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FIRE TEST CRITERIA FOR RECORDERS

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16. Abstract

Tests were conducted to investigate fire test criteria as applied to flight data and cockpit voice recorder systems and material. Studies were made to determine the effect of elevated temperature on various types of recording tapes and highly conspicuous exterior coatings which could be applied to recorder covers. Open flaming and enclosed furnace tests were performed on complete recording units in order to obtain data for formulating improved standardized laboratory test methods suitable for evaluating survivability of flight data and cockpit voice recorders in a crash-fire environment.

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INTRODUCTION

Purpose

The project objectives were to (1) establish an improved test method and/or criteria for the determination of the high-temperature survival capability of aircraft flight data and cockpit voice recorders, (2) eliminate multiple interpretation of present Technical Standard Order (TSO) requirements for recorder fire testing, and (3) investigate the integrity of high-conspicuity coatings suitable for use on aircraft recorder exteriors when exposed to high temperatures.

Background

Flight data recorders became a requirement in September 1957 for all aircraft over 12,500 pounds which would be for use in air carrier service over 25,000-foot altitudes. In August 1958, TSO-C51 (Reference 1) became effective. This standard established minimum performance requirements for these recorders.

Methods of recording are of two types: magnetic and direct-writing. In the latter type of system, the recording medium is either an aluminum or stainless steel ribbon. In this recording process, lines are engraved by diamond-pointed styluses on the metal tape medium as it moves over a scribing roller.

At the present time, five parameters are required to be recorded. These are indicated airspeed, altitude, heading, and vertical acceleration, all these with respect to time. There are presently studies underway to investigate the feasibility as well as the need for recording more parameters in a flight data recording system.

In 1964, the Federal Aviation Agency (FAA) issued a requirement for the installation of cockpit voice recorders in turbine-powered aircraft by July 1966 and in all pressurized reciprocating four-engine aircraft by January 1967. This equipment records aircraft cockpit voice communications by radio and communication on the aircraft's interphone system with the passenger compartment in addition to voice or audio signals identifying navigation or approach aids introduced into a headset for speaker. The requirements for these recorders are listed in TSO-C84 (Reference 2).

FAA Advisory Circular AC No. 20-36A (Reference 3) lists by manufacturer and model number voice and flight recorders acceptable under the TSO System. TSO-C51 and TSO-C84 specify standards for flight and voice recorders, respectively. In referring to the minimum standards of performance for aircraft recorders, whether flight data or voice recorders, the language used in the TSO allows for a freedom in determining tests to meet the performance requirements. The TSO specifies that the recorder be subjected to flames of at least 1100°C (2012°F) over at least 50 percent of the outside area for an uninterrupted period of at least 30 minutes with a maximum allowable tape signal change of 2 dB. This requirement specifies the temperature but not the source or the Btu rate of the flame. The temperature at the recorder flame impingement area must be 1100°C (2012°F). Thus, a recorder could meet the TSO requirements by passing a test in which the recorder is exposed to low heat output flames producing a temperature of 1100°C (2012°F) at a point a few inches in front of the recorder, while the temperature at the recorder case could be much less than 1100°C.

The facts are that between the years 1959 and 1967, four flight data recorders could not provide vital information as to the probable cause of the accident in which they were involved due to destruction by fire. These recorders experienced temperatures that exceeded TSO requirements or were broken open during crash impact, thereby negating the protective insulation provided the recorder medium. All of these recorders were the same model, a stylus type of instrument utilizing aluminum tape as the recording medium. (See Appendix A for a detailed history of destroyed recorders during this period.)

One of the more obvious deficiencies of both TSO-C51 and TSO-C84 concerns the exterior color and composition of the recorder covers. Both TSO's require that the recorder covers be painted a bright yellow or orange color, presumably to facilitate location in a wreckage. However, no requirement is provided regarding the material used to fabricate the recorder case or the type of paint used. Many of the present recorders are housed in aluminum dustcovers painted with a conspicuous orange or yellow paint. Since aluminum melts at 1200°F and the temperature of a crash fire is likely to be well above 1200°F, it seems that the brightly colored aluminum case should be inadequate. There are brightly colored ceramic coatings which manufacturers claim will remain intact upon exposure to temperatures up to 2000°F, but these must be applied to a high-melting point substrate. This fact precludes the use of aluminum as the cover material. Thus, with proper high-temperature resistance design, a recorder case could be constructed in such a way as to retain most of its original color upon exposure to temperatures up to 2000°F.

In order to ensure that all recorders conform equally to the TSO requirements, all such recorders must be tested under identical conditions. This can only be effected by establishing a more definitive standard test method, thus eliminating variations in testing procedures as exist at present.

DISCUSSION

Test Procedures and Results

Test procedures for accomplishing the project objectives were divided into three main phases.

Tests conducted under Phase I were formulated with the primary objective being to obtain information regarding the behavior of various types of recording tapes when exposed to a high-temperature environment. Tests under Phase II were directed toward determining a relationship between a TSO fire test and an electric furnace test both of the same duration. Tests under Phase III consisted of testing various types of ceramic and porcelain enamel coatings in order to establish that coatings are available which can resist deterioration and retain their original color at elevated temperatures.

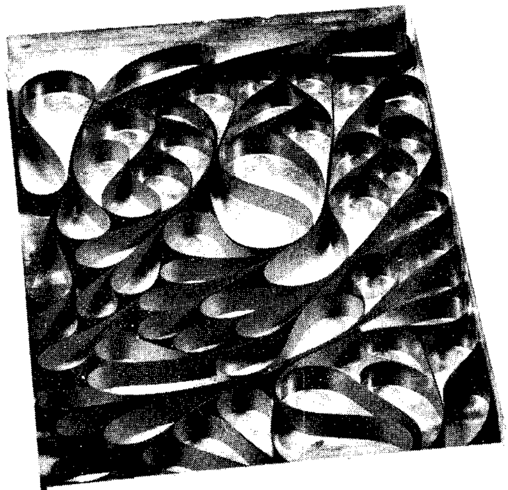
Phase I - Tape Tests: This consisted of high-temperature testing of prerecorded tapes constructed of (1) plastic, (2) aluminum, and (3) stainless steel. These tapes are used in modern flight data and cockpit voice recorders as the recording media. The plastic tape with a magnetic coating is primarily used for cockpit voice recorders while the aluminum and stainless steel tapes are used primarily for flight data recorders.

Magnetic Voice Recording Tape - These tests were conducted using a popular brand of basic tape, one representative of the tape which is used in aircraft cockpit voice recorders. Usually a polyester tape is specified in preference to acetate for recorders because of its better capabilities. However, due to an oversight, an acetate-base tape was used instead in this phase. A few comparison tests were performed later using a polyester-base tape, the results of which are included herein.

The acetate tape used in these tests was a silicone-lubricated, splice-free, general purpose tape. Dimensions were 1.5 mil thick and 1/4 inch wide. A complete 1200-foot reel of this tape was prerecorded with a 1000-cycle-per-second (Hz) signal which served as a yardstick in post-test signal loss analysis. Tape specimens approximately 25 feet long were cut from this master tape and prepared for testing by one of the following three methods designated in Table I by the letters (a), (b), and (c) described below:

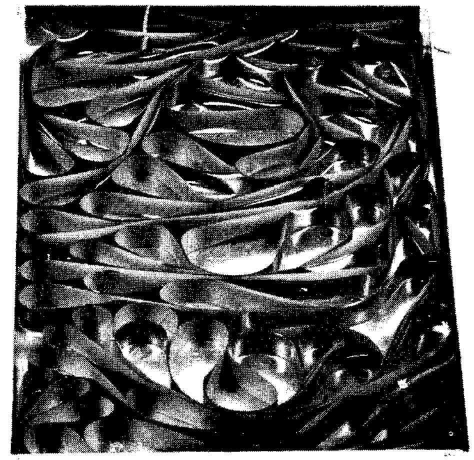
1. Method (a) - Rolled onto a small spool about 1 1/4 inches in diameter, as in a movie film wound on a reel, and placed in a small shallow open-top can.

2. Method (b) - Woven back and forth into a small shallow open-top tray similar to the method in which tape is stored in a continuous-recording cockpit voice recorder as shown in Figure 1.



TEST # 4 - C

250° F, 15 MINUTES, COVERED
TAPE STILL PLAYABLE



TEST # 10 - C

350° F, 15 MINUTES, COVERED
TAPE STILL PLAYABLE

TEST # 13 - C

400° F, 15 MINUTES, COVERED
TAPE NOT PLAYABLE

FIG. 1 MAGNETIC VOICE RECORDING TAPE TEST SPECIMENS; TAPE WOVEN IN TRAY

3. Method (c) - Prepared similarly as in (b) except a cover was placed over the tray.

The tapes were subjected to furnace tests using the various time and temperature combinations as shown below in Table I. The effect of the tests was measured in terms of the signal change (for Method (a) only) which is also shown in Table I. Specimens of Method (b) and (c) were physically compared with a like specimen of Method (a) without a signal analysis being performed.

TABLE I

MAGNETIC TAPE TESTS

Test No.	Furnce Temperature (^{o}F)	Exposure Time (min.)	Tape Installation Method	Signal Change For Method (a) Only (Average Value) (dB)
1	200	15	(a)	+0.5
2	200	30	(a)	-0.5
3	200	60	(a)	+0.2
4	250	15	(a), (c)	+0.1
5	250	30	(a)	0.0
6	250	60	(a)	-0.1
7	300	15	(a), (b), (c)	-0.5
8	300	30	(a), (b), (c)	-0.5
9	300	60	(a), (b), (c)	-3.0
10	350	15	(a), (b), (c)	-1.5
11	350	30	(a), (b), (c)	-2.0
12	350	60	(a), (b), (c)	0.0
13	400	15	(a), (c)	Unplayable

TABLE I (Continued)

MAGNETIC TAPE TESTS

Test No.	Furnace Temperature (^{o}F)	Exposure Time (min.)	Tape Installation Method	Signal Change For Method (a) Only (Average Value) (dB)
14	400	30	(a)	Unplayable
15	400	60	(a)	Unplayable
16	450	15	(a)	Unplayable

Note: "Unplayable" indicates that the tapes could not be played in a tape recorder after the completion of the tests due to excessive brittleness of the tape and curling at the edges.

The post-test signal change results, given in Table I, indicate varying effect at temperatures up to 350°F while above this temperature the tapes were unplayable due to distortion. All results, except that of Test No. 9, for tapes exposed to temperatures of 350°F or less are within the TSO limitation of a maximum loss of 2dB. The results of Method (a) indicate an acceptable heat resistance up to the 300°F test level. The tape remained flexible with some sticking together of adjacent layers for the 60-minute exposure resulting in the iron-oxide coating being pulled off when the roll was unwound. At the 350°F test level the roll of tape had hardened, although when unwound the single thicknesses of tape were flexible. However, it was observed that the edges of the tape were curled and that the coating pulled off upon unwinding to the extent that there were transparent sections where the entire coating had been stripped off. This condition is readily shown in Figure 2. No specimen tested above 350°F using installation Method (a) was in suitable condition to be played through a tape recorder.

Likewise, tapes that were tested above 350°F using Method (b) could not be played. A problem noted for Methods (a) and (b) tests was the prominent tendency for the tapes to dry out, thus causing a loss in flexibility and curl at the edges. On the basis of physical appearance, the tests conducted using Method (c) produced more favorable results since the cover on the tray reduced the rate at which volatiles were driven off from the tape. This extended the usefulness of the tape past 350°F, but not to 400°F.

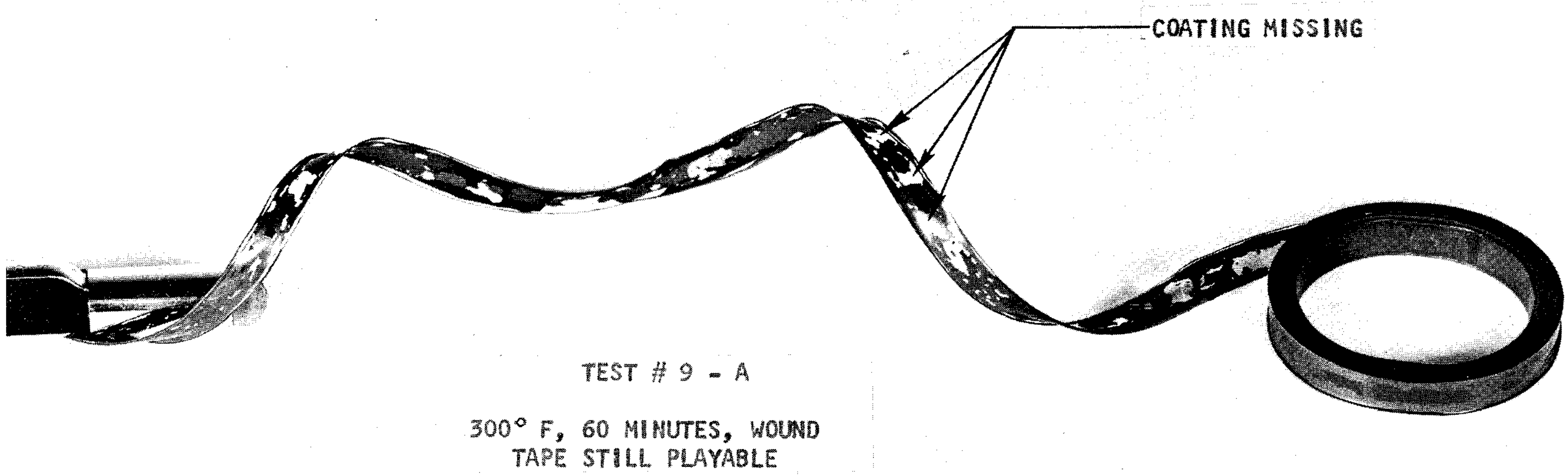


FIG. 2 MAGNETIC VOICE RECORDING TAPE TEST SPECIMEN; TAPE WOUND ON A REEL

Tapes tested at 300°F for 60 minutes employing Method (c) sustained negligible heat damage. For tapes tested at 350°F for 15 minutes, heat damage was slight and the tape was suitable for playback. Tests performed on all tapes at temperatures of 400°F and 450°F produced unplayable tapes which began to char with partial melting which progressed with increasing time exposure and higher temperature.

All tape specimens employing Method (a) which did not experience excessive heat damage and which were still able to pass through a tape recorder were analyzed for signal loss. A graphic representation of these results is shown in Figure 3. Three sets of data points are shown: one set for each time of 15 minutes, 30 minutes, and 60 minutes. It can be seen that the signal strength decreases with increasing temperature and that temperature affects the tape more adversely than length of time. In analyzing the results on the basis of constant temperature with time the variable, there is but a slight trend toward increasing signal loss with increased exposure time. It is noted that in the tests where the signal loss was considerable, adjacent layers of tape stuck together resulting in a consequent stripping of some of the iron-oxide coating from the substrate. However, when the coating remained in position there was only a small signal loss.

The most important observation in analyzing the results was that, if the coating adhered to the acetate backing and if it remained flexible enough to pass through a recorder, the signal was present and within acceptable limits of accuracy. Only when the iron-oxide coating was stripped off was the signal lost.

Several tests were performed using a mylar-base tape as the test specimens to obtain comparative data between mylar- and acetate-base tapes. These tests were performed in a manner identical to the acetate tape tests previously described, except that the tape was not prerecorded and therefore no signal analysis was performed. Table II following indicates the test conditions and results for the mylar tape tests.

TABLE II

MYLAR TAPE TESTS

Test No.	Furnace Temperature (^{o}F)	Exposure Time (min.)	Tape Installation Method	Results
1	350	30	Open tray	Tape playable
2	400	30	Open tray	Tape unplayable
3	400	30	Covered tray	Tape playable
4	450	30	Covered tray	Tape unplayable
5	350	30	Wound on reel	Tape playable
6	400	30	Wound on reel	Tape unplayable

After completion of these tests, the specimens were physically compared with similar specimens of acetate tape tested previously. In all cases the mylar-base tape proved more resistant to heat than the acetate-base tape by approximately 50^{o}F. As an illustration, the mylar tape in Test No. 1 was hardly affected by the 350^{o}F environment, whereas the acetate tape tested at this temperature showed edges which were prominently curled. The degree of curl of the acetate tape was not duplicated by the mylar tape until a test temperature of 400^{o}F was reached in Test No. 2. The upper limit of the mylar-base tape was determined to be between 400^{o}F and 450^{o}F at which temperature the tape was too curled and brittle to be played in a tape recorder.

It was again determined, as with the acetate tape tests, that the cover on the tray prevented the tape from drying out. Test No. 4 conclusively proved this point. When the cover was removed from the specimen, while the specimen was still hot, the tape could be heard to crackle and could be seen to further curl. Removal of the cover allowed an increase in the rate at which the volatiles were driven off causing further drying out of the tape, thus producing more brittleness and curling of the edges.

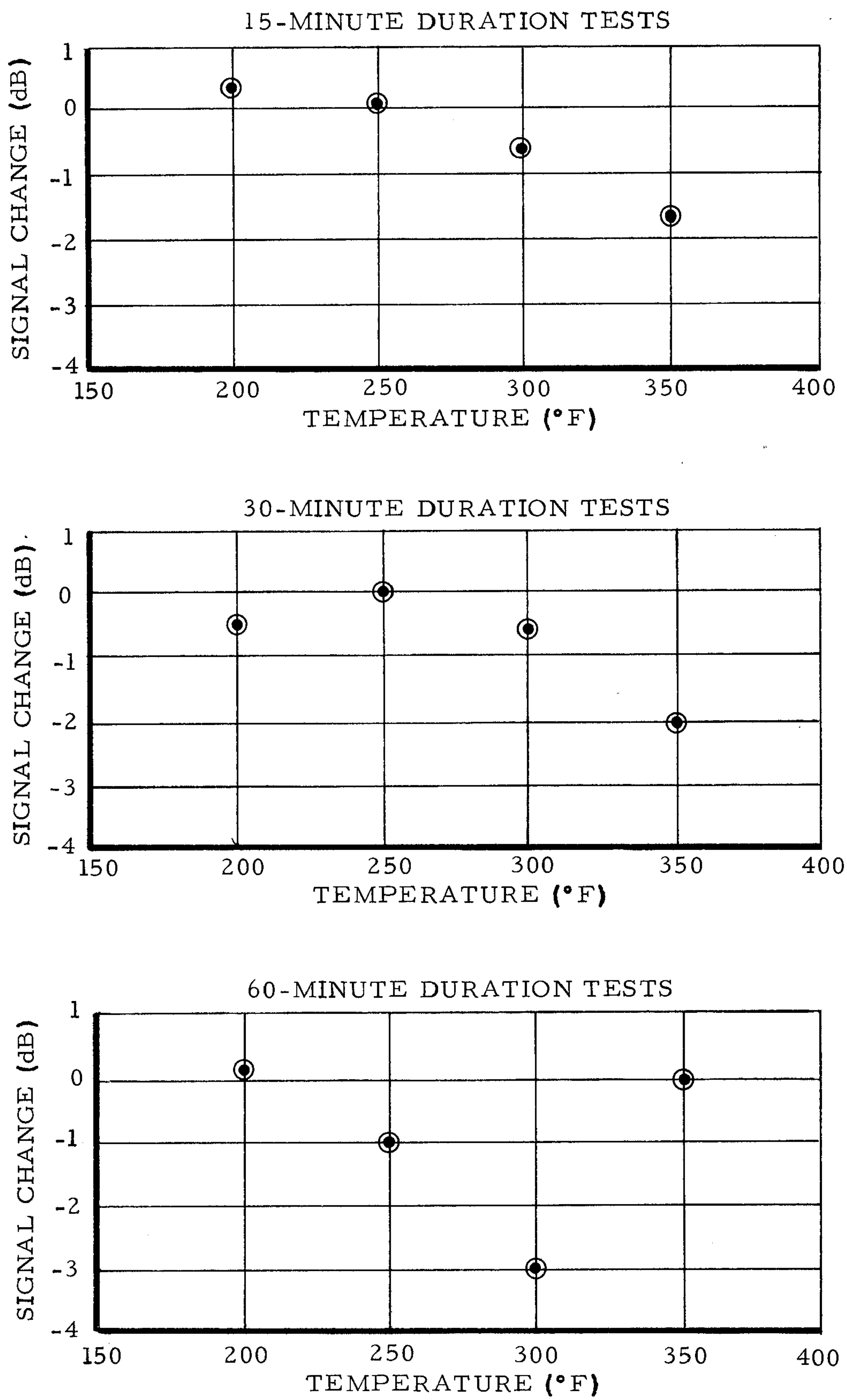


FIG. 3 GRAPHIC REPRESENTATION OF SIGNAL LOSS ANALYSIS

Similarly, the mylar tape in Test No. 5 was still in good condition physically, while the acetate tape specimen tested at 350°F was considered in poor condition due to the adherence of the plies of tape to each other. However, the mylar tape in Test No. 6, tested at 400°F, became fused together in spots as did the acetate tape tested at 350°F.

Therefore, it is concluded from the results of the tests listed in Table II that mylar-backed tape is slightly more resistant to heat than is acetate-backed tape, thus making the results of the tests reported above conservative for use as design criteria for magnetic recording tape.

Aluminum Flight Recorder Tape - These tests were conducted using standard aluminum flight data recorder tape which is 1 mil thick and 2 1/4 inches wide. The tape was prerecorded with a number of traces, cut into specimens 6 inches long, and rolled into a cylindrical shape of approximately 1 inch in diameter. The specimens were placed in an electric furnace at temperatures ranging from 400°F to 1175°F for periods of 30 to 60 minutes in accordance with the test schedule in Table III. As noted in the table, the specimens were unaffected by temperatures up to 1100°F. There were no dimensional changes nor any obliteration of the recorded data. Examination of the specimen which had been exposed to an 1125°F temperature in Test No. 16 showed that portions of the originally glossy tape surface had become matte in appearance. This phenomenon was due to partial melting of the aluminum. Under 30-power viewing well scribed traces could be followed through the matte area, while lightly scribed traces were somewhat obscured, and at a few places could not be distinguished. The specimen used in Test No. 17, which was exposed to a test temperature of 1150°F, produced a few more obscured areas than were found on Test No. 16 specimen. However, most of the traces were discernible. The specimen used in Test No. 18, which had been exposed to a temperature of 1175°F, was completely useless. The 1-inch rolled cylinder had become flattened and very fragile. Also, when any attempt was made to unfold the tape, it crumbled so that no data could be obtained from it.

The tapes subjected to Tests Nos. 10, 11, and 12 are shown in Figure 4. It should be noted that the traces are still clear in all cases.

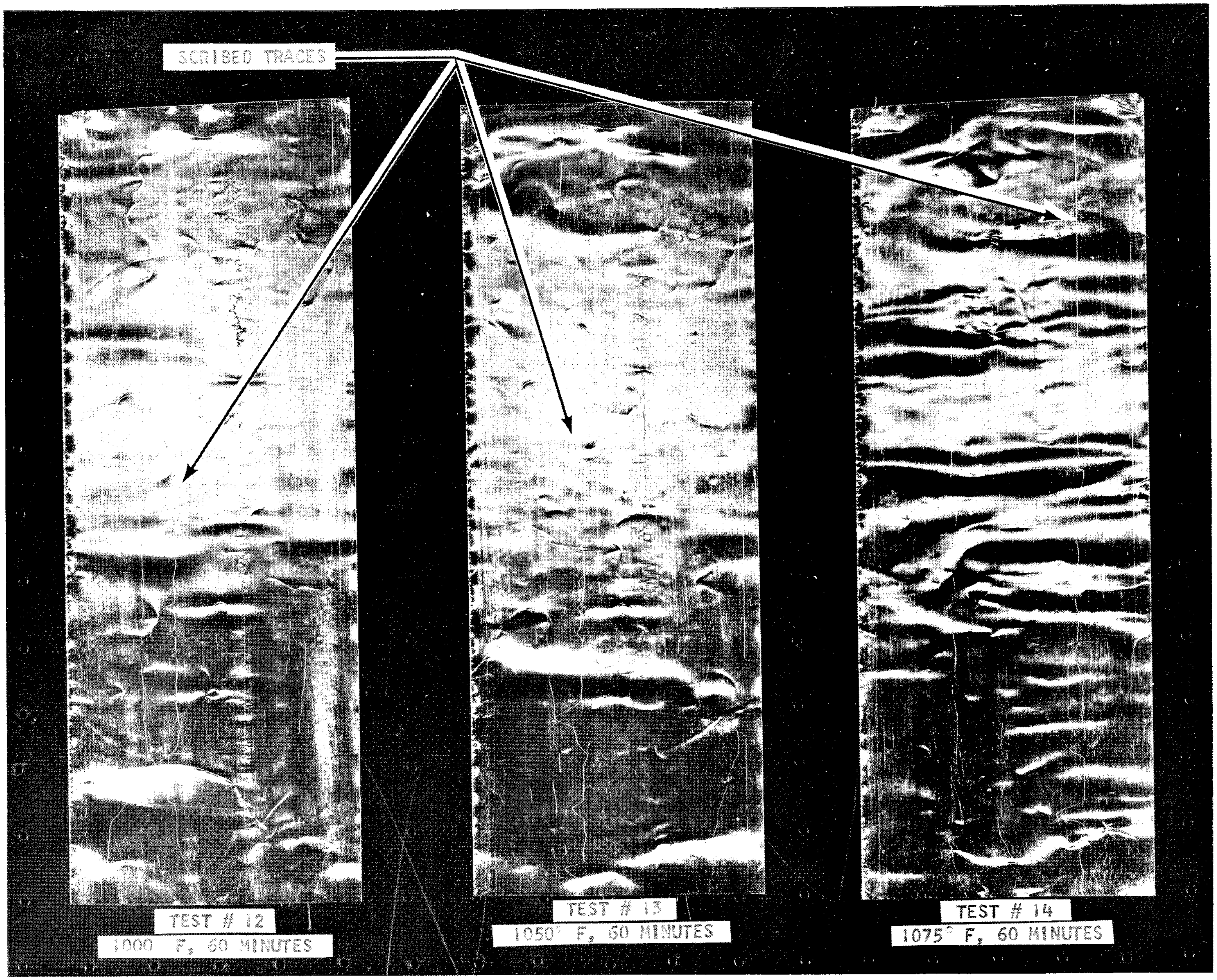


FIG. 4 ALUMINUM FLIGHT DATA TAPE TEST SPECIMENS

TABLE III

ALUMINUM TAPE TESTS

Test No.	Furnace Temperature (°F)	Exposure Time (min.)	Results
1	400	30	No change
2	400	60	No change
3	600	30	No change
4	600	60	No change
5	700	30	No change
6	700	60	No change
7	800	30	No change
8	800	60	No change
9	900	30	No change
10	900	60	No change
11	1000	30	No change
12	1000	60	No change
13	1050	60	No change
14	1075	60	No change
15	1100	60	Small loss in trace
16	1125	60	Small loss in trace
17	1150	60	Trace not legible in some areas
18	1175	60	Trace not legible, tape fused together

Stainless Steel Flight Recorder Tape - These tests were conducted using a standard stainless steel flight recorder tape with prerecorded traces. The tape was 1 mil thick by 5 inches wide with traces on both sides. Specimens 6 inches long were cut from the master tape and exposed to test temperatures in accordance with Table IV below.

TABLE IV

STAINLESS STEEL TAPE TEST SCHEDULE

Test No.	Furnace Temperatures (°F)	Exposure Time (min.)	Method of Cooling	Results
1	1500	60	Air cool	No change
2	1500	60	Water quench	No change
3	1750	60	Air cool	Traces difficult to read
4	1750	60	Water quench	Traces difficult to read
5	2000	60	Air cool	Traces could not be read
6	2000	60	Water quench	Traces could not be read

Measurements of the traces were made before and after exposure to elevated temperatures to determine the loss in recording accuracy of the tapes. This was accomplished by measuring the distance between individual traces to the nearest .001 inch under 30-power magnification before and after the temperature tests. The tape specimens were rolled into 1-inch cylinders and placed in a laboratory electric muffle furnace. Post-test cooling was accomplished in two ways as indicated in Table IV. Half the specimens were allowed to cool at ambient air temperature while the other half were water quenched. The water quenching was intended to simulate an exposed tape being struck by a stream of water or foam during crash-fire extinguishment. The specimens were allowed to remain at room temperature for 24 hours before examination.

Post-test examination of Tests Nos. 1 and 2 specimens revealed no difference occurring as a result of the cooling method used. The originally polished surface of each tape turned slightly dull with no measurable loss in accuracy of the traces discernible and only slight decrease in readability under 30-power magnification noted.

Post-test examination of Tests Nos. 3 and 4 specimens, subjected to higher temperatures, again revealed no difference between the two tapes due to the cooling method used. In these tests the original polished surfaces turned dull with a dark gray metallic color. The scribed traces were very faded and extremely difficult to follow even under 30-power magnification. Not one trace could be completely tracked across the specimen. The tape was examined in an "as-tested" condition without the use of etching or chemical treatment to enhance readability. Even though measurements were made with difficulty, no loss in accuracy was indicated.

Post-test examination of Tests Nos. 5 and 6 specimens, subjected to a temperature of 2000°F, again revealed no difference between the two tapes due to the cooling method used. Both tapes became extremely brittle and there was severe fragmentation upon unrolling. The water-quenched specimen was equally brittle along its entire length; whereas, the air-cooled specimen was most brittle in the area that was on the outside of the roll. Also, both specimens had turned very dull and black with some surface scaling. Some fusing of the metal between adjacent layers, particularly at the edges, was evident making it necessary that the tape and tape deck be pried apart. In several areas, the original finely scribed trace appeared as a wide indentation which precluded pinpoint measurement. Also, many of the traces could not be located because of the discoloration, scaling, and/or heavy oxidation of the tape. The specimens had increased in width as much as 7 percent due to heat deformation with a corresponding increase in separation between those scribed lines that could be located and measured.

A typical specimen with prerecorded traces before testing is shown in Figure 5.

Phase II - Recorder Tests: These consisted of high-temperature tests of complete cockpit voice recorder units to determine (1) survivability in a high-temperature environment, and (2) relationship between a TSO fire test and an electric furnace test. The test conditions and results for this phase are indicated in Table V.

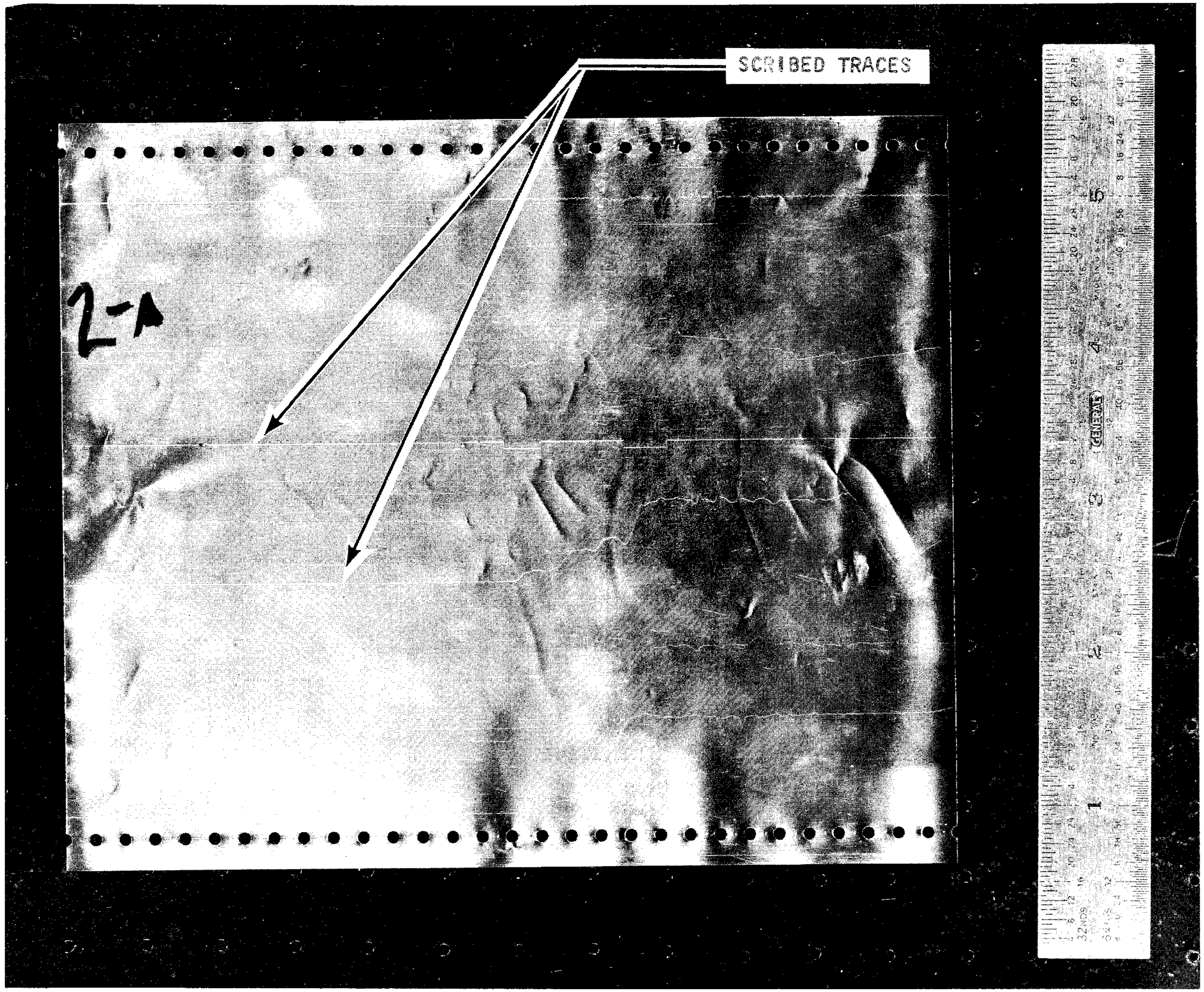


FIG. 5 STAINLESS STEEL FLIGHT DATA TAPE TEST SPECIMEN

TABLE V

RECORDER HIGH-TEMPERATURE TESTS

Test No.	Exposure Media	Test Temperature (°F)	Exposure Time (min.)	Signal Loss (dB)	Test Article
1	Fire Pit	1400	30	2 to 12	Recorder A
2	12 gph Torch	2000	60	*	Recorder B
3	12 gph Torch	2000	30	0	Recorder B
4	Electric Furnace	1800	30	2 to 7	Recorder B
5	Electric Furnace	1600	30	2 to 5	Recorder B

* Tape completely destroyed

Test No. 1 was conducted to determine the ability of a voice recorder to provide a readable tape after being subjected to a simulated crash-fire environment. Cockpit Voice Recorder A was used in this test. The mylar tape supplied with the unit was first removed from the recorder, prerecorded with a 1000-Hz signal, and replaced in the recorder. In addition, several temperature indicator cards (thermograms) were placed in the tape compartment so that the approximate maximum compartment temperature could be noted. These cards are designed to change color when a definite temperature is reached. The lowest temperature measurable was 500°F.

Recorder A was positioned on a steel stand approximately 5 feet above a 15-foot-diameter fire pit as shown in Figure 6. Wind velocity was measured by an anemometer while the flame temperature was measured by thermocouples placed 1 inch above and below the center of the recorder case.

The fuel pit was initially filled with 200 gallons of JP-4 fuel. Additional fuel was continuously fed to the fire during the test to maintain maximum fire intensity. The fire was allowed to burn for 30 minutes after which it was extinguished and the test article examined. The recorder being engulfed in the test flames together with the two heat flux sensors positioned on each side of the pit are shown in Figure 7.

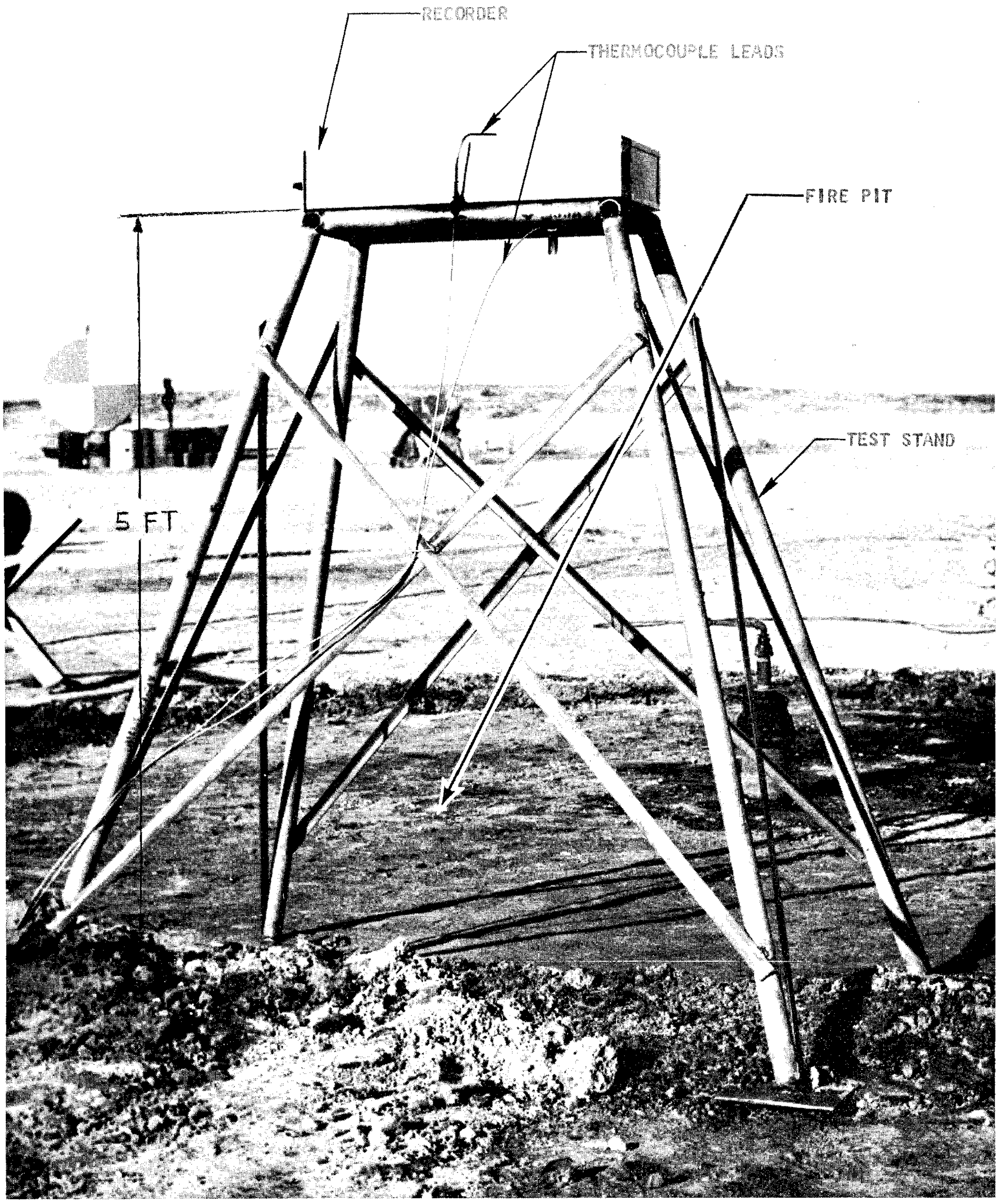


FIG. 6 POSITIONING OF VOICE RECORDER FOR FIRE PIT TEST

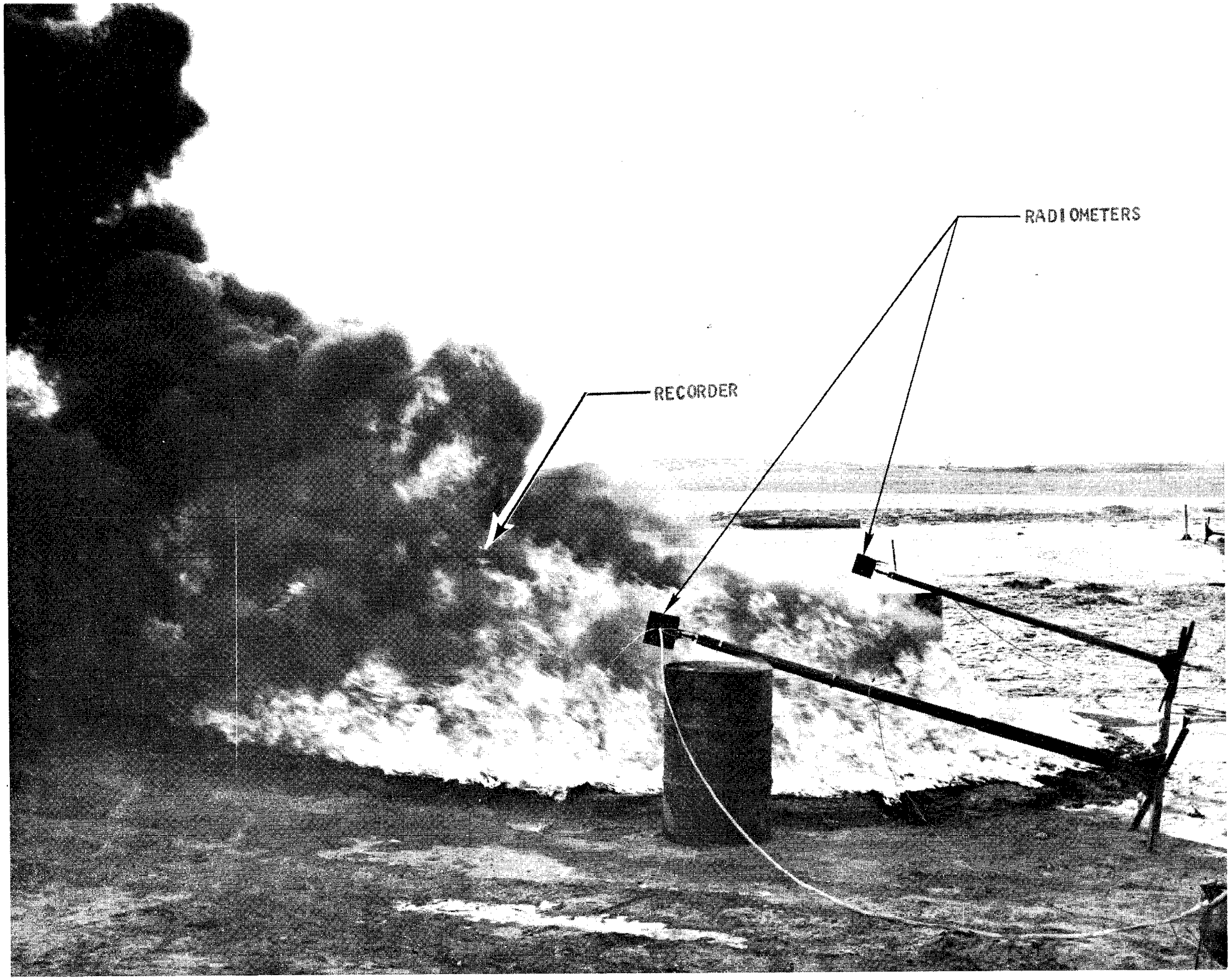


FIG. 7 FIRE PIT TEST OF VOICE RECORDER

The wind velocity was relatively high and variable, between 10 to 15 miles per hour, causing the flames to be erratic. As a result, the recorder was engulfed by the flames only about half of the 30-minute test duration. The average environmental temperature was approximately 1400°F peaking at 2000°F only occasionally. Thus, the test was not considered severe. Within the first 2 minutes of testing, the aluminum dust cover of the recorder had melted away. The recorder without its cover upon completion of the test is shown in Figure 8. Post-test examination of the recorder revealed that the temperature inside the tape compartment had not reached 500°F. Examination of the recorder tape revealed no damage except for a few blotches on it caused by the splashing of the liquid ablative used in the thermal liner of the recorder. Sections of the tape had fused to the melted plastic guides near the recording heads, resulting in some of the iron-oxide coating being removed from the tape at these points. The portions of the tape which were fused to the guides could not be removed without being severed in a number of places.

Playback analysis of the tape indicated a signal loss of between 2 and 12 dB. This is in excess of the requirement specified in TSO-C84, Part 3.13e, which specifies that only a 2-dB change is allowable.

Tests Nos. 2 through 5 in this phase of testing were performed in order to investigate the possibility of using an electric furnace rather than the presently used standard torch to evaluate the resistance of a recorder to fire and thereby provide a more controllable, repeatable, and consistant TSO test method which would also be much more readily available to manufacturers. The test article used in all four tests is designated as Recorder B. This type of recorder had been approved under TSO-C84. These were standard units except for the omission of electronics and the tape drive mechanism, but otherwise equivalent in their fire protection features to operating recorders. The components of the recorders are shown in Figure 9. The units used for Tests Nos. 2 and 3 were subjected to fire tests in which at least 50 percent of the outside area of the units was enveloped by 2000°F flames for 60- and 30-minute exposures, respectively, from a NAFEC 12-gallon-per-hour kerosene torch. (See Appendix B for description.) The recorders in Tests Nos. 4 and 5 were subjected to elevated temperatures by being placed in an electric furnace which had been preheated to temperatures of 1800°F and 1600°F, respectively. The furnace-tested recorders were suspended in the furnace to allow for 100-percent heat coverage, and the furnace was maintained at these temperatures during the test.

In all four tests, the tape compartment air temperatures were continuously recorded by chromel-alumel thermocouples the leads for which were protected by high-temperature insulation. Some of the operational wiring, which normally passes into the tape housing, was removed to allow space to insert the thermocouple. This eliminated the necessity of drilling holes in various components, thus preserving the thermal integrity of

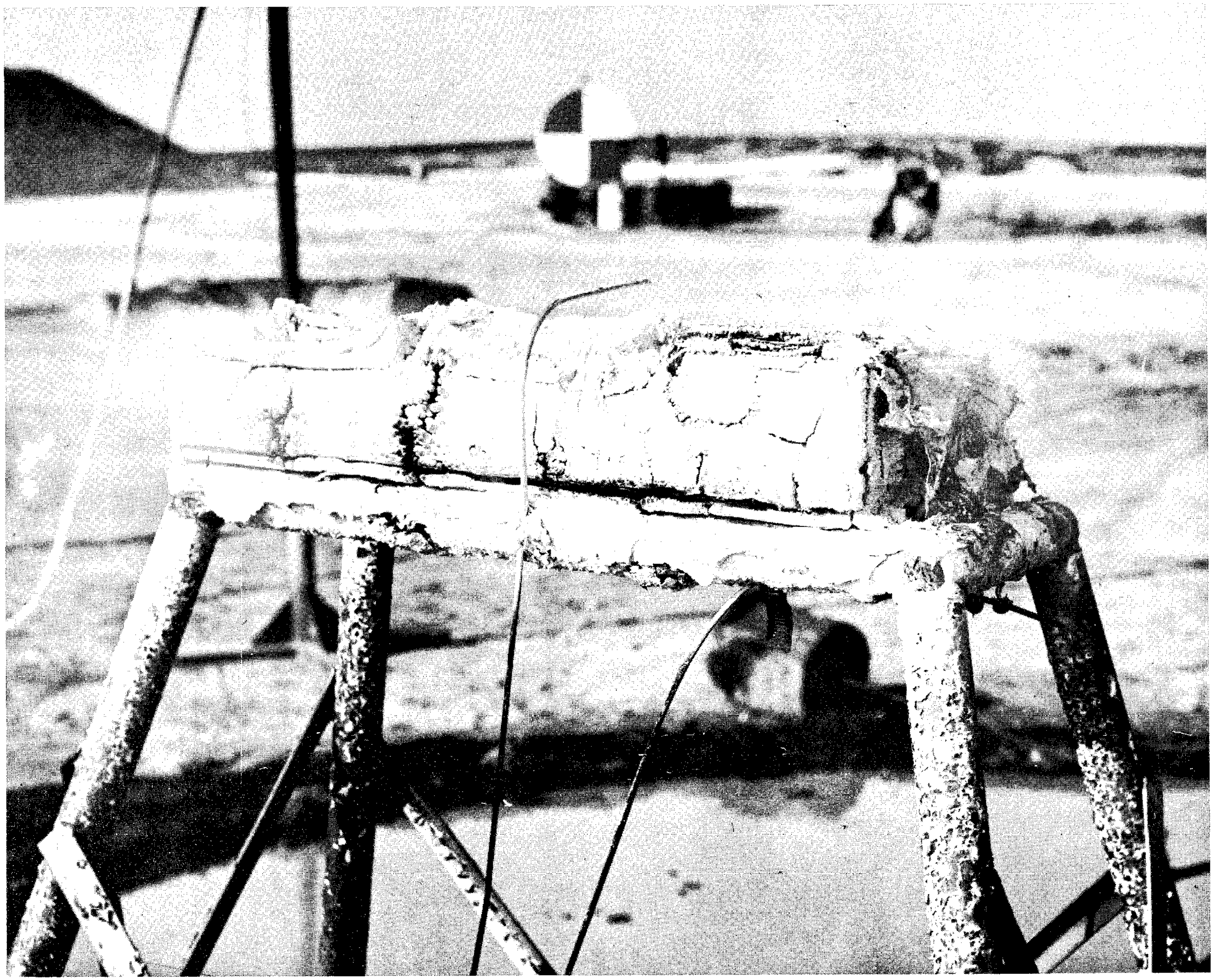


FIG. 8 RESULTS OF FIRE PIT TEST OF VOICE RECORDER

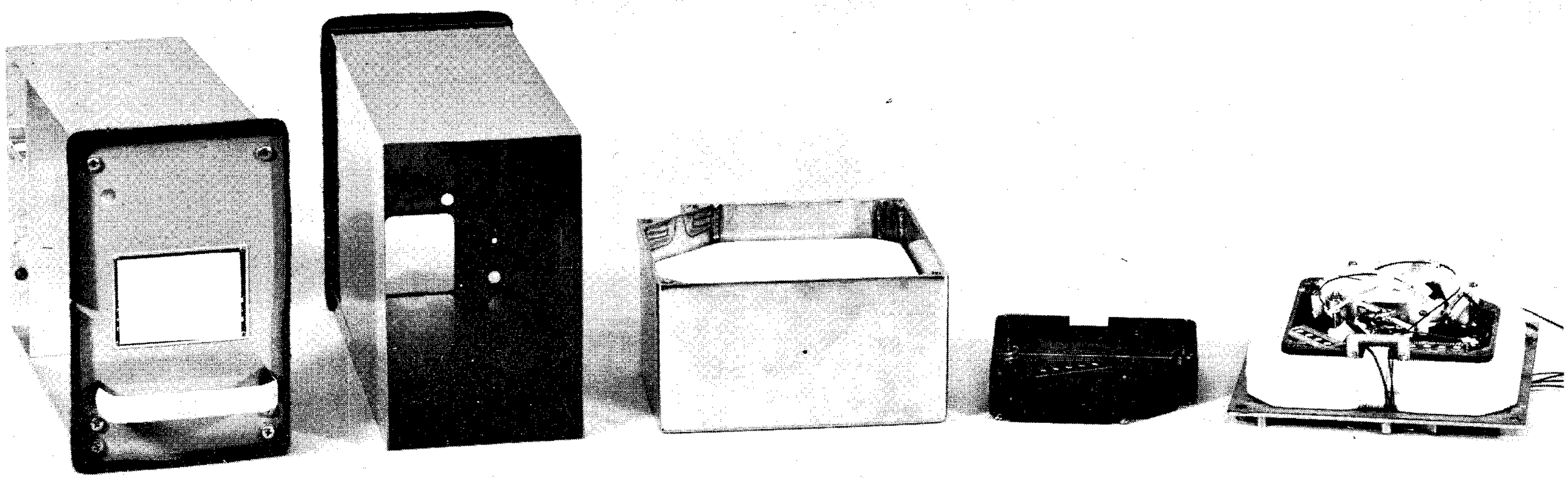


FIG. 9 BREAKDOWN OF COMPONENTS OF VOICE RECORDER USED IN PHASE II, TESTS NOS. 2 THROUGH 5

the recorder. The thermocouple measurements were supplemented by temperature indicator cards which were also placed in the tape compartment. All units were equipped with mylar tape containing a prerecorded 1000-Hz signal. Results of Tests Nos. 2 through 5 are given in Table V.

Post-test examination following Test No. 2 revealed that the 60-minute exposure of the recorder to the 12-gallon-per-hour burner caused complete destruction of the tape. It was charred beyond recognition. The temperature in the tape compartment reached well over 500°F according to the temperature cards and thermocouples. Thus, no useable tape data were obtained from this test.

Excellent tape data were obtained from Tests Nos. 3, 4, and 5. The temperature history of the tape compartment during each of these three tests is illustrated in Figure 10. It is noted that all three curves have the same basic trend. After a period of 4 minutes with practically no temperature change, the compartment temperature rose steadily followed by a brief interval where the temperatures remained relatively constant. Subsequently, the temperature rose steadily for the remainder of the test duration. The period during which the temperature remained constant represents a phase change in the thermal liner. A liquid ablative, largely water, provides an interval of constant temperature through heat loss from vaporization. Continued rise in the temperature curves indicates that the ablative has been spent and protection of the tape then becomes largely a function of the thermal conductivities of the individual components.

Post-test tape analysis following Test No. 3 indicated that there was virtually no change in the recorded signal on the tape exposed to the 30-minute flame test. From its external appearance, the tape was considered to be in excellent condition after testing. Post-test analysis of the tape following Test No. 4 indicated a signal loss of 2 to 7 dB in a portion of the tape which, upon physical examination, appeared in a wrinkled condition. This amount of signal loss would have represented no major problem had the signal been a voice recording. Analysis of other portions of this tape indicated a maximum loss of 2 dB which is within the TSO allowable range. Post-test analysis of the tape following Test No. 5 indicated a signal loss of 2 to 5 dB in one portion of the tape with a steady 2-dB loss in the remainder of the tape. The portion of the tape which exhibited the highest signal loss was on the outside of the reel.

From the damage observed in Tests Nos. 3 and 4 it is noted that the furnace test at 1800°F was more severe than for the 2000°F kerosene burner flame test. This was primarily due to the fact that while there was 100-percent envelopment of the recorder surface in the 1800°F environment, only part of the recorder surface (approximately 50 percent) was subjected to a 2000°F flame in the burner test.

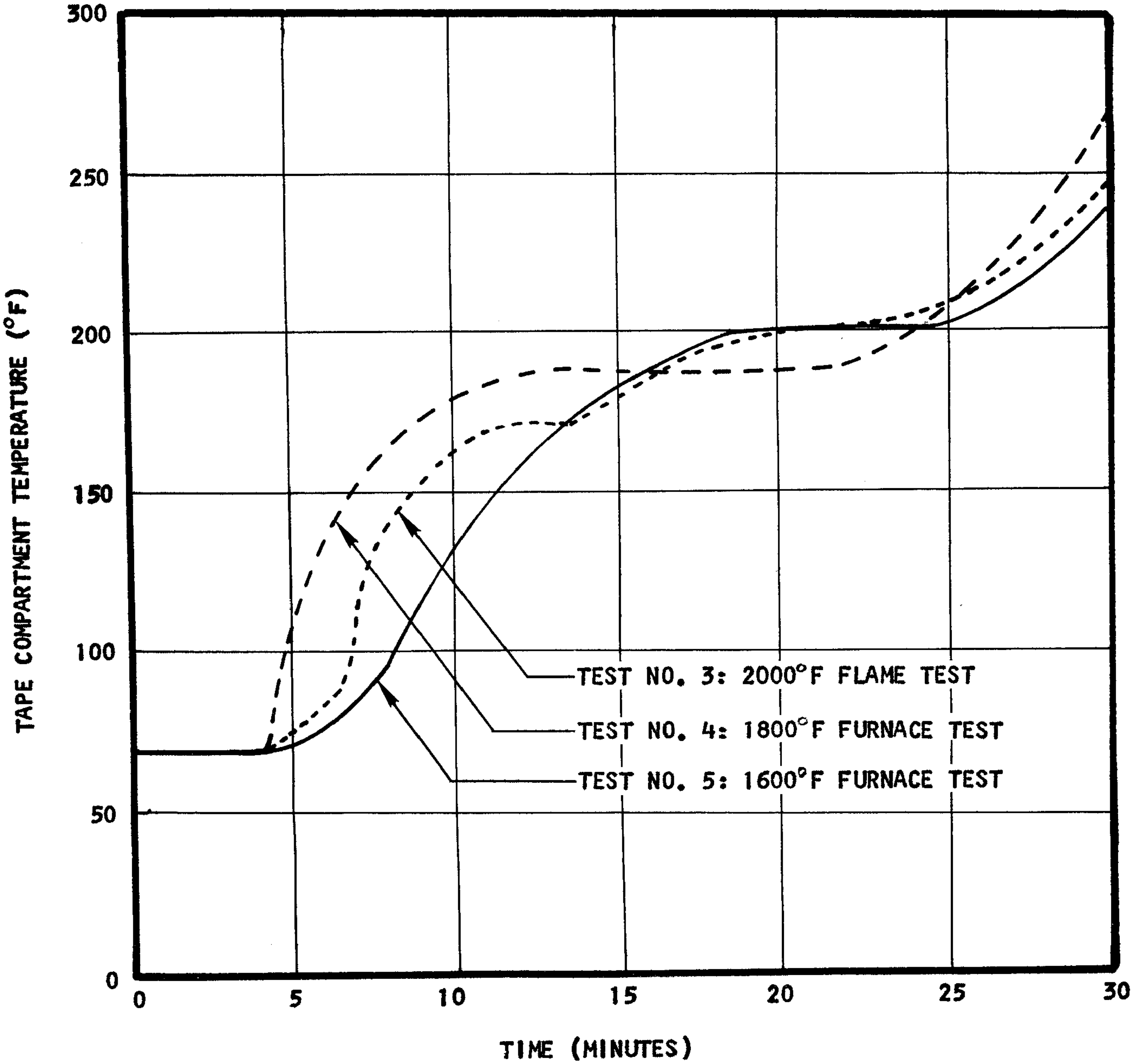


FIG. 10 TAPE COMPARTMENT TEMPERATURE HISTORY, PHASE II TESTING

The curve for the 1600°F furnace test follows closely the time-temperature history of the 2000°F kerosene burner fire test with the exception of the first few minutes. The temperature indicator cards corroborated the thermocouple information.

It was also noted that during the tests the bright orange paint on all five recorders was burned off almost immediately, and the aluminum case melted upon exposure of the heated environment. The concept of a brightly painted aluminum recorder case to facilitate its being located in a burned wreckage is fallacious if the paint burns off.

Phase III - Exterior Coating Tests: Eight high-temperature, high-conspicuity coatings were evaluated to determine their resistance to deterioration at elevated temperatures. The type and color of the coatings investigated are given in Table VI. The coatings are divided into two groups used to identify the test procedures employed.

The test coating was applied to sheets of stainless steel 6 by 12 inches by 1/8-inch thick, by the manufacturer and returned to NAFEC where the sheets were cut into 1- by 2-inch specimens for testing. A recording spectrophotometer was used to measure the percent reflectivity of the coatings over the visual frequency range before and after testing of all specimens.

Group I Tests - Coatings Nos. 1 through 3 were subjected to both the 2000°F flames produced by the NAFEC 2-gallon-per-hour kerosene burner, and to elevated temperatures of 1000°F to 2000°F in an electric furnace. The duration of all Group I tests was 30 minutes. Following removal of the specimens from the burner or furnace, they were immediately quenched in cold water. The results of these tests are given in Table VI.

During the burner flame test of Coating No. 1, it was noted that its surface was slightly tacky to a sharp-pointed probe. During the early stages of this test, a film of soot adhered to the coated surface. However, this condition disappeared when the surface of the test specimen became incandescent.

The results of the electric heating furnace tests performed on Coating No. 1 indicated that at 1700°F the coating had softened but was not tacky. However, at 1800°F the coating became softened to the extent that it was tacky with very little spalling of the coating occurring when it was suddenly quenched in water. At 2000°F the coating was liquid.

The results of the burner flame test of Coating No. 2 indicated that this was the least resistant to high-temperature heating with much spalling occurring when quenched. The electric furnace

TABLE VI

EXTERIOR COATINGS APPLIED TO STAINLESS STEEL

Coating No.	Group No.	Type Coating	Manufacturer	Color	2-GPH Kerosene Torch Flame Test Results (2000°F Flames)	Electric Furnace Test Results
1	I	Porcelain Enamel	X Company	Olive-Green	Coating tacky during test; still intact upon completion of test.	Coating softened at 1700°F; became tacky at 1800 F; melted at 2000°F.
2	I	Ceramic	Y Company	Yellow-Green	Spalling upon quenching; became detached from substrate when cooled.	Became detached from substrate at 1500°F.
3	I	Porcelain Enamel	X Company	Red-Orange	Some spalling upon quenching, but considered tolerable.	Softened at 1700°F; blackened and became detached from substrate upon quenching at 1800°F.
4	II	Porcelain Enamel	X Company	Red	----	Turned green between 1500°F and 1750°F; turned black at 2000°F; became soft at 1500°F; scratches remained at 1750°F.
5	II	Porcelain Enamel	X Company	Orange	----	Turned green between 1500°F and 1750°F; turned black at 2000°F; became soft at 1500°F; scratches remained at 1750°F.
6	II	Ceramic	Z Company	White	----	Became slightly darker at 2000°F; became detached from substrate at 1750°F.
7	II	Ceramic	Z Company	White	----	Turned light brown at 2000°F; became detached from substrate at 1750°F.
8	II	Ceramic	Z Company	White	----	Became slightly darker at 2000°F; became detached from substrate at 1750°F.

tests of this coating indicated that it was completely destroyed when quenched after exposure to a test temperature of 1500°F. Even at a test temperature as low as 1000°F, substantial spalling occurred from quenching.

The results of the 2000°F burner flame test of Coating No. 3 indicated that it softened while exposed to the fire but did not melt. Some spalling resulted from quenching in water, but the condition was considered tolerable. The electric furnace tests of this coating indicated that the coating softened at 1500°F, but was not tacky at that temperature. However, at 1700°F the coating started to melt while at 1800°F the coating oxides underwent a phase transformation and blackened. At this higher temperature, quenching completely destroyed the surface coating.

Group II Tests - Test Materials Nos. 4 through 8 were subjected to electric furnace tests only. The furnace was preheated to the desired temperature before the specimens were introduced into the heated environment for a period of 60 minutes. Two identical series of tests were conducted with the exception that after exposure, one specimen was allowed to cool in the ambient air while the other was water quenched. Test temperatures were 1000°F to 2000°F for Coatings Nos. 4 and 5, and 1500°F to 2000°F for Nos. 6, 7, and 8. Tests on the latter coatings were started at higher temperatures in anticipation that such coatings were more resistant to heat. These tests were conducted using temperature increments of 250°F. The chemical composition of the ceramic-type coatings in percent by weight for Coatings Nos. 6, 7, and 8 is shown in Table VII. It is seen that Coating No. 6 is primarily an aluminum-oxide ceramic coating, while Coating No. 7 is primarily a zirconium-oxide coating, and Coating No. 8 is a combination of silicon-oxide and zirconium-oxide.

TABLE VII

CHEMICAL COMPOSITIONS OF CERAMIC COATINGS
(Percent by Weight)

Oxide	Coating No. 6	Coating No. 7	Coating No. 8
ZrO_3	---	94.57	64.12
Al_2O_3	98.55	0.63	1.42
SiO_2	0.58	0.33	33.22
Fe_2O_3	0.10	0.33	0.14
TiO_2	0.04	0.39	0.19
Na_2O	0.31	0.02	0.07
CaO	0.19	3.73	0.57
MgO	0.23	---	---

The test results for Coatings Nos. 4 through 8, given in Table VI, indicated a definite loss in color with increasing test temperature. Water-quenched and air-cooled specimens were identical in appearance in all tests with the exception of a slight amount of spalling occurring at the edges of Coatings Nos. 4 and 5 specimens when these were water quenched. Coatings Nos. 4 and 5 produced very pronounced color changes at the 1500°F test temperature. Both the red and the orange specimens became progressively more green with increasing temperature. At a test temperature of 2000°F, both had turned black with no resemblance to the original color remaining. From the standpoint of visual appearance, 1500°F would be the tolerable upper temperature limit for these coatings with 1750°F being acceptable as an upper limit only with a substantial color change allowed. The results of the spectrophotometer tests performed on these coatings are shown in Figures 11 and 12. The curves in these figures have 1000°F as the lowest test temperature indicated, since this curve is also representative of the reflectivity of an untested specimen. It is obvious from these figures that a substantial color change occurred at the 1500°F test level for both specimens. These porcelain enamel coatings became soft at temperatures

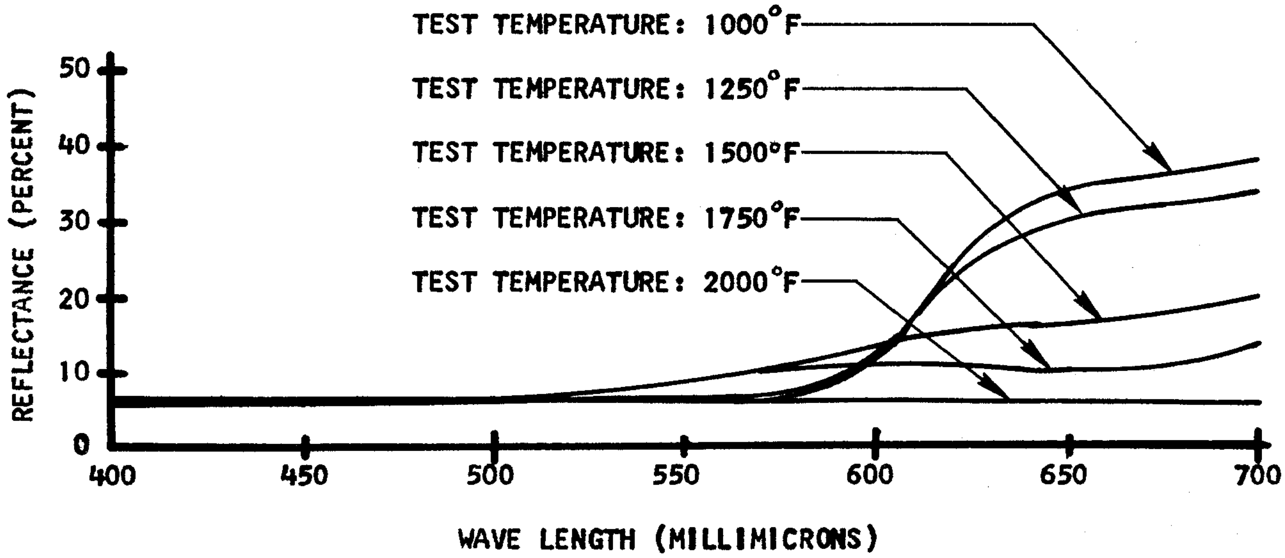


FIG. 11 EFFECT OF TEMPERATURE ON REFLECTIVITY OF RED PORCELAIN ENAMEL COATING (MATERIAL NO. 4)

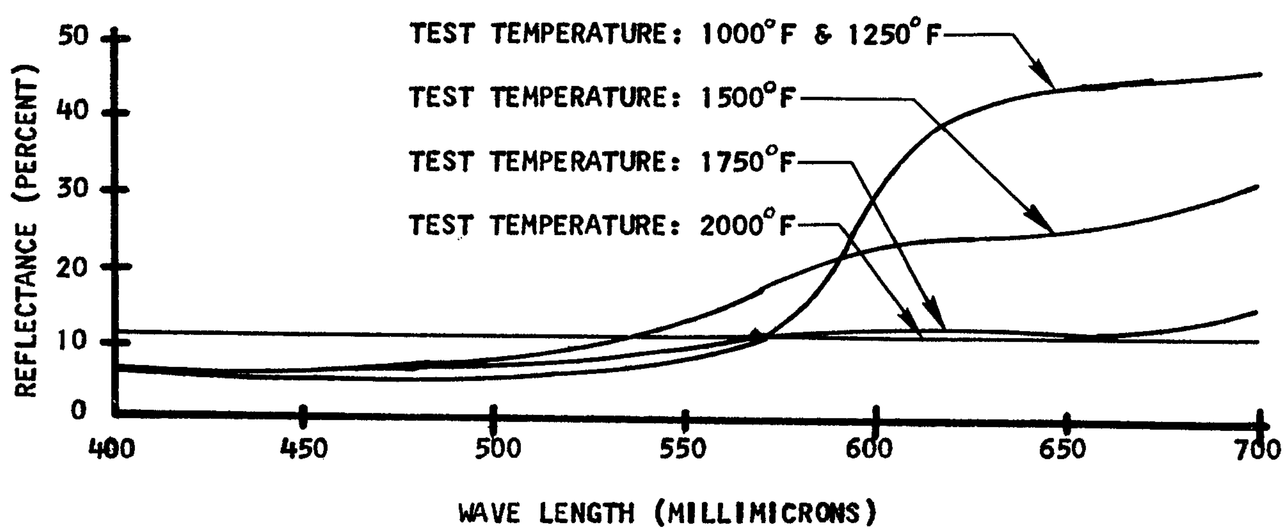


FIG. 12 EFFECT OF TEMPERATURE ON REFLECTIVITY OF ORANGE PORCELAIN ENAMEL COATING (MATERIAL NO. 5)

above 1500°F. Scratches made on the coatings exposed to 1750°F remained intact (i.e., the coating did not flow back together).

The results of the tests performed on Coating No. 5, the orange porcelain enamel, are shown in Figure 13. From this photograph of the specimen damage, it is seen that very little difference does indeed exist between the air-cooled and water-quenched specimens. Also, the degree of blackening with increasing temperature is apparent.

Coatings Nos. 6, 7, and 8 became progressively darker with increasing temperature. Coating No. 7 produced the most pronounced color change, becoming light brown at 2000°F. From the standpoint of color change alone, Coatings Nos. 6 and 8 would be considered acceptable up to a temperature of 2000°F. However, all three of these coatings have one serious problem. At temperatures of 1750°F and above, the coatings become detached from the substrate. In some cases, the entire coating becomes detached as one piece. This phenomenon can be readily seen in Figure 14, which shows the results of tests performed on Coating No. 8. Since the coatings became detached from the substrates, no attempt was made to subject these specimens to spectrophotometer reflectivity tests.

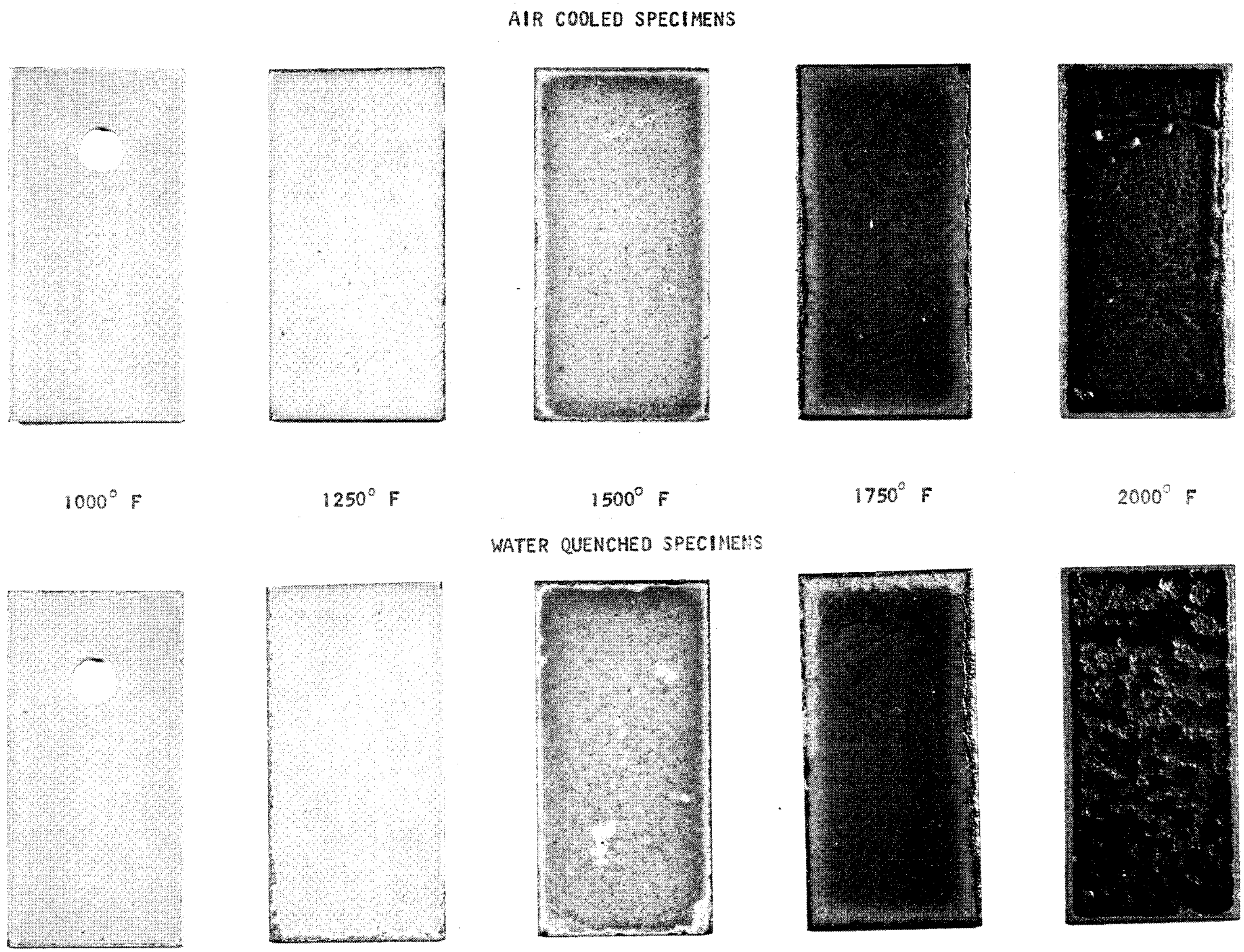


FIG. 13 RESULTS OF ORANGE PORCELAIN ENAMEL COATING TESTS (MATERIAL NO. 5)

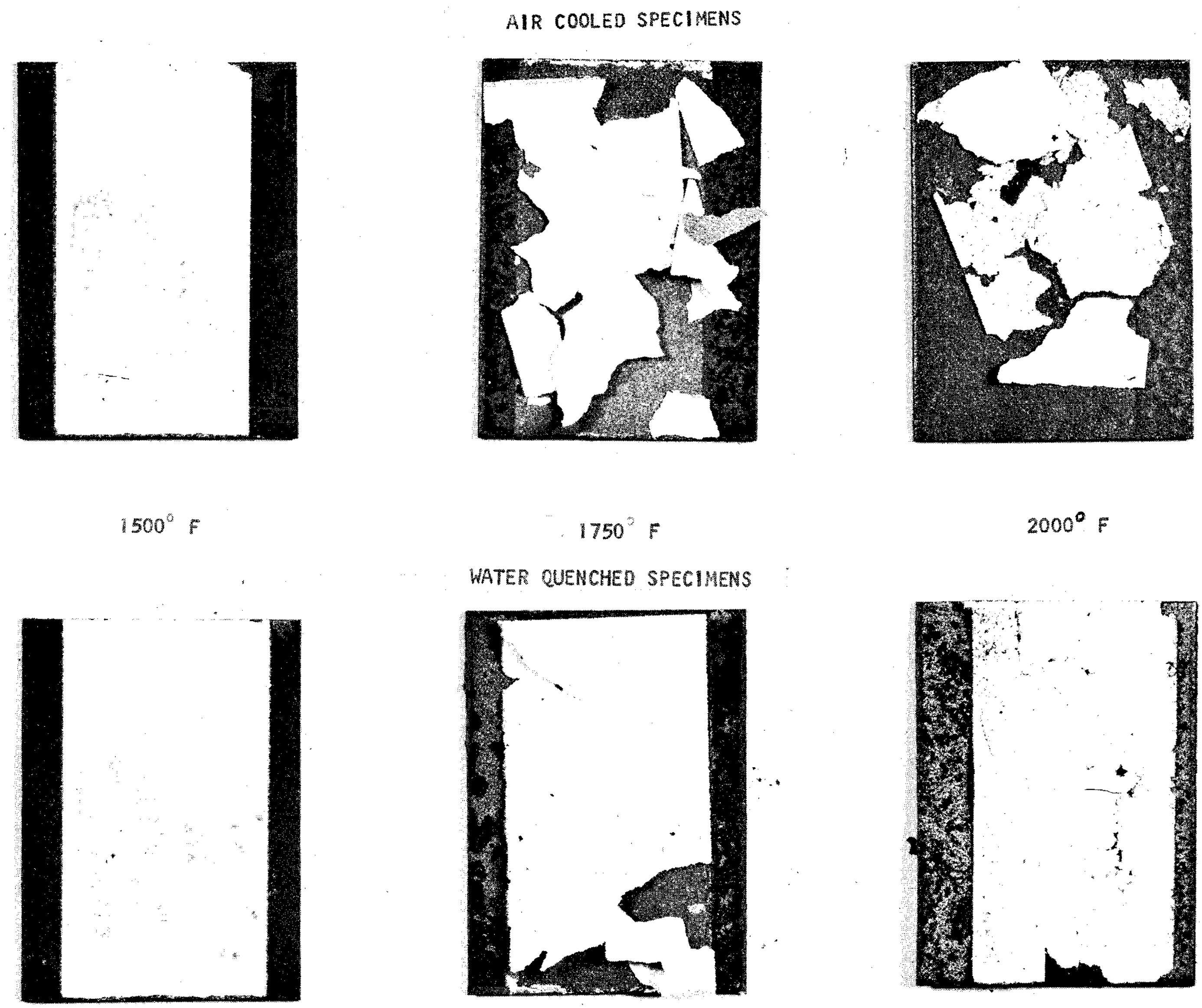


FIG. 14 RESULTS OF CERAMIC COATING TESTS (MATERIAL NO. 8)

SUMMARY OF RESULTS

The results obtained from this investigation of fire test criteria for recorders are as follows:

1. Magnetic voice recording tape remained in a playable condition with signal losses within tolerable limits when exposed to elevated temperatures up to 300°F for a duration of 60 minutes. At and above this temperature, the tapes were unplayable. However, this limit was increased to 350°F by enclosing the tape in a covered container, as in actual use, which impedes drying out of the tape.

2. Aluminum flight recorder tape remained readable when exposed to elevated temperatures up to 1175°F for a duration of 60 minutes. At and above this temperature, the tapes were unreadable.

3. Stainless steel flight recorder tape remained readable when exposed to elevated temperatures up to 1750°F for a duration of 60 minutes. At and above this temperature, the tapes were unreadable.

4. A 30-minute fire pit test, with an average test flame temperature of 1400°F, performed on Cockpit Voice Recorder A resulted in a signal loss in excess of the allowable value specified in TSO-C84.

5. A 60-minute, 2000°F flame test, using the NAFEC 12-gallon-per-hour kerosene torch with Cockpit Voice Recorder B as the test article, resulted in a completely destroyed tape.

6. A 30-minute, 2000°F flame test, using the NAFEC 12-gallon-per-hour kerosene torch with Cockpit Voice Recorder B as the test article, resulted in no signal loss in the recorder tape, thus satisfactorily meeting the TSO fire test requirement.

7. Results of the electric furnace test at a 1600°F temperature performed on Cockpit Voice Recorder B indicated that the tape compartment time-temperature curve for a 30-minute duration closely paralleled the same curve for the kerosene torch test of the same period.

8. Porcelain enamel coatings became progressively darker with increasing temperature until at 2000°F the color became completely black.

9. Ceramic coatings proved to be very resistant to heat, but became detached from their substrate when exposed to temperatures of 1750°F or more, thus producing an unsatisfactory condition, especially in the event of water quenching.

CONCLUSIONS

Based on the results obtained from the investigation of fire test criteria for recorders, it is concluded that:

1. A suitable and uniform test method for the crash-fire testing of aircraft flight data and voice recorders would be insertion of the complete recorder for 30-minutes duration in an electric furnace operating at $1600^{\circ}F$.

2. The design criteria for cockpit voice recorders employing magnetic recording tape must insure that the tape will not be exposed to temperatures above $300^{\circ}F$ for useable survival of the tape under the above-stated test method for simulating a severe aircraft fire accident.

3. The recorded signal strength on magnetic recording tape used in a voice recorder does not decrease excessively when exposed for up to a 60-minute duration to elevated temperatures below the melting temperature of the tape.

4. The physical condition of the tape backing and the adherence of the iron-oxide coating to the backing are the limiting factors to satisfactory playback after the recording tape is exposed to elevated temperatures near the melting temperature of the tape.

5. Exposure of magnetic recording tape to temperatures above $300^{\circ}F$ for durations of 15 minutes or more results in loss of flexibility and severely curled edges which preclude playback through a recorder.

6. Magnetic recording tape on a reel at the elevated temperatures will adhere to itself between adjacent plies in contact. An attempt to separate the plies results in the iron-oxide coating being stripped from the backing, thus producing a poor, unacceptable recording.

7. The design criteria for flight data recorders employing aluminum recording tape must insure that the tape will not be exposed to temperatures above $1150^{\circ}F$ for useable survival of the tape under the above-stated test method for simulating a severe aircraft fire accident.

8. Design criteria for flight data recorders, employing stainless steel recording tape, must insure that the tape will not be exposed to temperatures above $1500^{\circ}F$ for useable survival of the tape under the above-stated test method for simulating a severe aircraft fire accident.

9. Cockpit voice recorders similar to those presently in service cannot meet the TSO-C84 signal loss requirements when exposed to simulated crash-fire conditions in the NAFEC fire pit for 30 minutes.

10. Cockpit voice recorders similar to those presently in service cannot meet the TSO-C84 crash-fire requirement when exposed to the NAFEC 12-gallon-per-hour kerosene torch flame for 60 minutes. However, they can meet the present requirement of 30 minutes' duration.

11. The test method of using an electric furnace operating at a temperature of 1600°F can satisfactorily be substituted for the presently specified fire test to satisfy the crash-fire requirements of TSO-C51 and TSO-C84.

12. Rapid color deterioration of porcelain enamel coatings at temperatures above 1500°F should preclude their use on recorders which may be exposed to temperatures up to 2000°F. This type of coating is satisfactory for use only when exposure temperatures are below 1500°F.

13. The detachment of ceramic coatings from their substrates at test temperatures above 1750°F should preclude their use for recorder cases unless a better bonding method is used to maintain the coating adherence to the metal up to 2000 F. This type of coating is satisfactory for use only when exposure temperatures are below 1750°F.

APPENDIX A

ACCIDENT HISTORY OF FLIGHT DATA AND COCKPIT VOICE RECORDERS

Since the introduction of turbine-powered aircraft in air carriers in 1959 to September 1965, the Civil Aeronautics Board has investigated over 181 accidents in which the aircraft involved had a flight recorder installed. Of these, 125 provided vital information although six sustained some impact damage. Only 10 flight recorders could provide no information for the following reasons: (1) three tapes were fragmented by impact forces, (2) three were consumed by fire, and (3) two had expended the tape prior to the accident; one was malfunctioning, and one was not turned on. The remaining two accidents were such that the recorders were not necessary to determine the probable cause.

The number of accidents since September 1965 involving flight recorders is not known at this time. However, it is known that during the time interval between September 1965 and August 1966, one flight recorder was lost due to fire damage. The breakdown of flight recorders totally destroyed by fire and unable to provide vital information regarding the probable cause, between 1959 and August 1966, is shown below:

1. United Air Lines - Viscount - Parrotsville, Tennessee, July 9, 1964.
2. Trans World Airlines - CV880 - Kansas City, Missouri, September 13, 1965.
3. Pan American World Airways - B707 - Montserrat, British West Indies, September 17, 1965.
4. Braniff Airways - BAC-111, Falls City, Nebraska, August 6, 1966.

As indicated, four flight recorders have been destroyed by fire. All of these were of the same type, employing aluminum tape.

The number of cockpit voice recorders involved in aircraft accidents is not known exactly, but it is believed to be about four previous to December 1966. All were recovered except in one accident occurring in October 1966 which involved a West Coast Air Line DC-9. This voice recorder sustained extensive fire damage resulting in the complete destruction of the tape. Therefore, no information on the crash could be provided. The aluminum recorder case, with its highly conspicuous exterior coating, was also destroyed. The recorder remained in the wreckage for 48 hours before it could be recovered and at the end of this time, it still could not be handled without asbestos gloves.

It is neither known how long it was involved in the fire, nor under what circumstances it was found (i.e., beneath wreckage, in a fuel puddle, etc.).

A TSO fire test was performed on an identical recorder by an independent testing company, and the recorder survived this test. The tape compartment temperature had risen to 350°F after a 40-minute test duration, 10 minutes longer than required by TSO-C84. The tape was still playable after the test. Obviously, the TSO fire test was not as severe as the crash fire.

APPENDIX B

DESCRIPTION OF THE NAFEC 12-GALLON-PER-HOUR KEROSENE TORCH

The apparatus used to supply the flames suitable for fire testing flight data and voice recorders is called the NAFEC 12-gallon-per-hour kerosene torch. This device was developed at NAFEC specifically for the purpose of testing these recorders in accordance with TSO-C51 and TSO-C84 which specify 2000°F flames covering 50 percent of the external area of the recorders. It was used to supply the flame required in a number of recorder tests described in this report. This brief description is provided to give the reader a better understanding of the operation of the device.

The torch is basically a modified gun-type conversion oil burner with auxiliary air supplied by separate blower. Any burner may be used to produce the same results. The auxiliary air is supplied by a centrifugal blower driven by a 1/2-horsepower, 3450 rpm motor. Air is forced into the torch through the draft tube opening. An overall picture of the torch is provided in Figure 2.1.

The burner unit of the torch has been modified by replacing the original fuel nozzle with one having an 80-degree spray angle and capable of delivering approximately 12 gallons of kerosene per hour. The exact fuel rate (12 gallons per hour) is obtained by properly adjusting the fuel pump pressure by means of the relief valve on the return line. The fuel is sprayed into a funnel-shaped extension attached to the draft tube where it mixes with the normal and auxiliary air and combination takes place. Initial ignition is obtained from a seat of ignitors which are part of the burner unit. The extension is about 14 1/2 inches long, with an oval-shaped opening 8 inches high and 16 inches wide. Baffle-type defectors are located in the extension to cut down turbulence and provide a uniform flame. The fuel and air ratio is controlled by regulating the amount of auxiliary air entering the extension. This is accomplished by adjusting a damper plate on the inlet of the auxiliary air blower. Under proper conditions for fuel and air flow, the temperature of the flames 4 inches in front of the extension will be 2000°F± 100°F, while the Btu output measured by the temperature increase of water flowing at 500 pounds per hour through a 1/2-inch copper tube located 4 inches in front of the extension will be 9,000± 500 Btu per hour.

It is obvious, therefore, that a piece of equipment which is to be subjected to a fire test employing the NAFEC 12-gallon-per-hour kerosene torch to supply the flames must be placed in front of the burner extension a distance of 4 inches since this is the location of the standard flame temperature and heat output.

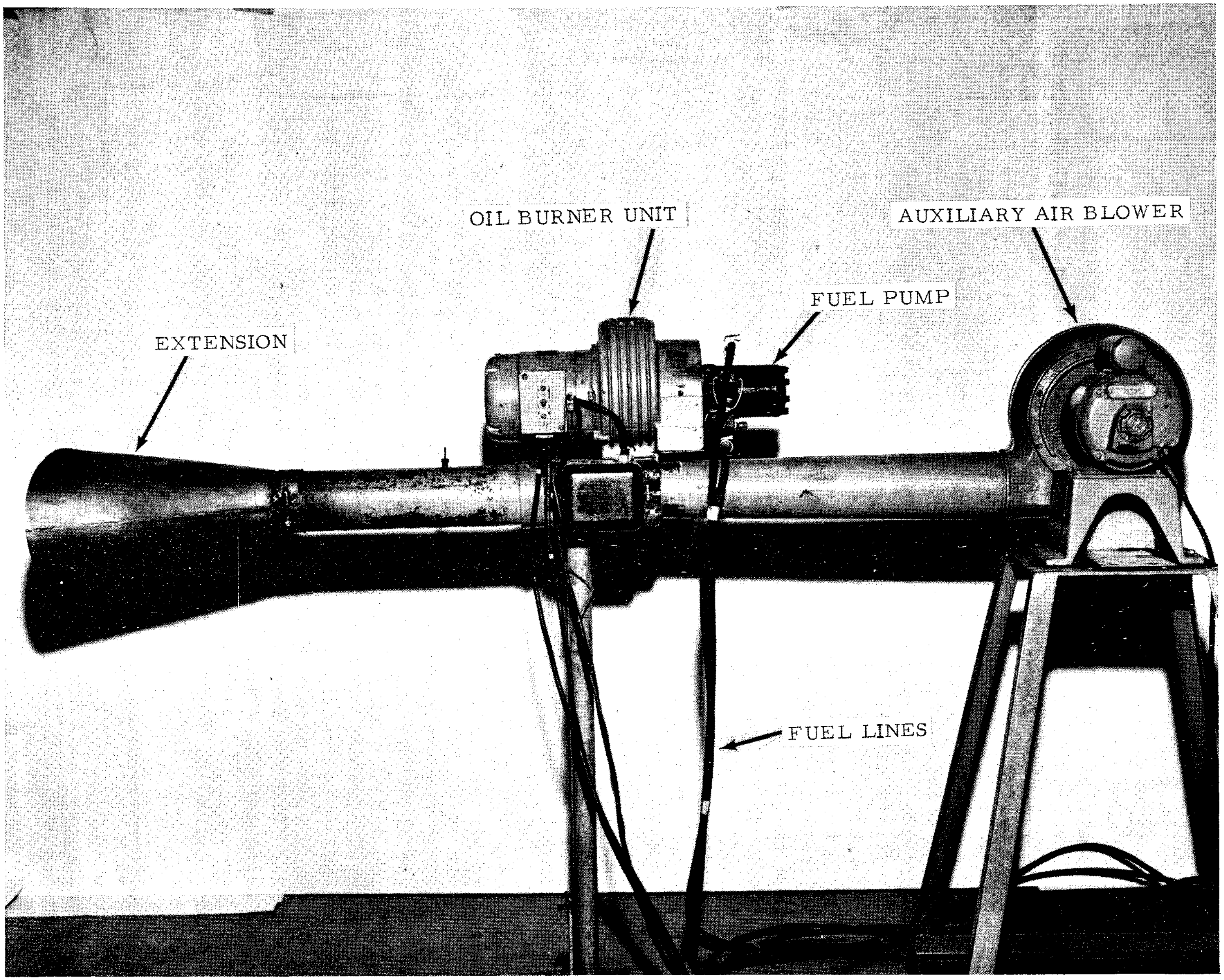


FIG. 2.1 NAFEC 12-GPH KEROSENE TORCH

APPENDIX C

REFERENCES

1. Technical Standard Order-C51, August 1958, "Aircraft Flight Recorder."

2. Technical Standard Order-C84, November 1963, "Cockpit Voice Recorders."

3. Federal Aviation Agency AC No. 20-36A, "Index of Materials, Parts and Airplanes Certified under the Technical Standard Order System," April 1966.