic Bonder, Sandwiched between .015-inch Stainless Steel | .250 | .014 | 80 | 2 | 9 | |
| 25 | Hard Asbestos Fiber, Ceramic Bonder, Sandwiched between .015-inch Stainless Steel | .406 | .014 | 80 | 2 | 10 | |
| 26 | Ablative Material backed by .060-inch 1040 Steel (black color) | .500 | .029 | 80 | 2 | - | Ablative material was completely gone at end of test, insinuating that the steel backing plate was the only material which withstood the flame. Test duration: 2 minutes. |
| 27 | Ablative Material backed by .060-inch 1040 Steel (white color) | .500 | .029 | 80 | 2 | 14 | |
| 28 | Transpiration Cooled, 3 x 3 Stainless Steel Basket Weave Air Mat with Polyurethane Sealant Coating | 1.000 | .200 | 85 | 3 | - | When sealant was burned away by the test flame, the cooling airflow was 84 SCFM. Failure occurred only after a 1/4-inch instrumentation line separated due to excess heat, allowing excessive cooling air to escape without cooling the mat. The urethane coating melted at about 300°F. Test duration: 147 seconds. |

TABLE 2.--TESTS PERFORMED ON POTENTIAL FIREWALL MATERIALS (Continued)

| Test No. | Material & Description | Thickness (inches) | Density ($lb/in^3$) | Engine Setting (% rpm) | Distance of Specimen from Burner-Can (inches) | Time to Failure (sec) | Remarks |
|---|---|---|---|---|---|---|---|
| 29 | Zirconia Felt Laminate: Aluminum Foil Faceplate, Zirconia Felt, .015-inch Hastelloy X Backplate | .205 | .034 | 85 | 3 | 3.5 | The felt was blown apart by the flame blast. |
| 30 | Zirconia Felt & Cloth Laminate: .005-inch Titanium Faceplate, Zirconia Cloth, Zirconia Felt, .005 Titanium Backplate | .225 | .014 | 85 | 3 | 2.0 | The felt and cloth were blown apart by the flame blast. |
| 31 | Zirconia Felt Bonded to .015-inch Hastelloy X Backplate | .200 | .030 | 85 | 3 | 0.0 | The felt was blown apart before the fuel valve was actuated. |
| 32 | Zirconia & Synthetic Cloth Laminate: Aluminum Foil Faceplate, Zirconia Cloth, Two Layers of Synthetic Cloth, .015-inch Hastelloy X Backplate | .110 | .080 | 85 | 3 | 4.0 | The material was blown apart by the flame blast. |
| 33 | All Carbon System, Heat Stabilized to a Minimum of 700°F, 60% Fiber Content | .260 | .040 | 85 | 3 | 35 | |
| 34 | All Carbon High-Temperature Ablative Material, 40% Fiber Content | .292 | .040 | 85 | 3 | 156 | The specimen fractured at time of failure. It also glowed red all during the test except for the first 10 seconds. |
| 35 | The same material as Test No. 34 except the specimen was nickel plated. Plating was about .C10-inches thick | .280 | .054 | 85 | 3 | 19 | The nickel coating separated from the specimen when exposed to the test flame. |

test results. Test No. 1 was performed on a specimen of material which meets present requirements for aircraft powerplant firewalls. This material is required to withstand 2000°F flames from a standard burner for 15 minutes. However, as noted in the table, the specimen failed in 2 seconds when exposed to the burn-through flame. Test No. 2 was performed with the test conditions changed as indicated in the table. The time-to-failure of this specimen was the same as for Test No. 1 specimen. A number of tests described later were performed under these conditions to eliminate the down blast from an unfailed specimen which heated the test can when the distance from the can was 2 inches but was negligible when this distance was increased to 3 inches. The increased distance, therefore, meant longer burner-can life. Test No. 3 was performed to indicate the effect of preheating the specimen as in tests performed before the positioning actuator was installed. It is noted that the time-to-failure was increased to 4 seconds for .015-inch thick stainless steel.

Tests Nos. 4 through 9 were performed under the same test conditions and with the same type material in order to investigate the effect of increasing the distance between the firewall and the combustors. It is noted that the time-to-failure was increased by only 2 seconds with an increase in distance from 3 inches to 8 inches. No tests were performed at distances greater than 8 inches.

Tests Nos. 10 through 17 were performed on various thicknesses of stainless steel to measure the severity of the flame by its effect on these specimens. The data from these tests indicated that the severity of the flame increases appreciably when the engine power is increased from 80 percent to 85 percent. The time-to-failure in Test No. 11 was 2 seconds less than for Test No. 10, while the thicker specimens produced even larger time differentials with increased power setting. The tests performed with a power setting of 80 percent produced no failure in a 2-minute test duration as noted in Tests Nos. 12, 14, and 16, while relatively short times-to-failure were noted for the correspondingly same thickness specimens in Tests Nos. 13, 15, and 17, which were performed at an 85-percent power setting.

Test No. 18 was performed to obtain a comparison between preheated specimens and nonpreheated specimens of thicknesses greater than .015 inch. Comparing the results of Test No. 18 and Test No. 11, it is noted that the lack of preheat increased the time-to-failure from 4 to 10 seconds.

Tests Nos. 19 and 20 were performed on specimens of titanium which because of its light weight and usefulness at elevated temperatures, was thought to be a good potential firewall material for this type of engine failure. As indicated in the table, however, the two titanium specimens failed in a very short period of time. These failures resulted in a shower of hot molten titanium.

The remainder of the tests listed in the table were conducted on specimens which were submitted as potential firewall materials by commercial manufacturers. As noted in the table, some were tested at 2-inch distance from the can and 80-percent engine power setting while others were tested at a 3-inch distance and 85-percent power. As noted, some were preheated while others were not.

Tests Nos. 21 and 22 were performed on the same type of material, which is described in the table, with the second specimen being considerably thicker than the first. Also, the material used in Test No. 21 was backed with stainless steel, while the others were unbacked. The specimen used in Test No. 21 is shown mounted in the fixture just prior to the test in Figure 6 and after completion of the test in Figure 7. The effect of the burn-through flame is apparent in the latter figure. The time-to-failure for this material, including the backing plate, was 2.5 seconds. The result of Test No. 22 was better, with a time-to-failure of 49 seconds.

Test No. 23 was performed on a silica glass material which is presently being used commercially as a firewall material for protection from a burn-through failure. The specimen is shown mounted in the fixture just prior to the test in Figure 8 and after completion of the test in Figure 9. As noted in the table, failure occurred in 3.7 seconds.

Tests Nos. 24 and 25 were performed on the same type of material, which is described in the table, with the second specimen being somewhat thicker. Both specimens were sandwiched between .015-inch-thick stainless steel to add strength. The thickness of the materials given in the table are total thicknesses, including the stainless steel. Failure occurred in approximately 10 seconds.

Tests Nos. 26 and 27 were performed on basically the same type of material with only slight differences in chemical composition. Both specimens were backed with SAE 1040 steel of a thickness which may be considered excessive for weight reasons. The results indicated in the table for Test No. 26 show that the specimen withstood the burn-through flame for 2 minutes at which time the test was stopped in order to protect the burner-can. Examination of the specimen showed that none of the test material remained on the backing plate, indicating that it had been eroded or blown away by the flame. Therefore, it may be assumed that the material did not withstand the flame, but that it was the steel backing plate that kept the specimen from failing. There is more evidence available to substantiate this assumption by referring to the results of Test No. 16. At 80-percent engine power setting, although the distance from the can was 3 inches, no failure occurred using .064-inch-thick stainless steel. Although the type of steel and distance from the can were different, the tests were quite similar and may be considered comparable.

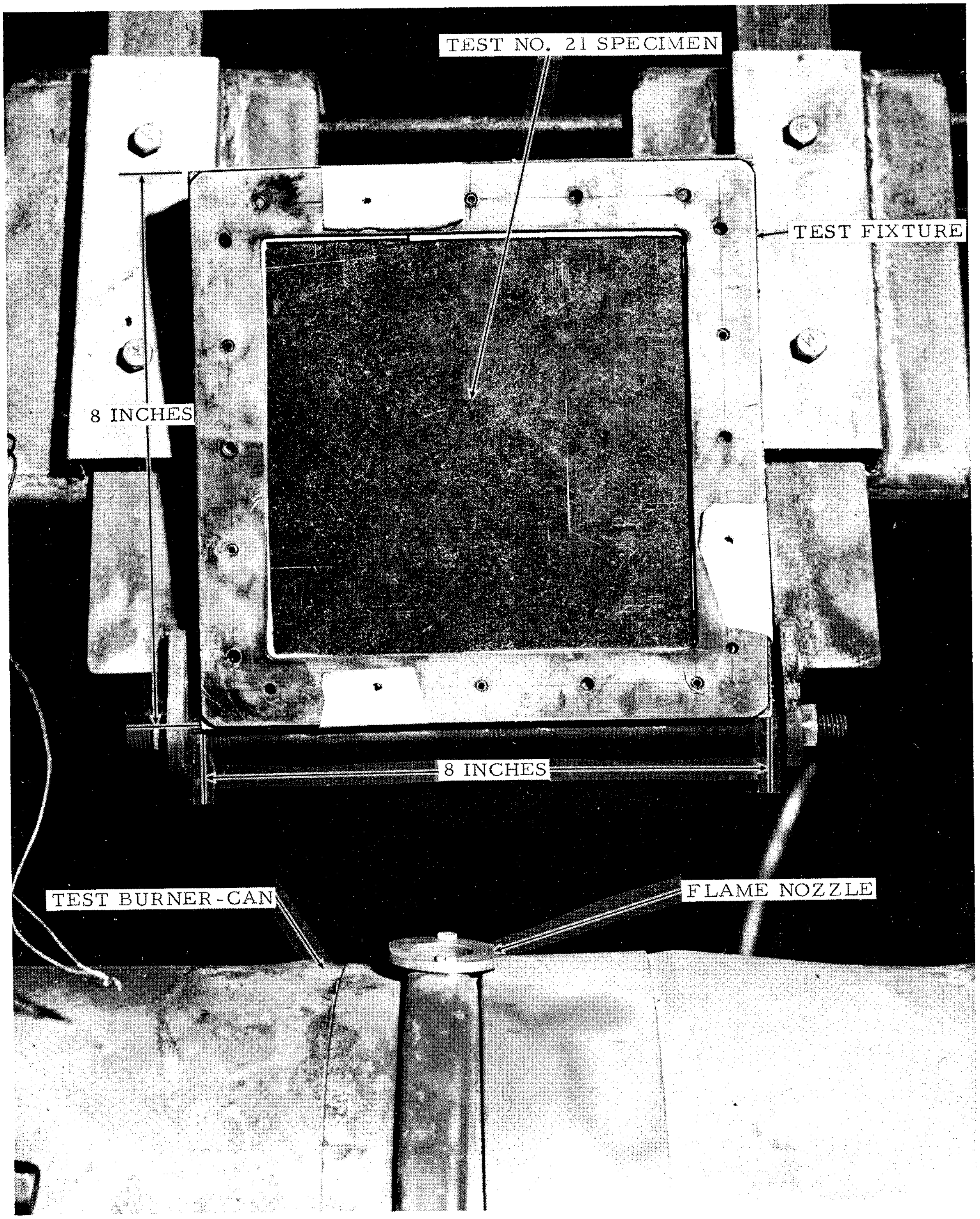


FIG. 6 TEST NO. 21 SPECIMEN IN TEST FIXTURE PRIOR TO TESTING

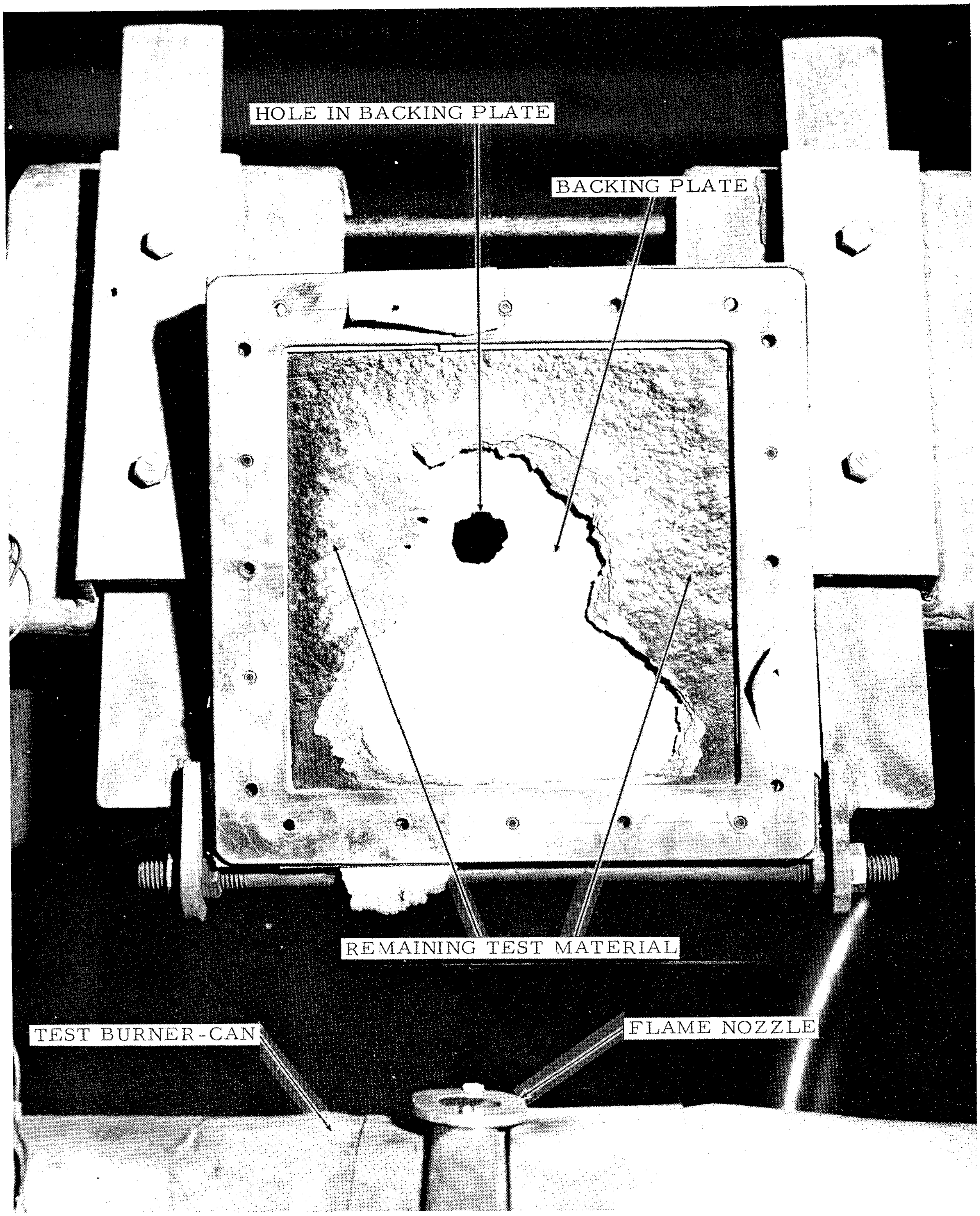


FIG. 7 TEST NO. 21 SPECIMEN AFTER EXPOSURE TO BURN-THROUGH FLAME.
FAILURE OCCURRED IN 2.5 SECONDS

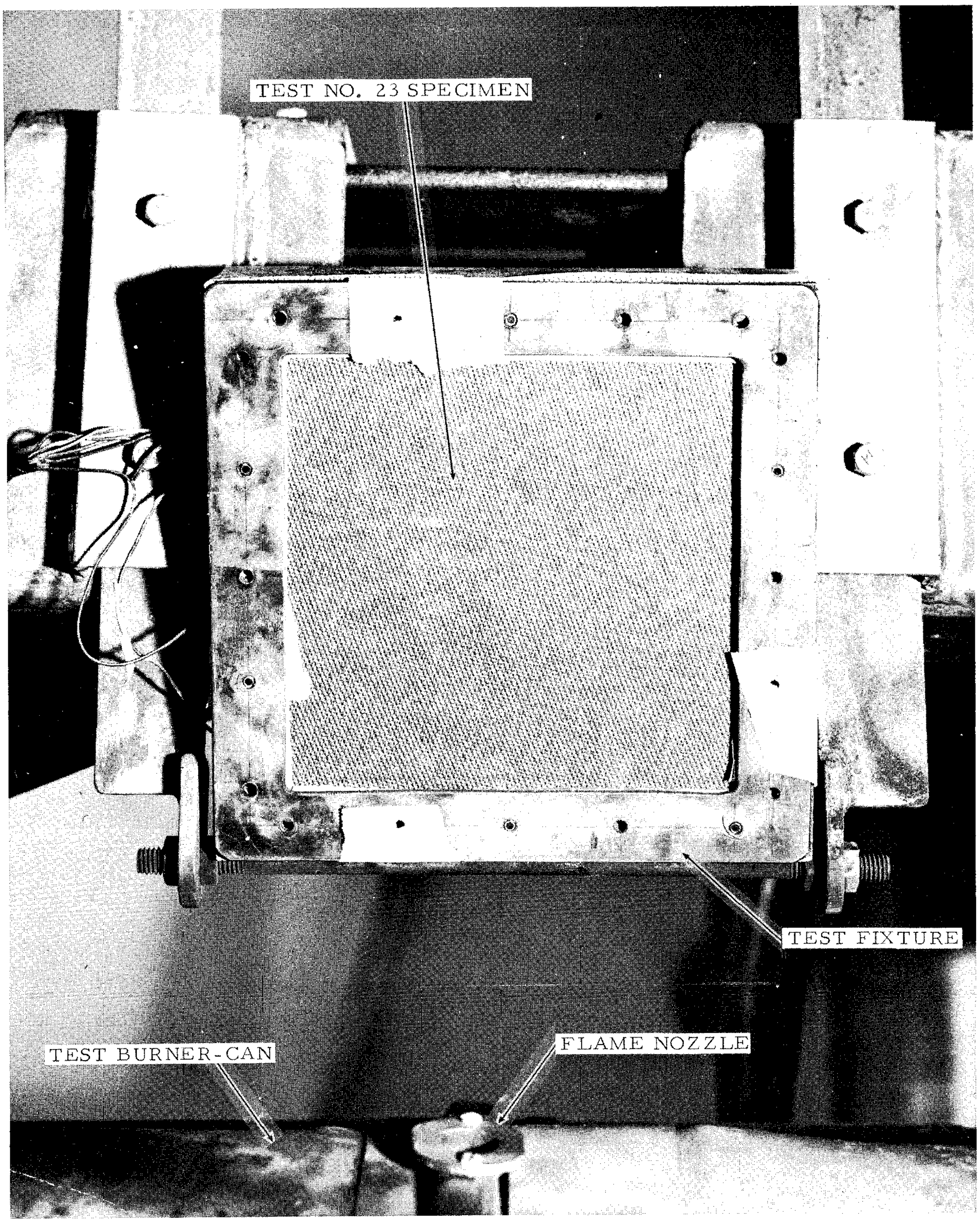


FIG. 8 TEST NO. 23 SPECIMEN IN TEST FIXTURE PRIOR TO TESTING

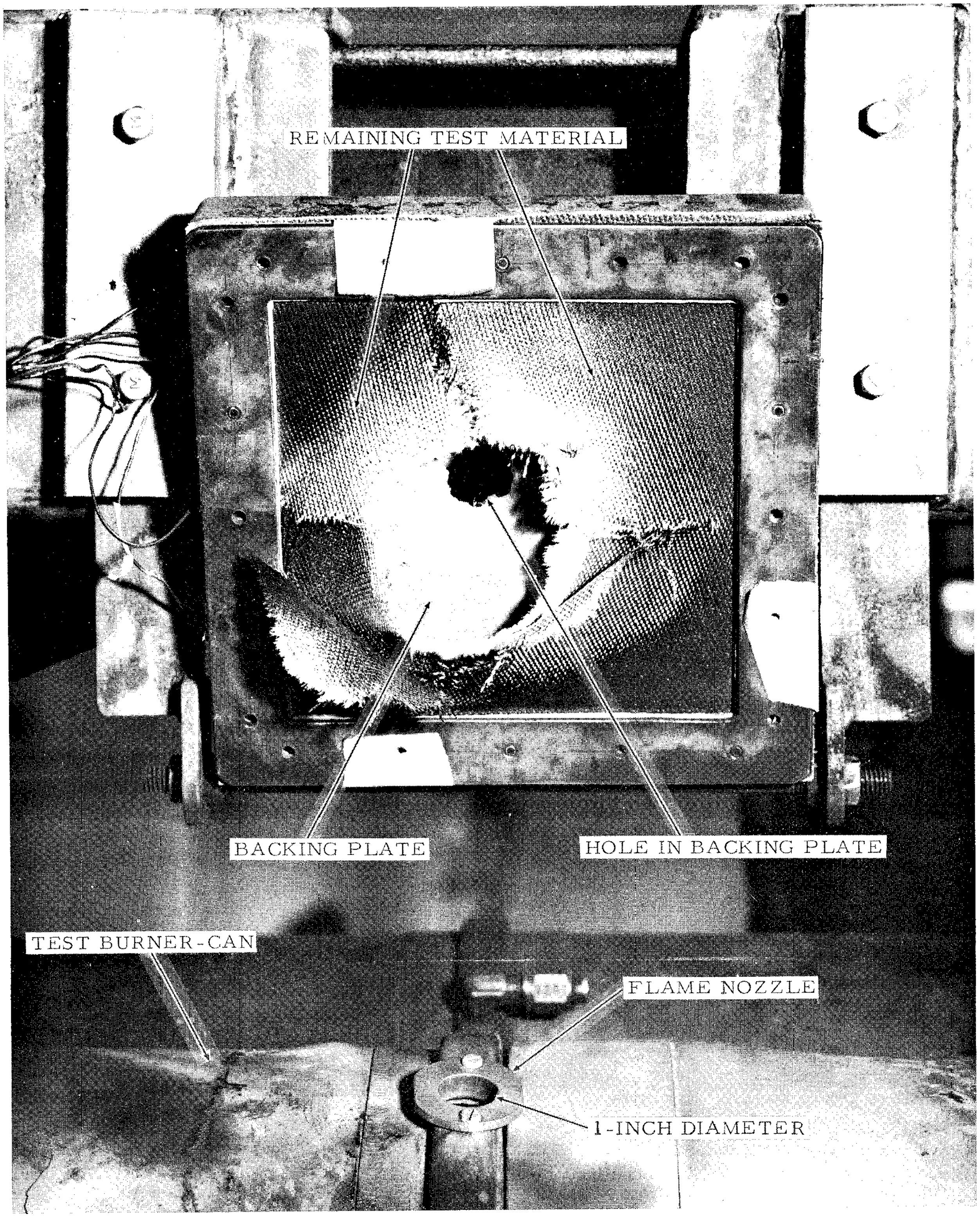


FIG. 9 TEST NO. 23 SPECIMEN AFTER EXPOSURE TO BURN-THROUGH FLAME. FAILURE OCCURRED IN 3.7 SECONDS

However, the result of Test No. 27 shows a failure of the material and the steel backing plate in only 14 seconds. The only plausible reason for the different results obtained in this test and Test No. 26 is that the white material of the latter test, which remained intact around the failed area, kept the heat from the flame concentrated in one area, thus increasing the temperature of the steel to beyond the structural limit while the black material protected the backing plate for a period of time until it was burned and blown off.

Test No. 28 was performed on a material which was quite different from others tested. The material was a transpiration-cooled air mat which was fabricated by weaving strands of stainless steel wire into a textile-like material forming a pillow-like container. The thickness of the material was .020 inch. The overall dimensions of the pillow were 6 inches by 6 inches by 1-inch thick. Tabs were provided for mounting in the test fixture. A polyurethane coating was applied to the steel mesh in order to allow a static pressure to be maintained inside the pillow. If proven satisfactory, the mat would be pressurized to about 65 pounds-per-square-inch (gage) by aircraft engine bleed air. The pressure would remain static until melting or burning of the polyurethane coating occurred. When a burn-through failure occurred, the heat of the flame would melt the sealing coating and allow the bleed air to escape, thus cooling the woven steel and providing the protection required. The specimen used in Test No. 28 was connected by a 1-inch line to a 450-cubic-foot air reservoir which was pressurized to 65-pounds-per-square-inch (gage). There was also a connection to which was attached a 1/4-inch line for pressure instrumentation, and thermocouples were imbedded in the front and back faces of the specimen to record the appropriate temperatures. A flow meter was installed to the 1-inch line to measure the flow rate of the cooling air. The result of the test is given in the table. The material withstood the flame as long as the air system remained operative. Some leakage of cooling air through the sealing material before the mat was exposed to the test flame was noted. Also, the manufacturer specified that the maximum ambient temperature to which this material could be exposed before melting was about 300$^{o}$F, which was far below the ambient temperatures encountered in present and future engine combustion sections. There were, according to the manufacturer, other higher temperature coatings which could have been used, but further tests would have had to be run to determine their reliability.

Tests Nos. 29 through 32 were performed on various combinations of zirconium cloth and felt with various combinations of face and back plates of Hastelloy X and aluminum as listed in the table. None of these tests produced a time-to-failure of over 4 seconds, and in most tests the cloth or felt was blown apart as soon as the flame came into contact with it.

Tests Nos. 33 through 35 were performed on basically the same type of material; i.e., a fiber-impregnated carbon material, the difference being in amount of fiber content and method of manufacture. The specimen used in Test No. 33 produced a time-to-failure of 35 seconds, and the specimen used in Test No. 35 produced a time-to-failure of 19 seconds, both of which are considered relatively poor for specimens of such thickness and density. However, the specimen used in Test No. 34 withstood the burn-through flame for over 2-1/2 minutes before it failed. It should be noted that the specimen glowed red during the entire test except for the first 10 seconds. This indicated that the back side temperature was quite high.

## Flame Impingement Angle Tests

In conjunction with the tests performed to find a material to be used as a firewall for protection against a burn-through failure, a short series of tests was performed to determine the effect of changing the angle at which a material is exposed to the burn-through flame. In the tests described in Table 2, all specimens were located in a position to allow the flame to impinge perpendicularly on the front face of the specimen. The conditions and results of tests conducted to investigate the effect of impingement angel on the time-to-failure of a firewall material are listed in Table 3.

TABLE 3.--EFFECT OF FLAME IMPINGEMENT ANGLE ON FIREWALL MATERIAL

| Angle of Specimen from Normal (degrees) | Engine Power Setting (percent) | Distance From Can (inches) | Time-to-Failure (seconds) |
|---|---|---|---|
| 0 | 80 | 2 | 2 |
| 15 | 80 | 2 | 2 |
| 30 | 80 | 2 | 2 |
| 45 | 80 | 2 | no failure in 1 minute |
| 60 | 80 | 2 | no failure in 1 minute |

All tests were performed at an engine power setting of 80 percent and at a distance from the can to the center of the specimen of 2 inches. All specimens were .015-inch-thick 347 stainless steel. At specimen angles of $15^{\circ}$ and $30^{\circ}$ from normal, the time-to-failure was no different from the time-to-failure for perpendicular impingement, which is given for Test No. 1 of Table 2. However, when the specimen angle was increased to $45^{\circ}$ and $60^{\circ}$, no failure occurred in a test duration of 1 minute. The lack of failure in the last two tests was apparently due to the fact that the offset angle of impingement decreased the normal force component of the flame dynamic pressure to the level where the material could structurally withstand it.

Flat-Plate Impingement Characteristics of the Flame

An investigation was undertaken to define the impingement characteristics of the burn-through flame in order to provide a better understanding of the conditions which a firewall material must withstand. Information furnished by the J-47 engine manufacturer indicated that the estimated maximum flame temperature was approximately 3000°F, with a flow rate through a 1-inch-diameter hole of approximately 1 pound per second and a velocity of 2800 feet per second (sonic) at the burn-through hole with the gases expanding to supersonic velocities after leaving the burner-can.

Since a firewall material will act as a flat-plate in the supersonic flame at the time of a burn-through failure occurence, a test program was undertaken to determine the flat-plate impingement characteristics for the J-47 engine burn-through flame at various engine power settings and at various representative distances from the modified burner-can. The characteristics measured were the temperature at the plate and in the core of the flame and the pressure exerted on the plate by the flame at the center of impingement. The temperature measured will hereafter be termed "reference temperature" and the pressure measured will be termed "plate pressure."

The method of approach employed to measure these characteristics involved the fabrication of a 1/2-inch-thick steel plate with provisions for installation of a thermocouple for measurement of the reference temperature and with a hole drilled through it which was attached to a mercury manometer by steel tubing for measurement of the plate pressure. The positioning of the plate over the burn-through hole, the back side attachment of the thermocouple, and the pressure-transmitting tubing are shown in Figure 10. A view of the front side of the steel plate is shown in Figure 11. It is noted from the latter figure that the thermocouple and the hole were quite close together so that the experimental data were from approximately the same area of the flame. The plate was accurately placed in the burn-through flame to allow the hole for measuring the plate pressure to be located as close as possible to the exact center of the flame since this was where the plate pressure was maximum. (See Reference 2, Figure 16.) The thermocouple was installed from the back side at a 45° angle and positioned so that it was about 1/32 inch in front of the front face of the plate and completely insulated from any part of the plate. The thermocouple consisted of an all-platinum negative lead and a 13-percent rhodium, 87-percent platinum positive lead.

The series of tests conducted encompassed taking instrumentation readings at engine power settings of 50, 60, 70, 75, 80, 85, 90, and 95 percent of rated engine rpm for distances from the burner-can varying from 1 to 8 inches at 1/2-inch intervals. The data collected are listed in Tables 4 and 5. Table 4 lists the temperature readings

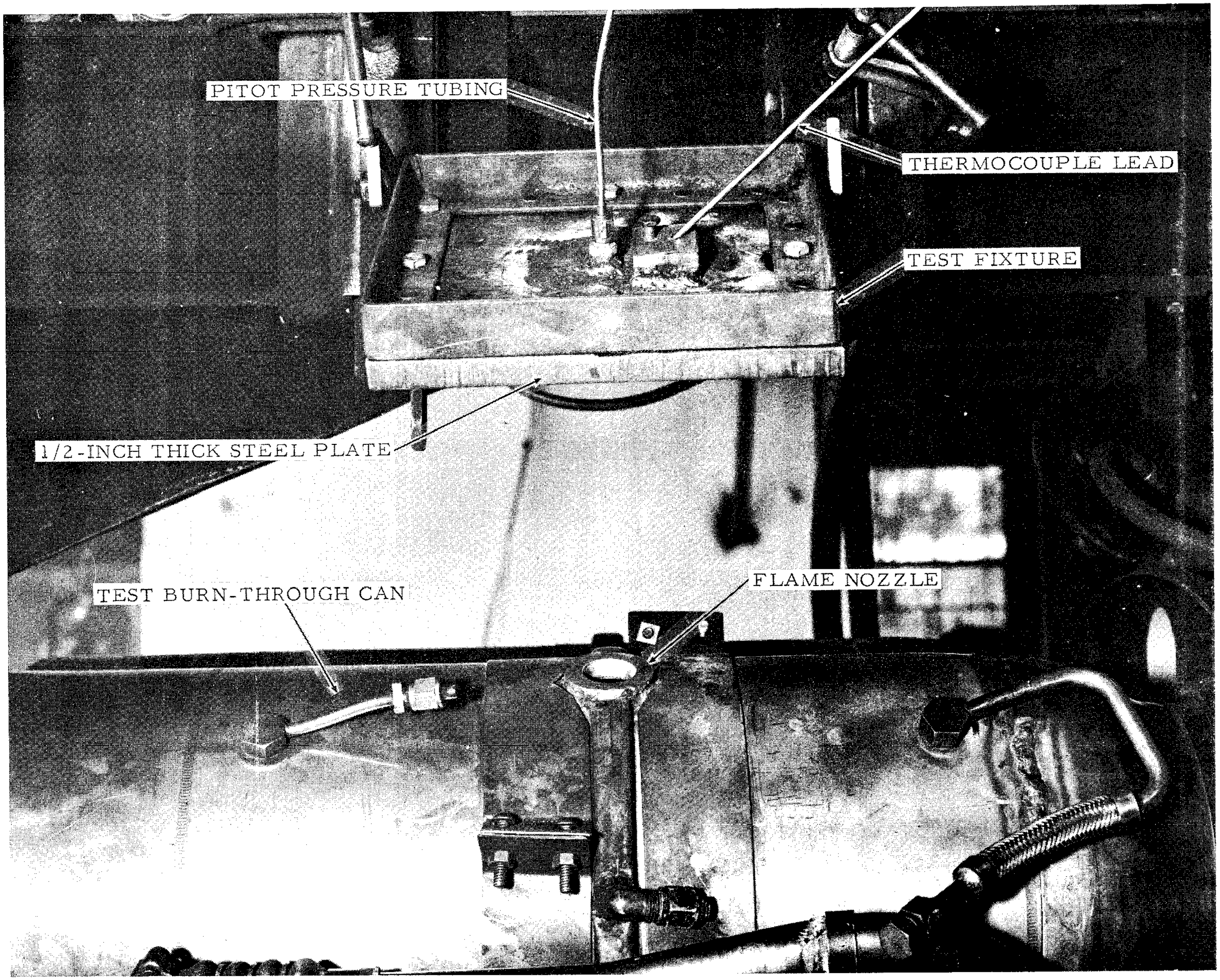


FIG. 10 POSITIONING OF $\frac{1}{2}$-INCH THICK STEEL PLATE OVER BURN-THROUGH HOLE FOR MEASURING FLAME CHARACTERISTICS AT $7\frac{1}{2}$-INCH DISTANCE FROM THE BURNER-CAN

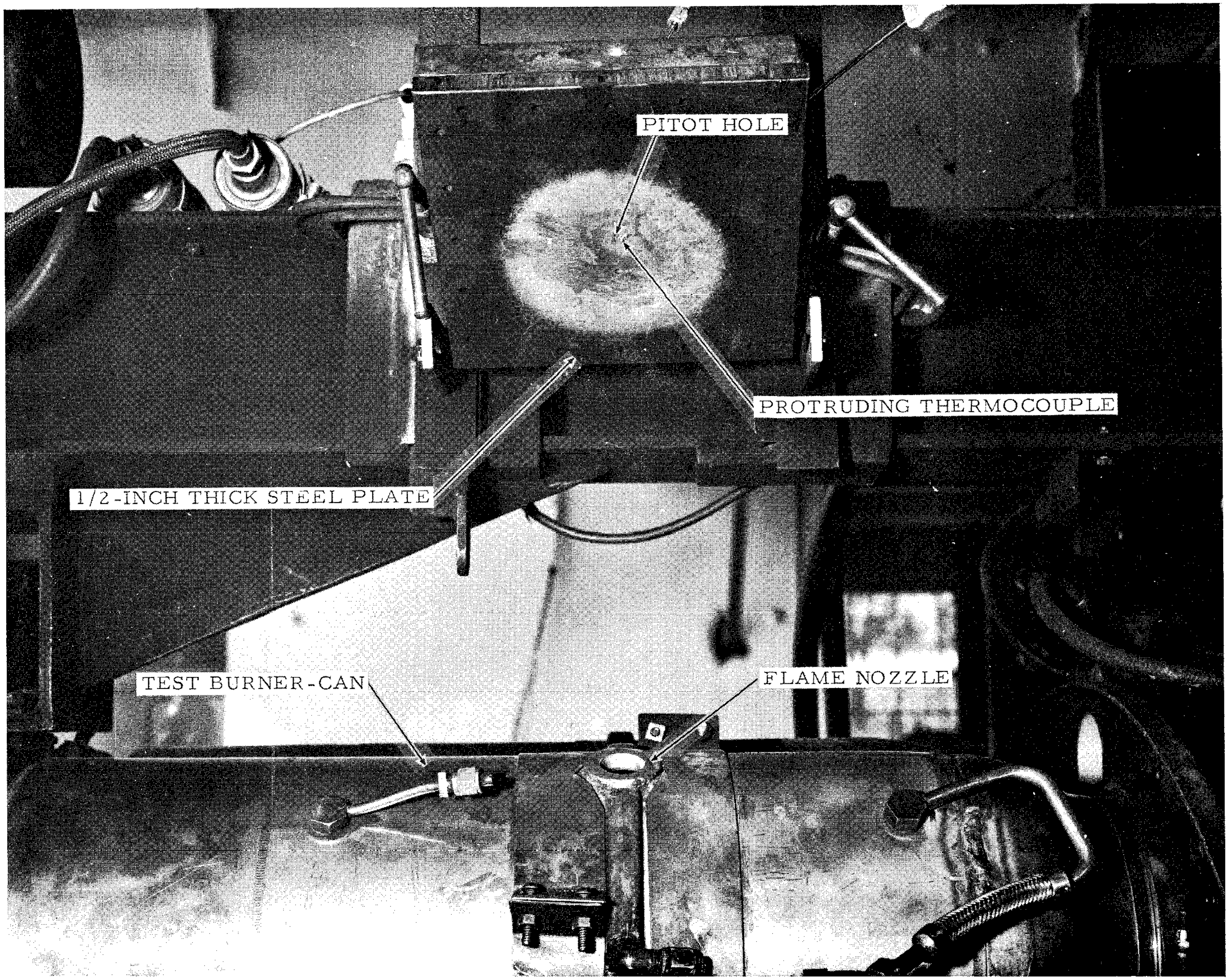


FIG. 11 VIEW OF UNDER-SIDE OF $\frac{1}{2}$-INCH STEEL PLATE

TABLE 4.--PLATE IMPINGEMENT TEMPERATURE CHARACTERISTICS OF BURN-THROUGH FLAME

| Engine Power Setting | Distance from Burner-Can (inches) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 1.5 | 2 | 2.5 | 3 | 3.5 | 4 | 4.5 | 5 | 5.5 | 6 | 6.5 | 7 | 7.5 | 8 |
| (% rpm) | (°F) | (°F) | (°F) | (°F) | (°F) | (°F) | (°F) | (°F) | (°F) | (°F) | (°F) | (°F) | (°F) | (°F) | (°F) |
| 50 | 1600 | 1700 | 1750 | 1650 | 1600 | 1500 | 1350 | 1300 | 1175 | 1100 | 1050 | * | * | * | * |
| 60 | 2050 | 2050 | 2100 | 1925 | 1775 | 1775 | 1600 | 1425 | 1300 | 1175 | 1125 | 1100 | 1025 | 1050 | 1150 |
| 70 | 2300 | 2400 | 2450 | 2300 | 2350 | 2300 | 2050 | 1975 | 1875 | 1625 | 1650 | 1400 | 1325 | 1225 | 1400 |
| 75 | 2350 | 2600 | 2550 | 2475 | 2300 | 2350 | 2175 | 2150 | 1925 | 1800 | 1725 | 1550 | 1450 | 1450 | 1550 |
| 80 | 2450 | 2500 | 2700 | 2575 | 2575 | 2600 | 2425 | 2450 | 2375 | 2275 | 2325 | 2125 | 1925 | 1950 | 1875 |
| 85 | 2550 | 2550 | 2575 | 2675 | 2425 | 2650 | 2525 | 2475 | 2525 | 2525 | 2450 | 2375 | 2200 | 2175 | 2300 |
| 90 | 2650 | 2750 | 2650 | 2725 | 2675 | 2650 | 2750 | 2525 | 2675 | 2675 | 2675 | 2625 | 2550 | 2550 | 2575 |
| 95 | 2650 | 2875 | 2775 | 2525 | 2825 | 2700 | 2850 | 2775 | 2760 | 2750 | 2750 | 2700 | 2650 | 2550 | 2750 |

* These readings were below 1000°F, which was the minimum recordable temperature.

TABLE 5.--PLATE IMPINGEMENT PRESSURE CHARACTERISTICS OF BURN-THROUGH FLAME

| Engine Power Setting | Distance from Burner-Can (inches Hg absolute) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (% rpm) | 1 | 1.5 | 2 | 2.5 | 3 | 3.5 | 4 | 4.5 | 5 | 5.5 | 6 | 6.5 | 7 | 7.5 | 8 |
| 50 | 44.37 | 43.11 | 43.86 | 42.54 | 40.85 | 39.58 | 39.56 | 37.53 | 37.03 | 36.48 | 35.95 | 36.30 | 34.64 | 34.14 | 33.01 |
| 60 | 46.87 | 53.11 | 54.36 | 52.79 | 51.85 | 50.83 | 49.76 | 44.78 | 44.28 | 42.98 | 42.70 | 40.93 | 39.14 | 39.39 | 37.26 |
| 70 | 61.12 | 69.86 | 68.36 | 67.54 | 67.60 | 66.08 | 65.31 | 62.03 | 61.73 | 57.73 | 56.70 | 54.18 | 50.14 | 47.64 | 46.51 |
| 75 | 67.87 | 72.86 | 77.61 | 74.54 | 75.10 | 73.83 | 73.31 | 70.78 | 71.53 | 66.48 | 64.95 | 61.93 | 56.14 | 54.89 | 53.26 |
| 80 | 73.62 | 66.36 | 87.11 | 75.04 | 82.85 | 81.33 | 77.06 | 78.78 | 80.78 | 76.23 | 74.20 | 72.93 | 65.34 | 61.64 | 61.26 |
| 85 | 79.12 | 69.86 | 57.86 | 84.49 | 70.85 | 92.08 | 80.56 | 82.78 | 86.78 | 85.48 | 82.45 | 80.43 | 74.89 | 72.14 | 69.01 |
| 90 | 84.12 | 74.36 | 58.36 | 84.08 | 74.60 | 69.83 | 94.81 | 79.28 | 83.03 | 88.73 | 90.70 | 87.18 | 81.64 | 80.64 | 75.96 |
| 95 | 88.87 | 77.86 | 61.36 | 48.79 | 74.10 | 66.58 | 94.06 | 87.53 | 78.53 | 97.48 | 91.45 | 94.43 | 85.39 | 86.64 | 79.76 |

taken directly from the thermocouple probe while Table 5 lists the absolute pressure readings in inches of mercury picked up by the hole in the plate.

To more fully visualize the meaning of the data and the type of flame that is emitted from the test burner-can, three photographs of the flame taken during the impingement tests are provided in Figures 12 through 14. All three photographs were taken during tests with the steel plate located 7.5 inches from the burner-can. Figure 12 portrays the flame with an engine power setting of 70-percent rpm; Figure 13, 80-percent rpm; and Figure 14, 90-percent rpm. Referring to Table 6, it is seen that all three figures represent supersonic flow since the ratio $P_\infty/P_o$ is less than the critical ratio 0.546 (assuming K = 1.3) for these power settings.

TABLE 6.--BURNER-CAN STAGNATION PRESSURE TABULATION

| Engine Power Setting, (% rpm) | Burner-Can Stagnation Pressure ($P_o$), (inches Hg absolute) | $P_\infty/P_o$ |
|---|---|---|
| 50 | 45.22 | .662 |
| 60 | 55.17 | .542 |
| 70 | 72.17 | .414 |
| 75 | 84.92 | .351 |
| 80 | 96.67 | .310 |
| 85 | 108.42 | .276 |
| 90 | 122.42 | .244 |
| 95 | 134.92 | .222 |

The ratio of $P_\infty/P_o$, where $P_\infty$ is the ambient pressure and $P_o$ is the chamber or burner-can stagnation pressure, determines the characteristics of the flame. Figure 1 of Reference 2 indicates the type of flow patterns which occur with different pressure ratios. These ratios are for air with a K of 1.4. The K for the gases present in the burn-through flame is assumed to be 1.3. However, the information is still pertinent for the burn-through flame with the ratios changing slightly for a given type of flame. Combining information in Reference 1 with Figure 1 of Reference 2 it is seen that for K = 1.3, subsonic flow will

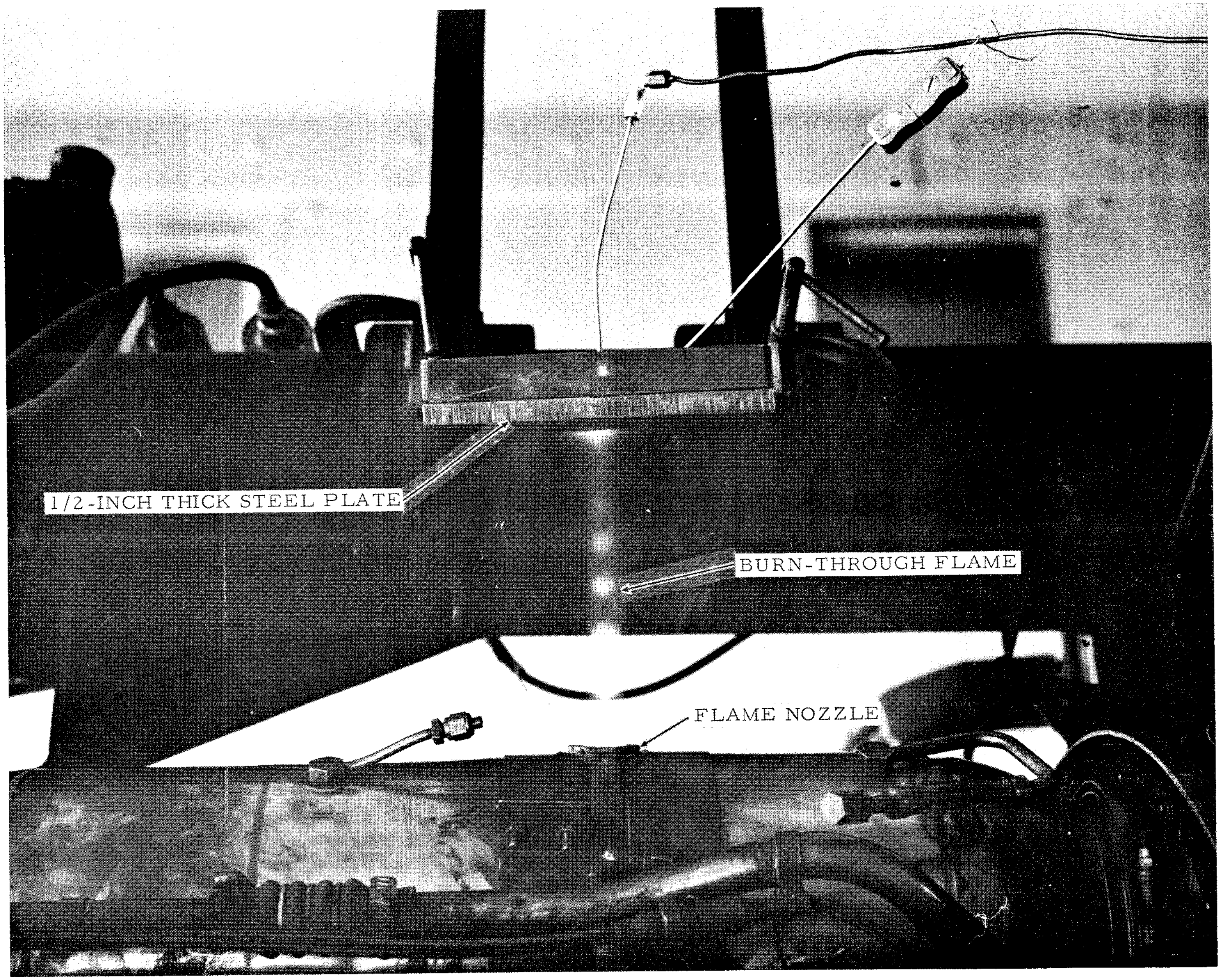


FIG. 12 MEASUREMENT OF BURN-THROUGH FLAME IMPINGEMENT CHARACTERISTICS AT 70-PERCENT ENGINE RPM AND $7\frac{1}{2}$ INCHES FROM THE BURNER-CAN

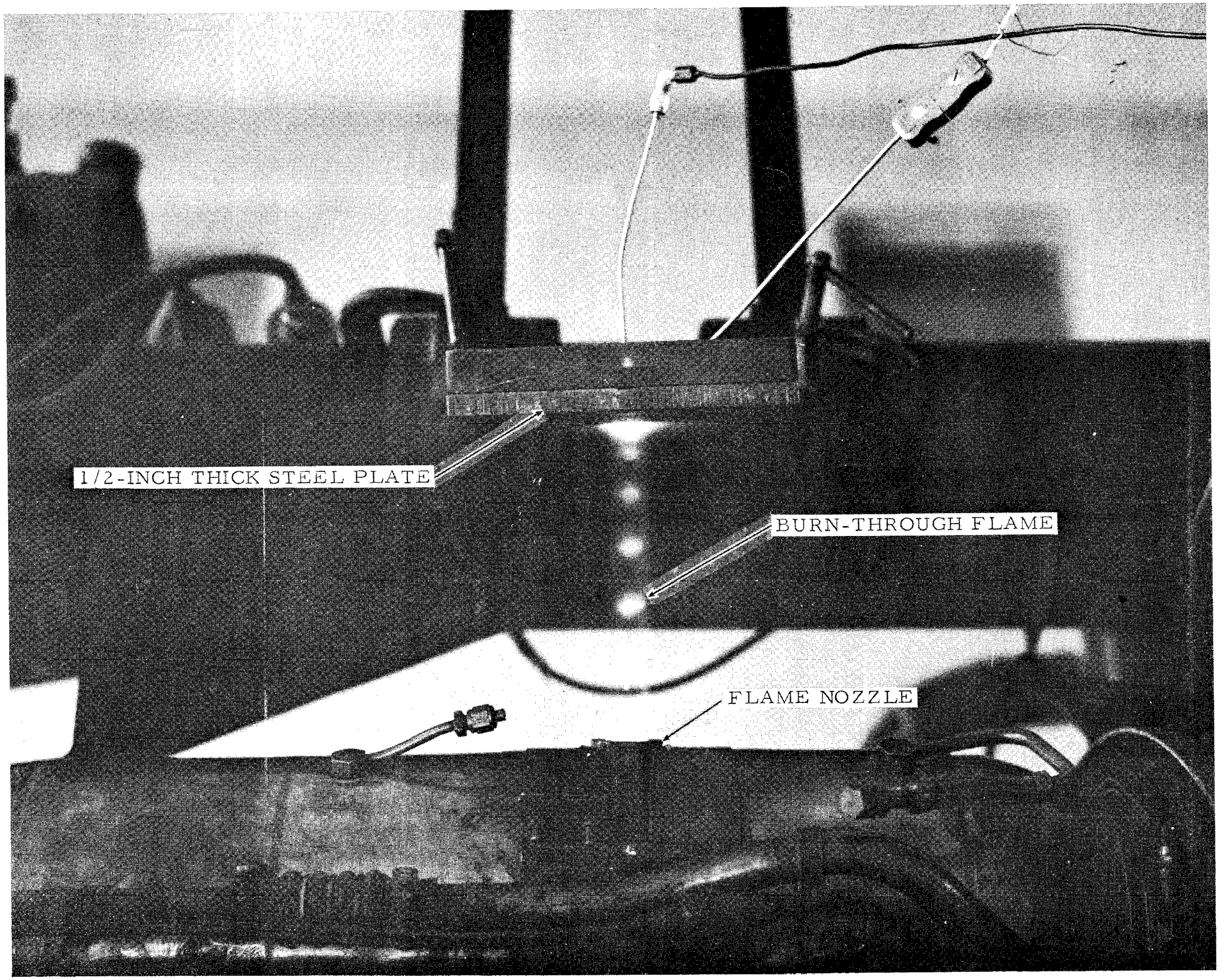


FIG. 13 MEASUREMENT OF BURN-THROUGH FLAME IMPINGEMENT CHARACTERISTICS AT 80-PERCENT ENGINE RPM AND $7\frac{1}{2}$ INCHES FROM THE BURNER-CAN

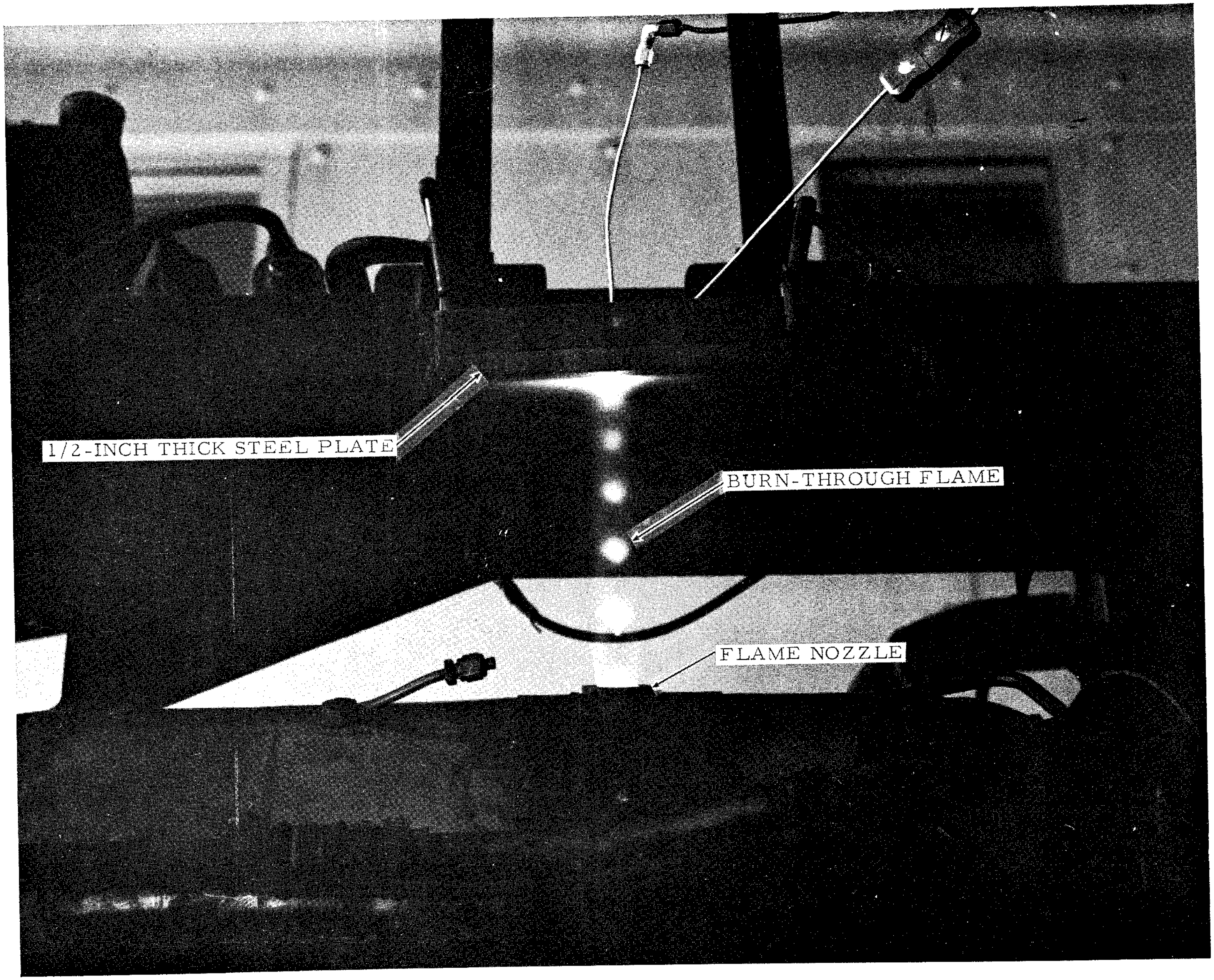


FIG. 14 MEASUREMENT OF BURN-THROUGH FLAME IMPINGEMENT CHARACTERISTICS AT 90-PERCENT ENGINE RPM AND $7\frac{1}{2}$ INCHES FROM THE BURNER-CAN

result from ratios of $P_\infty$ to $P_0$ between 1 and 0.546; moderately underexpanded flow will result from ratios between 0.491 and 0.268; and highly underexpanded flow will result from ratios between 0.268 and 0. The subsonic flow is characterized by a lack of shocks, while the moderately underexpanded flow is characterized by shock cells with oblique shocks, and the highly underexpanded flow is characterized by shock cells with normal shocks.

Figure 12 shows a flow which is moderately underexpanded, with the pressure ratio at this power setting being toward the higher end of the range. Therefore, the shocks become weak with the flow shocking down after four or five shocks to subsonic flow before the gases reach the steel plate. This is apparent in the figure since there are no shock diamonds in the area of the plate.

Figure 13 shows a flow which again is moderately underexpanded, but at this engine power setting the pressure ratio is toward the lower end of the range causing the shocks to be stronger than those seen in Figure 12. With the stronger shocks, the flow does not shock down to subsonic velocity before the gases reach the plate (except as noted below) as indicated by the presence of shock diamonds in the area of the plate in the photograph.

Figure 14 shows a flow which according to the compression ratio given in Table 6 for the 90-percent power setting is of the highly underexpanded type. However, the shocks still appear as oblique and not normal. This is due to the fact that the ratio is still quite close to the moderately underexpanded range. As before, it is seen that the flow has not shocked down to subsonic flow in the region of the plate.

The flames, noted in Figures 13 and 14, would remain supersonic in nature for another few inches if it were not for the plate interrupting the flow. The plate naturally forces the gases to slow down and change direction. In order for the gases to accomplish this sudden change, a normal shock is formed. The gases upstream of this shock are supersonic while the downstream gases are subsonic. The normal shock can be seen in both Figures 13 and 14 about one-half inch in front of the plate. Table 52 of Reference 1 presents the properties of a perfect gas with $K = 1.3$ before and after a normal shock. It is noted from this table that with increasing upstream Mach Number, the downstream Mach Number decreases and the static pressure, temperature, and density ratios (downstream to upstream) all increase. Also, for any single Mach Number greater than Mach 1, the static pressure, temperature, and density of the gases will be greater downstream of the shock than upstream of it. This explains the bright, opaque area in the region directly in front of the plate. This area is due to the increase in temperature, pressure, and density as the gases cross the normal shock. The same phenomenon occurs downstream of an oblique compression shock since the gases slow down when crossing the shock thus increasing the static pressure, temperature, and density sufficiently to form the opaque area termed a shock diamond.

The gases accelerate when they cross the expansion shock, which forms the downstream portion of the diamond, thus losing static pressure, temperature, and density and the flame again becomes transparent.

Reference 3 provides a very illustrative description of how the oblique shocks are formed and shows the pressure distributions in the flame near the nozzle in a simplified form. It is seen from this illustration that there is a portion of the flame just upstream from the shock which has a static pressure below the ambient pressure surrounding the flame. Reference 3 also provides information on calculating flow angles, mach angles, and velocities. This method of approach is known as the Method of Characteristics, which solves for these flow characteristics when chamber pressure, temperature, and gas parameters are known. A computer program has been developed which employs this principle.

With the above description of the mechanics of the burn-through flame, the information in Tables 4 and 5 becomes more understandable. The pressures given in Table 5 are stagnation pressures which are either ratioed with the ambient pressure to obtain the stream Mach Number for subsonic flows in the area of the plate or used as the stagnation pressure downstream of a normal shock and ratioed with an upstream stagnation or static pressure (using Table 52 of Reference 1) for supersonic flows in the area of the plate to obtain the free stream Mach Number. Since it was not determined at which conditions a normal shock was formed, and since, if a normal shock was formed, no upstream pressure measurements were recorded, the free stream Mach Numbers were not calculated. In order to obtain information upstream of the normal shock, a specially designed supersonic probe would have to have been employed.

Although the Mach Number of the free flow was not obtained from the data in Table 5, the data provides useful information with regard to the project objectives. The pressures measured indicate the impingement pressures which a potential firewall material must withstand in order to provide protection against a burn-through type of failure at the distances and engine power settings specified in the table.

Likewise, the information provided in Table 4 indicates the temperatures of the impinging gases which a candidate firewall material must withstand at the distances and engine power settings specified in the table. It is noted that these temperatures are minimum values, since they are uncorrected for velocitv error, conduction error, and radiation error as identified in Article 52 of Reference 4. The calculation of these errors is omitted from this report since a number of assumptions are required which provides only an estimated, not an accurate value for the degree of error involved.

Pressure-Box Flame Simulation

In order to evaluate the merits of potential firewall materials by means of a laboratory-type device, a few methods of simulating the actual burn-through flame were investigated. With such a device, testing of materials could be accomplished in a much less complex manner than setting a specimen in place and running an engine modified to produce a burn-through failure. One attempt to simulate the burn-through flame was accomplished by use of what was termed a "pressure box." This involved simulating the dynamic pressure of the burn-through flame with a static pressure and the temperature of the flame with an oxygen-propane flame. A pressure box, which would allow a test panel 8 inches square to be mounted on one side, as shown in Figure 15, was fabricated. The test panel was bolted to the flanges of the box and sealed so that the box could be pressurized to simulate the dynamic pressure of the burn-through flame. The box was pressurized with the specimen in position, heating the specimen with an oxygen-propane flame, and noting the time-to-failure of the specimen. Since data previously described were readily for available for comparison, the times-to-failure of like specimens were compared. The burner used to supply the flame is shown in Figure 15. The burner was adjusted to provide a flame temperature of 3000°F (measured with a platinum-platinum-rhodium thermocouple) at the area of impingement with the specimen. A failure which resulted from this type of testing is shown in Figure 16. It is seen to be a tensile failure resulting in a line tear instead of the shear-type failure characteristic of the failures which occur in specimens exposed to the engine burn-through flame.

Test panels mostly of .015-inch-thick stainless steel were tested using the pressure-box. The results of these tests are given in Table 7.

TABLE 7.--PRESSURE-BOX TESTING RESULTS

| Test No. | Specimen Thickness (inches) | Flame Temperature (°F) | Box Pressure (psig) | Time-to-Failure (seconds) |
|---|---|---|---|---|
| 1 | .015 | 3000 | 30 | no failure |
| 2 | .015 | 3000 | 45 | 20 |
| 3 | .015 | 3000 | 60 | 12.5 |
| 4 | .015 | 3000 | 75 | 10 |
| 5 | .032 | 3000 | 75 | no failure |

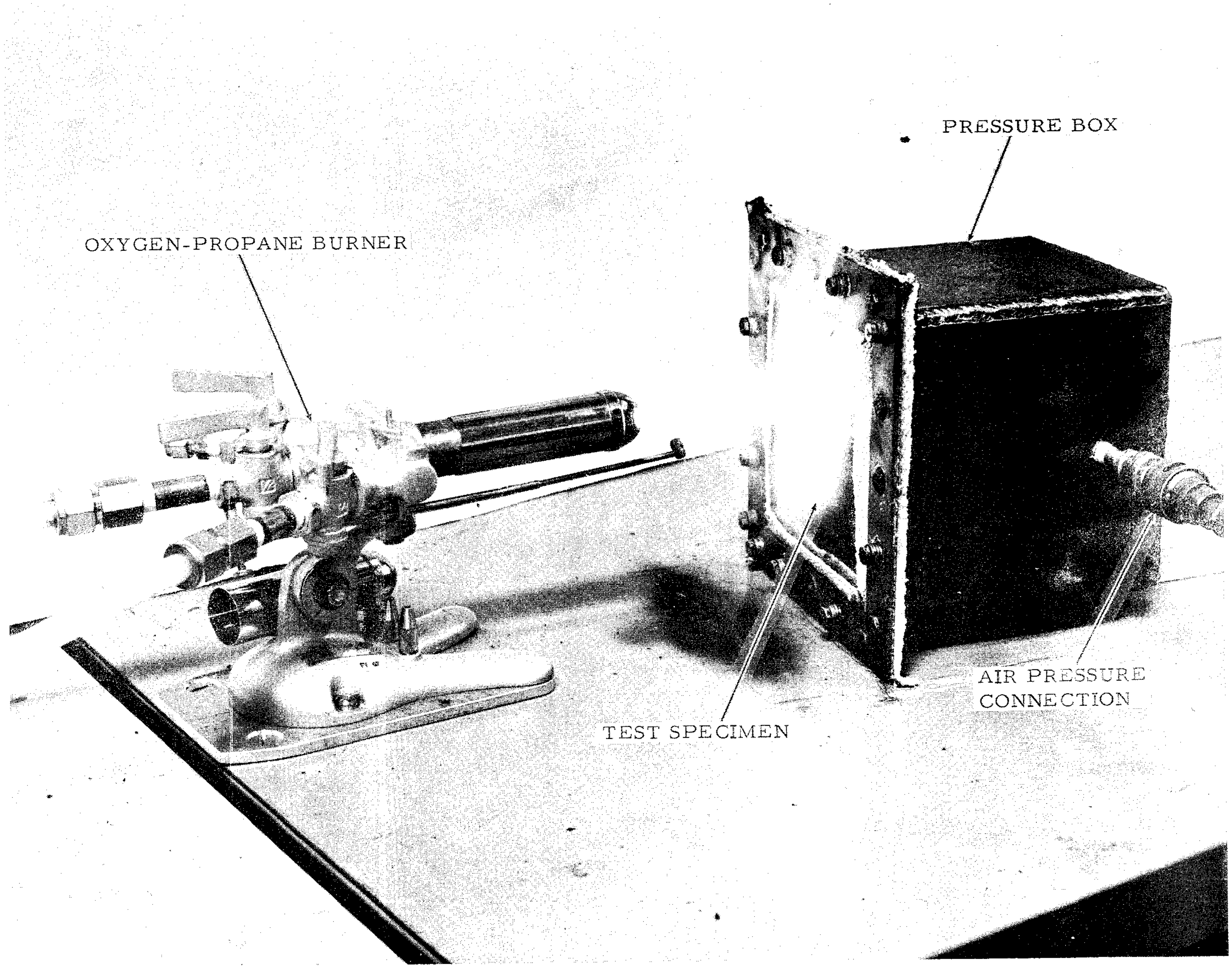


FIG. 15 PRESSURE-BOX TEST IN PROGRESS

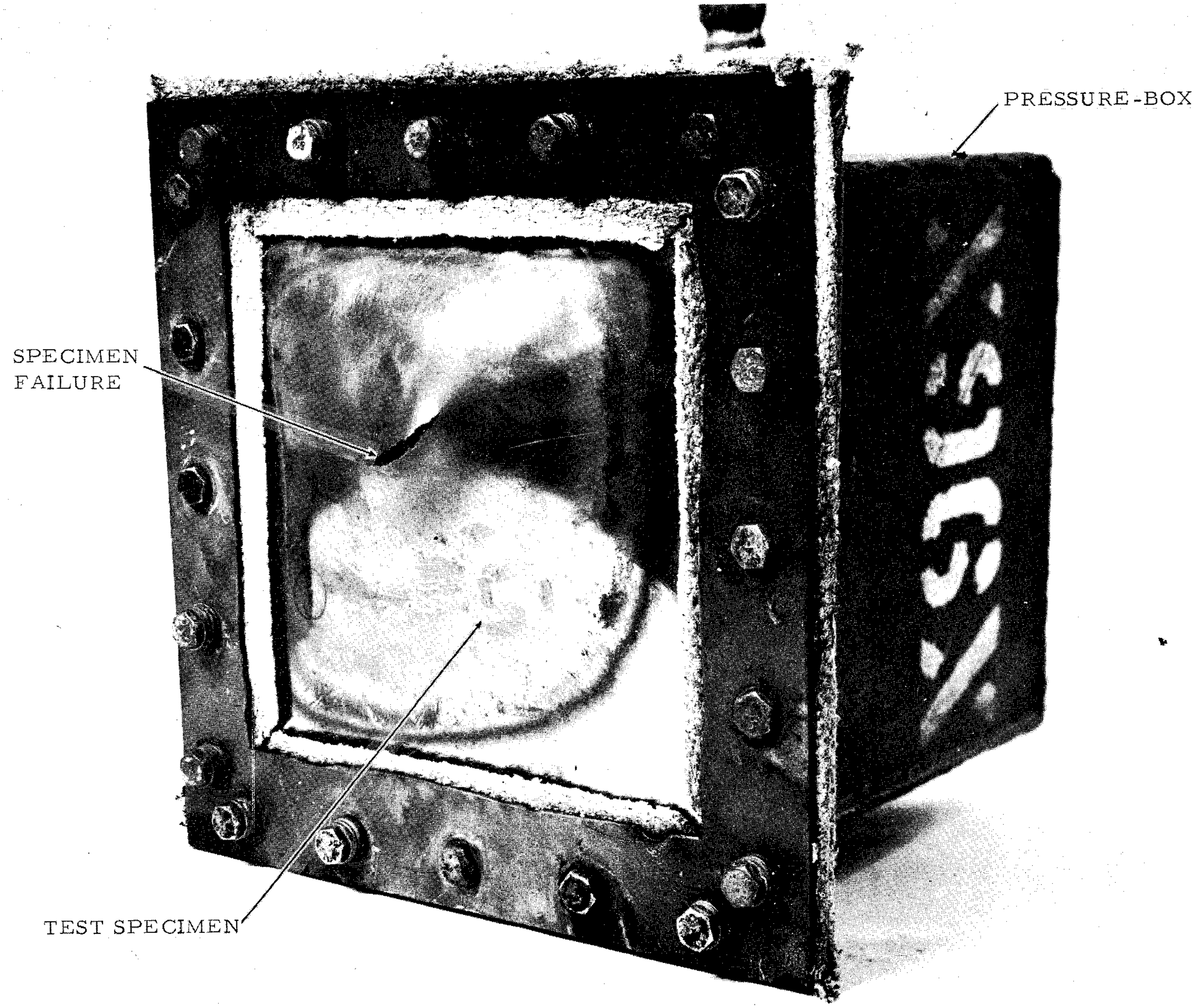


FIG. 16 FAILED PRESSURE-BOX TEST SPECIMEN

As noted in the table, the shortest time-to-failure for .015-inch stainless steel was 10 seconds with a box pressure of 75 pounds per square inch (gage). This pressure represented a pressure ratio between the box pressure and ambient of about 6:1, which was greater than the dynamic pressure of the burn-through flame (about 4:1). However, the time-to-failure was considerably greater than the engine-produced failure in a similar specimen (2 seconds). The result of Test No. 5 shows that no failure occurred in a specimen .032-inch thick, while a failure did occur in a similar engine-tested specimen in Test No. 11 of Table 2 in 4 seconds. No further tests were performed with the pressure-box since the results obtained in these five tests indicated that this type of simulation was unsatisfactory.

Combustion Chamber Simulator Development

Continued effort to develop a burn-through flame simulator resulted in the fabrication of a Combustion Chamber Simulator, which hereafter will be termed "the simulator." The simulator was designed along the lines and principles of a burner-can, except on a much smaller scale. A combustion chamber was fabricated from a 4-inch-diameter steel tube with a 1/4-inch-thick wall and a nozzle which was bolted to the outlet end. The nozzle was internally hemispherical with a 1/2-inch-diameter nozzle hole to allow the burning gases to exhaust. The hole was reduced from the 1-inch diameter employed in the engine burn-through can in order to reduce the quantity of combustion air required, since the air supply was limited.

An air chamber was mounted on the end of the pipe opposite the nozzle, to which were attached two 1-1/4-inch lines, connecting the air chamber with an air reservoir. This combination was bolted to a standard oil burner unit which provided a convenient stand, along with providing the fuel pump for supplying the fuel to the simulator. The device is shown from opposite sides in Figures 17 and 18. A fixture in which specimens were mounted was attached to the forward end of the simulator as may be seen in these figures. An ordinary automobile spark plug, as seen in Figure 18, was used to provide ignition. Since ignition was difficult at times, a line connected to a portable propane cylinder was run into the combustion chamber so that the propane could be ignited prior to the fuel ignition, thus warming the chamber and aiding ignition of the fuel.

The fuel used in the simulator was JP-4 and was supplied through a standard oil burner nozzle capable of supplying 24 gallons of fuel per hour. The nozzle and the forward end of the air chamber with the combustion chamber removed are shown in Figure 19. Shown in the figure is the pattern of the air holes supplying combustion air from the air chamber to the combustion chamber. These were 12 3/8-inch-diameter holes.

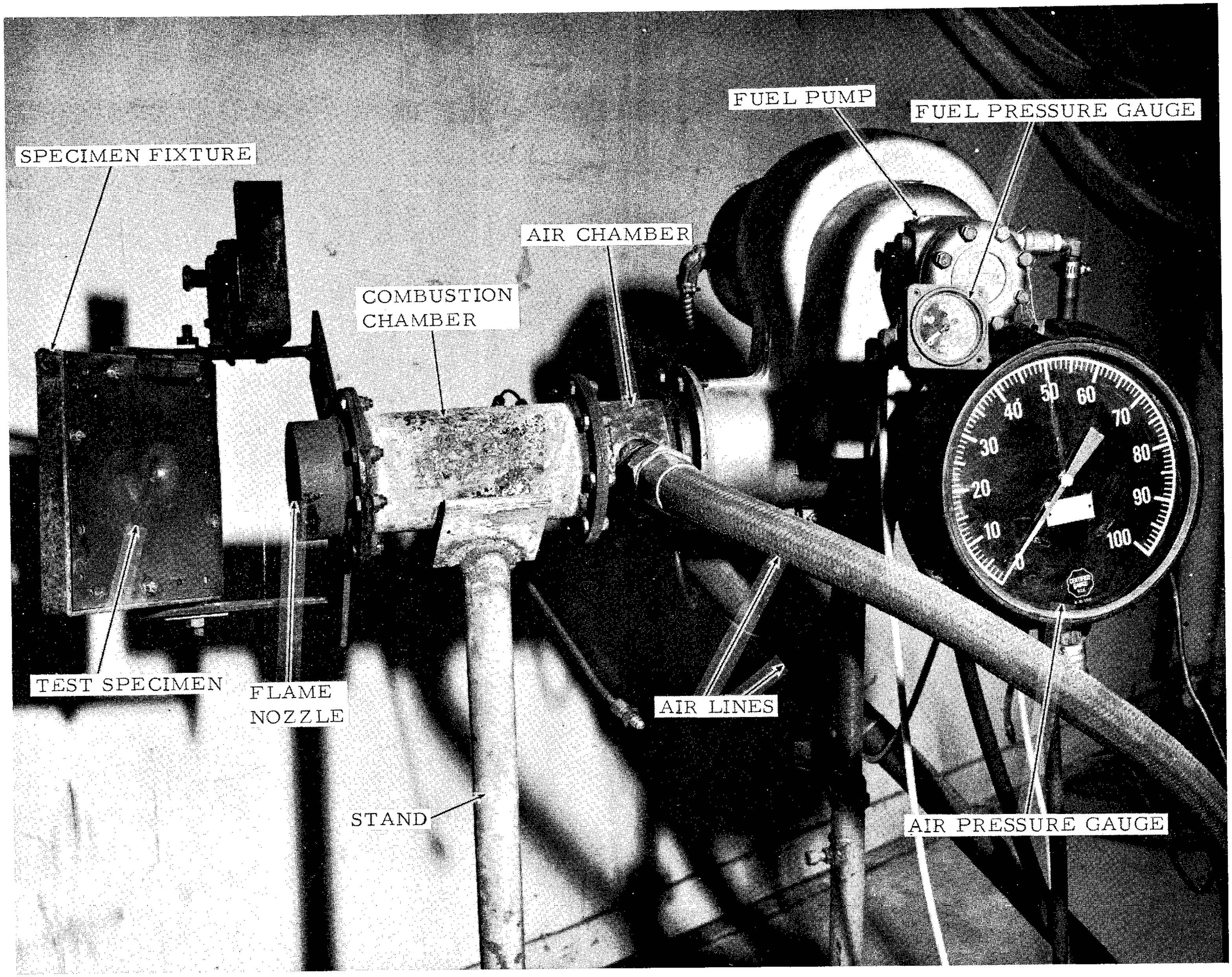


FIG. 17 LEFT SIDE VIEW OF BURN-THROUGH FLAME SIMULATOR

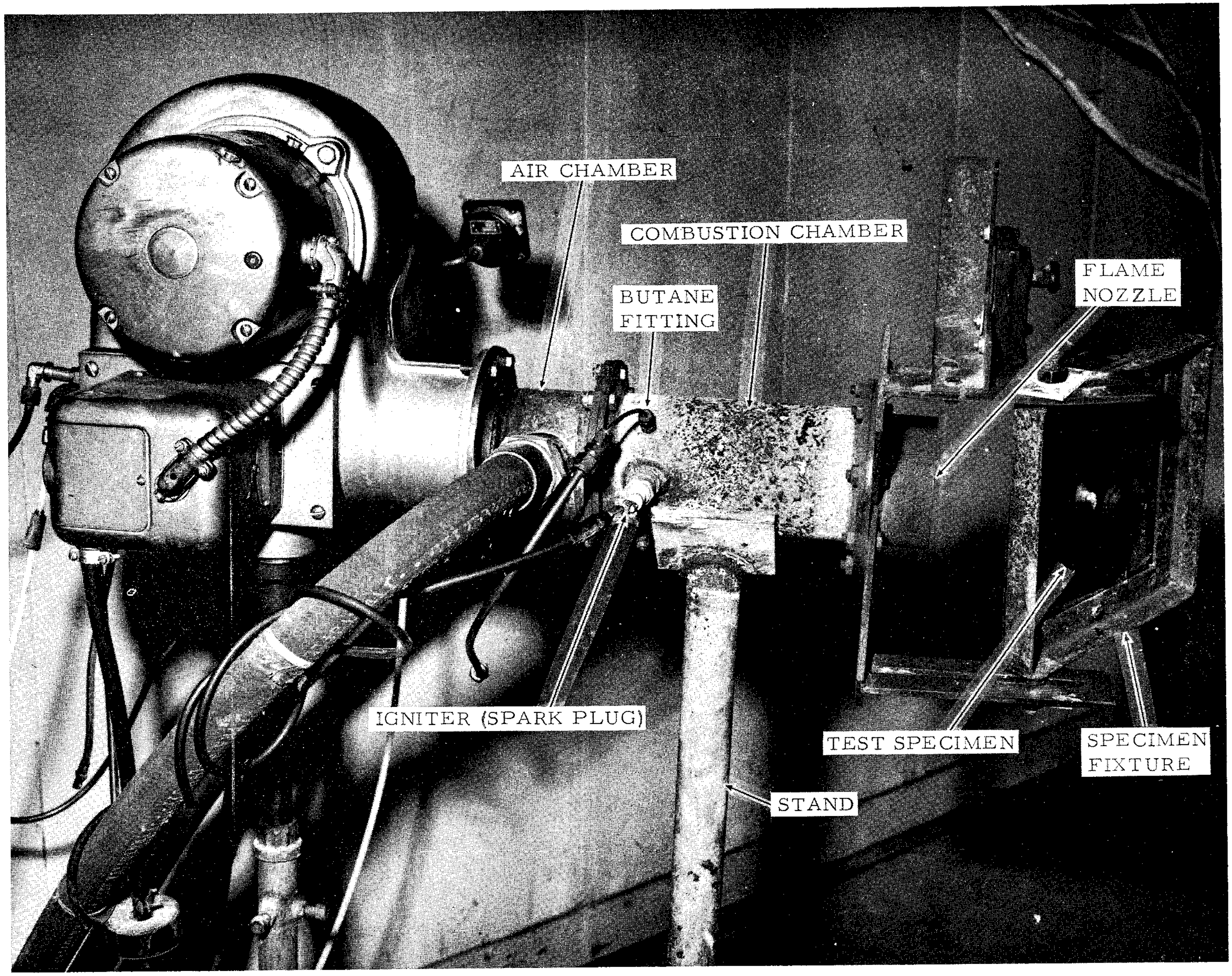


FIG. 18 RIGHT SIDE VIEW OF BURN-THROUGH FLAME SIMULATOR

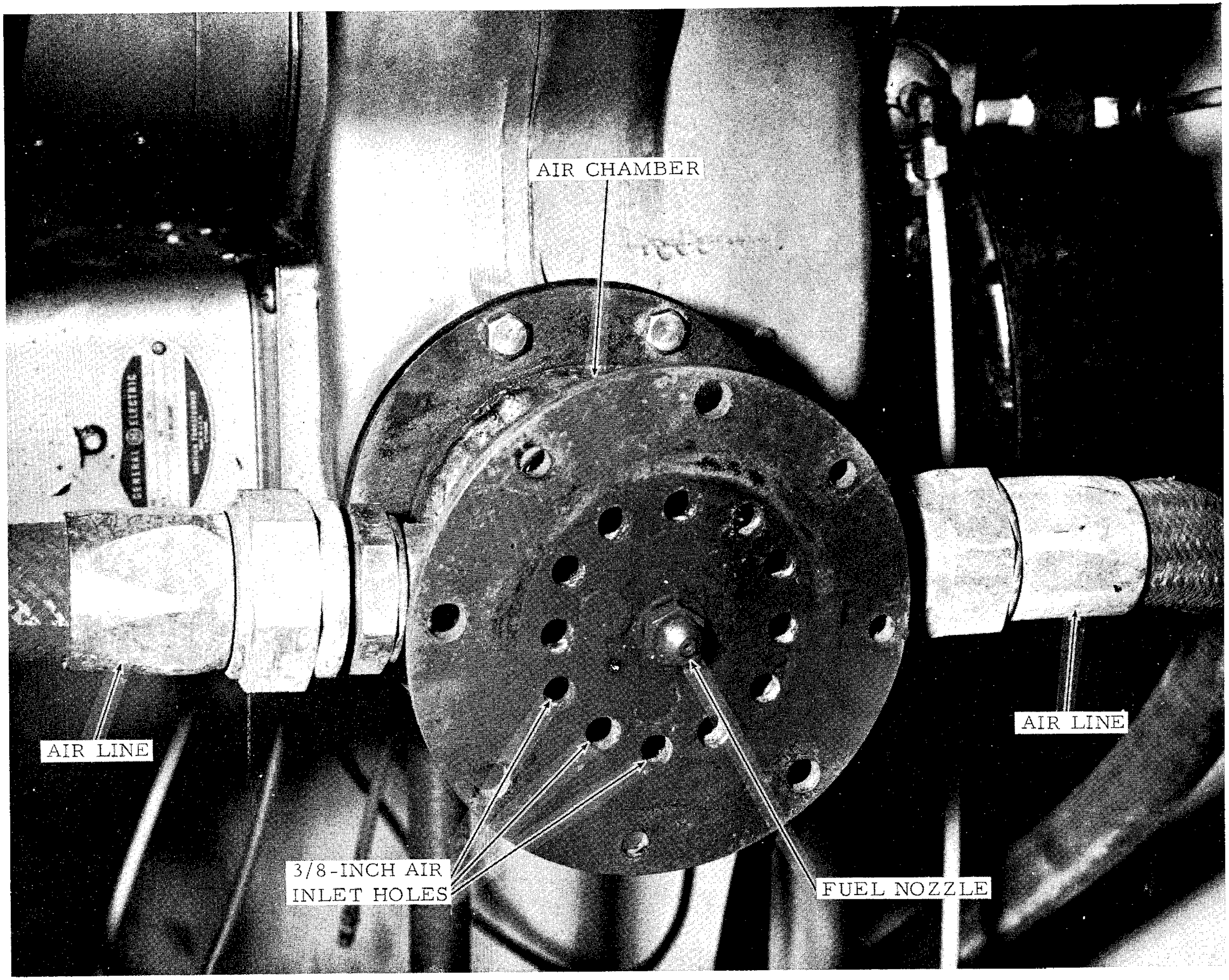


FIG. 19 VIEW OF AIR CHAMBER OF BURN-THROUGH FLAME SIMULATOR

The propane, fuel, and air to the combustion chamber were manually controlled, the first two with needle valves and the air with a gate valve. Gages indicating air pressure, fuel pressure, combustion chamber pressure, and fuel flow were connected to the system. Air at an initial pressure of 120 pounds per square inch (gage) was supplied from a reservoir of 450-cubic-foot capacity. This allowed for an operating time of about 1 minute at maximum fuel flow. Fuel was supplied from the oil burner pump at 100 pounds per square inch (gage).

The operating procedure for testing a specimen by means of the simulator was as follows:

1. The specimen was positioned out of the gas stream from the nozzle, and all valves were closed.

2. The propane valve was opened; the air valve was cracked; and the ignitor energized.

3. After the propane was burning for about 10 seconds, the fuel valve was cracked and air pressure increased.

4. The propane was turned off and the fuel and air control valves opened gradually together until maximum combustion chamber pressure was reached and a fairly rich flame was noted. If the flame was too lean, the flame temperature was too low.

5. The specimen was manually pulled into position and the time-to-failure noted from this time.

With all equipment operating at optimum settings, the following results were obtained using the same 1/2-inch steel plate that was used to measure the engine flame impingement characteristics:

1. Reference temperature: 2700°F

2. Plate pressure: 66.5 inches of mercury (abs.)

3. Time-to-failure of .015-inch-thick stainless steel: 3 seconds at about 2.5 inches from nozzle.

4. At least five shock diamonds were clearly visible in the flame when the fuel-air ratio was rich.

5. Fuel flow was 6 gallons per hour although the nozzle was rated at 24 gallons per hour. This was due to insufficient fuel pressure.

6. Combustion chamber pressure was 65 pounds per square inch (gage). This could be increased to 75 pounds per square inch, and combustion could still be maintained. However, at 75 pounds per square inch (gage), the flame severity was decreased due to the cooling effect of the increased amount of air and the added back pressure on the fuel nozzle which reduced the fuel flow.

These results indicated that the simulator flame closely paralleled the engine-produced burn-through flame with regard to plate impingement temperature and pressure, and the time-to-failure of .015-inch-thick stainless steel, but was not quite equal to it. It was also noted that the results were not always the same, indicating that the flame severity was erratic. This was attributed to the inability of the fuel pump to supply the required fuel to the nozzle which was operating at 25 percent of rated capacity. A fuel pump with a greater capacity and a higher operating pressure could be expected to produce a more severe and a more stable flame.

## SUMMARY OF RESULTS

The results obtained from the tests conducted are as follows:

1. A burner-can failure suitable for testing potential firewall materials was produced in one of the combustors of a J-47 engine.

2. The present firewall material, .015-inch-thick stainless steel, failed in 2 seconds when exposed to the burn-through flame.

3. Various thicknesses of stainless steel up to and including .064 inch failed in less than 17 seconds when exposed to the burn-through flame with an engine power setting of 85 percent and at a distance of 3 inches from the burner-can.

4. Specimens of .015-inch-thick stainless steel failed in less than 5 seconds when exposed to the burn-through flame with an engine power setting of 80 percent and at distances from the burner-can of 8 inches or closer.

5. Burn-through flame tests performed on specimens of titanium resulted in shorter times-to-failure than stainless steel of the same thickness.

6. Of a number of nonmetallic or metallic-nonmetallic laminate specimens tested, three withstood the burn-through flame for 2 minutes or more.

7. When the angle of flame impingement was decreased from perpendicular ($90^{\circ}$) to $45^{\circ}$ or less, .015-inch-thick stainless steel material did not fail when exposed to the burn-through flame.

8. The flat-plate impingement characteristics of a burn-through flame for distances from the can of 1 to 8 inches (at 1/2-inch intervals) and for engine power settings between 50 and 95 percent are given in Tables 4 and 5. The maximum measured reference temperature was 2875°F, and the maximum measured plate pressure was 97.48 inches of mercury absolute.

9. Flame simulation, using a pressure-box to simulate the dynamic pressure of a burn-through flame, resulted in failure of a specimen of .015-inch-thick stainless steel with 75 pounds per square inch (gage) in the box in approximately 10 seconds and no failure when a specimen of .032-inch-thick stainless steel was tested.

10. A Combustion Chamber Simulator was designed and fabricated to simulate the burn-through flame. The best result from tests run with this simulator was the failure of a specimen of .015-inch-thick stainless steel in approximately 3 seconds. Measured impingement characteristics were a maximum reference temperature of 2700°F and a maximum plate pressure of 66.5 inches of mercury absolute.

## CONCLUSIONS

Based on the results obtained from the tests conducted, it is concluded that:

1. A burner-can failure can be produced in jet engines which have separate flame tubes or cans.

2. Stainless steel in thicknesses of .064 inch or less, including the presently used firewall material, will not provide adequate protection against a burn-through failure when located within 3 inches of the combustion chamber.

3. The distance at which the firewall material is located from the burner-cans (to an 8-inch maximum) has little effect on the ability of the material to withstand a burn-through failure.

4. Titanium is no more resistant to the burn-through flame than stainless steel of the same thickness.

5. Two of the materials tested in the burn-through flame have the capability of becoming good firewall materials against such a failure. Further tests are required on the carbon material to determine the back-side temperature, and modifications are required on the air mat before a more definitive statement can be made.

6. In an engine with a compression ratio of 5.5:1 or less, if the angle of impingement between a burn-through flame and the present firewall material is $45^{\circ}$ or less, no failure will occur when the distance from the burner-can to the firewall is 2 inches or more.

7. A firewall material employed for protection against a burn-through failure in an engine with a compression ratio of 5.5:1 must withstand gas temperatures up to $2875^{\circ}F$ and gas impingement pressures up to 97.48 inches of mercury absolute.

8. The Combustion Chamber Simulator is a good means for simulating a burn-through flame, but modifications are required to fully develop its potential.

9. The severity of a burn-through flame increases considerably when the engine power is increased from 80 to 85 percent.

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