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AFAPL-TR-75-73

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INVESTIGATION OF TITANIUM COMBUSTION CHARACTERISTICS AND SUPPRESSION TECHNIQUES

FIRE PROTECTION BRANCH
FUELS AND LUBRICATION DIVISION

FEBRUARY 1976

TECHNICAL REPORT AFAPL-TR-75-73
FINAL REPORT FOR PERIOD 1 JANUARY 1974 – 1 MARCH 1975

AIR FORCE AERO-PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

NOTICE

This technical report has been reviewed and approved for publication.

DUANE G. FOX
Project Engineer
Fire Protection Branch
Fuels and Lubrication Division
Air Force Aero-Propulsion Laboratory

FOR THE COMMANDER

BENITO P. BOTTERI
Chief, Fire Protection Branch
Fuels and Lubrication Division
Air Force Aero-Propulsion Laboratory

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This test program studies the burning characteristics of titanium under air flow conditions. The flat plate titanium samples are ignited by molten titanium from an electrically heated ignitor. Air flow conditions that support sustained combustion of a single sample are determined. The burn rate is measured on all test with steady state burning.

Argon gas is shown to be a feasible extinguishing agent for a titanium fire. Quick injection of a sufficient amount of argon gas to maintain a 60%

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20. ABSTRACT - Continued

concentration by volume of argon results in quick suppression by oxygen depletion. Carbon dioxide (CO_2), a common fire extinguishing agent, is shown to sustain titanium burning at an accelerated rate.

The ultraviolet (UV) radiation emitted by burning titanium is shown to be of a sufficient intensity for existing UV fire detectors to detect at reasonable distances.

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FOREWORD

This report was prepared by Duane G. Fox of the Fire Protection Branch, Fuels and Lubrication Division, Air Force Aero-Propulsion Laboratory (AFAPL/SFH). The work reported herein was performed under Project 3048, "Fuels, Lubrication, and Fire Protection," Task 304807, "Aerospace Vehicle Fire Protection," Work Unit 30480773, "Aircraft Fire and Explosion Prevention." This work was performed at the request of the Components Branch of the Turbine Engine Division in support of Work Unit 30661005, "Compressor Rotor Rub Test." Test conditions and requirements were supplied by Mr. Charles W. Elrod, AFAPL/TBC.

This report covers research accomplished in-house from January 1974 to March 1975.

The author appreciates the assistance received from Mr. Jon R. Manheim, AFAPL/SFH, in designing the combustion chamber and extinguishing test hardware and in developing the experimental tests. Special thanks are given to the following individuals: Messrs. Peter Danelak, Harvey Reeves, Glen Boggs, and Robert Esch of AFAPL for their invaluable help in the execution of the experiments.

This report was submitted by the author July 1975.

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SECTION I

INTRODUCTION AND SUMMARY

A. INTRODUCTION

This test program was initiated to study the burning characteristics of titanium under specified flow conditions and to find a technique for extinguishing an on-going titanium fire in a test facility. The work was accomplished prior to the operation of a full-scale, single stage compressor test facility.

This program had two primary objectives: (1) Tests were conducted to determine what conditions (air temperature, air pressure, and air flow) are required for sustained combustion on a single compressor blade and representative flat plate sample. The burning rate was determined for all cases of sustained combustion. (2) Suppression studies were conducted to determine what concentration of an inert gas such as argon is required to extinguish a titanium fire.

B. SUMMARY

It was found that the burning characteristics of titanium samples are not strongly dependent on air flow temperature or pressure within the limits established in this program ($121^\circ C < T < 399^\circ C$, $448\ kPa < P < 1138\ kPa$). The initiation of sustained burning and burning rates are more dependent on the sample shape, thickness, and relative position to the air flow. Limited testing of a β alloy of titanium indicates that material composition does affect the burning characteristics.

Measurement of the ultraviolet (UV) radiation emitted from the burning titanium indicates that the UV emitted from a 2.54 x 7.62 cm sample is at least an order of magnitude greater in intensity than from a 5-inch diameter hydrocarbon fuel fire. Utilization of a UV fire detector for detecting a titanium fire is thus feasible.

It was shown that, for the test conditions studied, an argon gas concentration of at least 60% is required to extinguish a burning titanium sample. The argon dilutes the oxygen concentration to a level that will not support sustained combustion. Since substitution of argon for air can be done rapidly without significantly changing the total air flow through a test device, this extinguishment technique is applicable to turbine engine compressor test facilities where titanium combustion presents a hazard. The argon concentration must, however, be maintained until either the molten material cools sufficiently to prevent re-ignition or until the air flow is reduced so that sustained burning can not continue.

While steady-state burning data was obtained for the single sample, direct extrapolation to a rotating environment with complex air flow patterns such as exists in a turbine engine compressor is not possible. At best the steady-state burning data obtained can be used in computer modeling of the complex solid combustion phenomenon. The critical factor in achieving sustained burning following ignition and localized burning is the air flow and how it removes oxidized material from the surface. This phenomenon was not thoroughly studied in this effort.

C. ADDITIONAL INVESTIGATIONS REQUIRED

Although the testing performed provides baseline data on the burning characteristics of titanium in air flow, additional testing should be conducted to more fully characterize and define the effects of the ignition source and the air flow over the sample. The effects of a stacked sample array simulating an actual compressor also need to be adequately defined. This information will be required when the combustion phenomenon is modeled. Tests should also be conducted with other types of extinguishing agents.

SECTION II

EXPERIMENTAL EQUIPMENT

A. TEST FACILITY

The tests were conducted in a test facility located at the Air Force Aero-Propulsion Laboratory at Wright-Patterson AFB. The facility was developed to test turbine engine combustors. The facility provides air at a regulated pressure, temperature, and flow. A simplified schematic indicating the components of importance to the titanium combustion tests is shown in Figure 1. The control instrumentation is shown in Figure 2 and Figure 3. The overall test facility is shown in Figure 4.

The air is supplied by piston compressors and is then heated to the required temperature by a furnace. Pressure is maintained at a prescribed value in the test chamber by a feed back controller which opens or closes a bleed off valve. The flow is regulated by opening or closing a plug type orifice at the end of the air flow section. The plug orifice was operated by a remote switch in the control room.

The test sequence used was to first set the desired air temperature and pressure and then regulate the plug to get the required air flow. Closing the plug, for example, decreases the flow through the test chamber and increases the amount of bleed off.

The flow is determined by measuring the differential pressure (ΔP) across a two-inch diameter venturi and using the standard equation which relates the ΔP to the mass flow in pounds of flow per second. For ease of operation, tables were tabulated by a computer. By entering the temperature, static

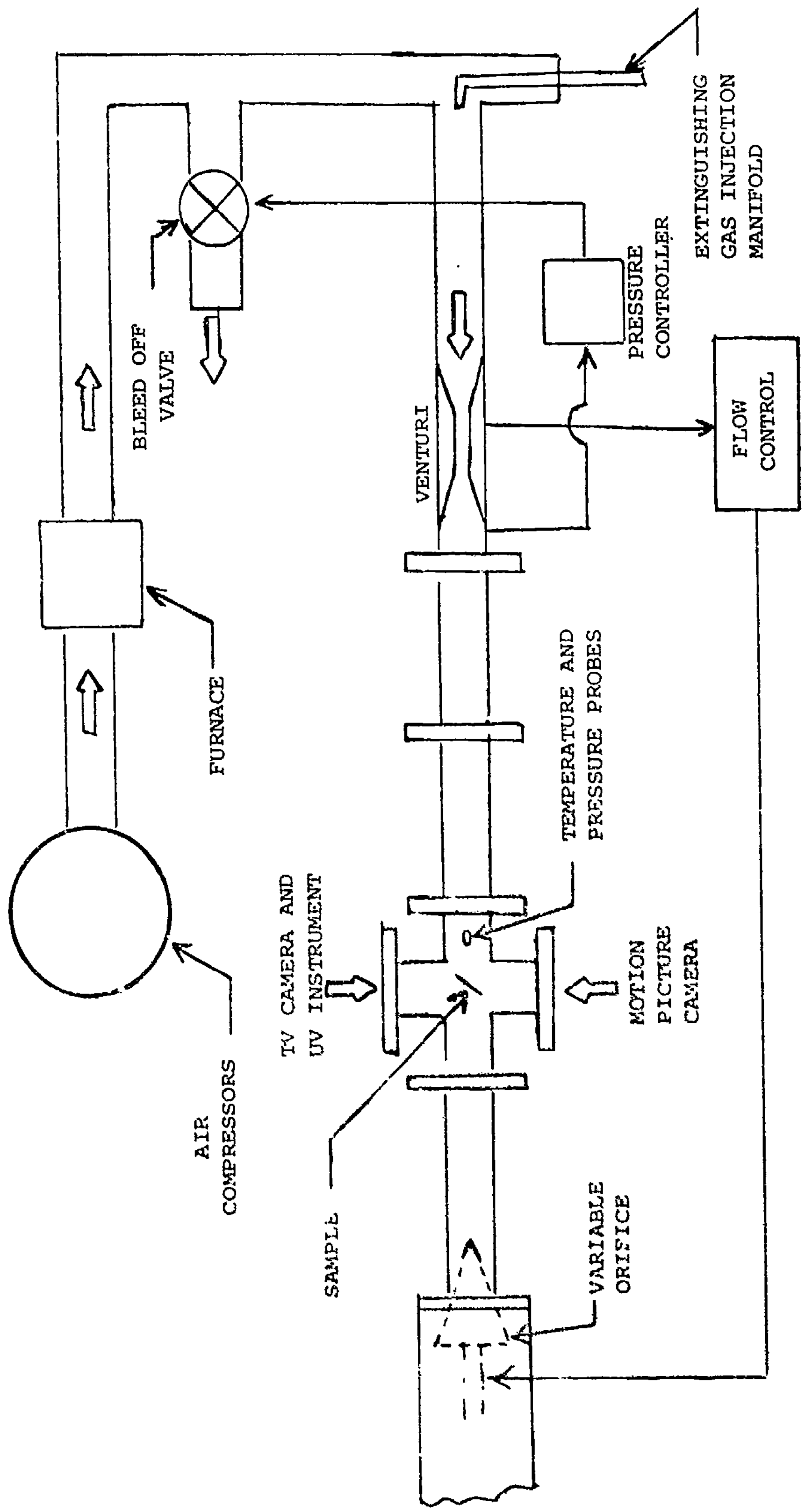


Figure 1. Titanium Test Facility Schematic

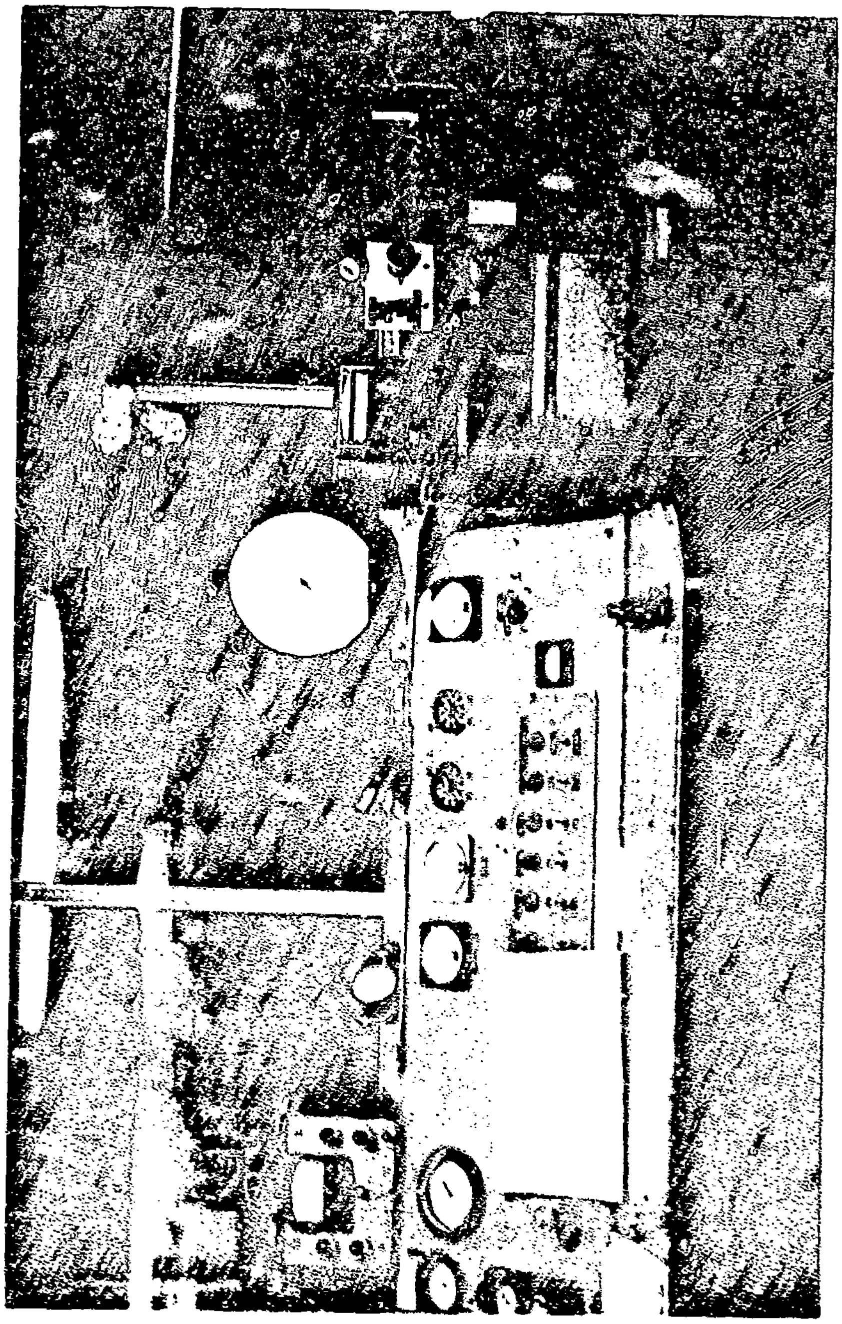


Figure 2. Air Supply Control Instrumentation

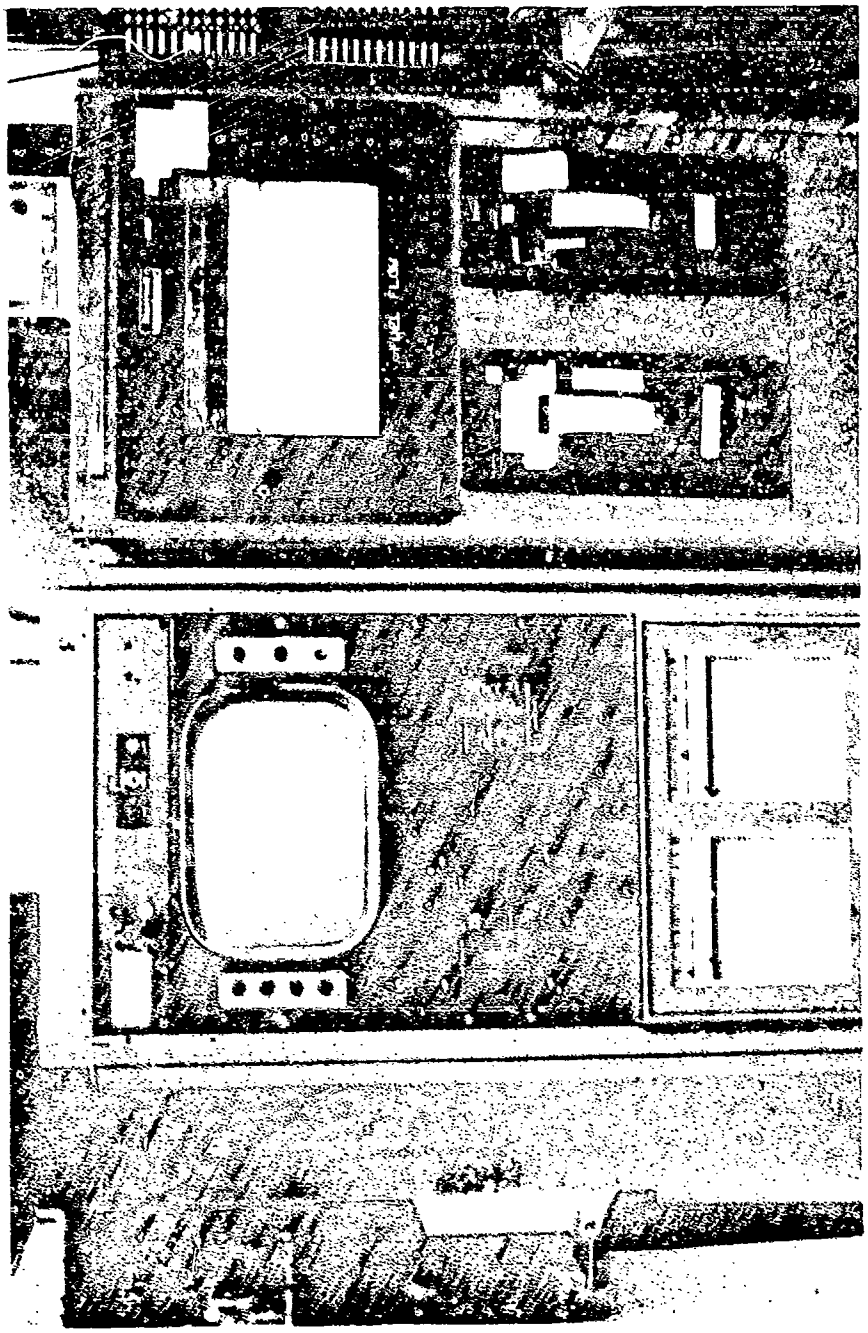


Figure 3. Air Supply Parameter Instrumentation

Figure 4. Photograph of Titanium Test Hardware

pressure, and differential pressure, the table gives the mass flow. The flow is reported in both Kg/sec and lb mass/sec in this report. Air velocity in the chamber is calculated from the pressure, flow, and temperature and is reported in both meters/sec and feet/sec.

B. COMBUSTION TEST CHAMBER

The test chamber was designed to use readily available materials in order to shorten fabrication time. The original chamber, prior to a few later modifications, is shown in Figure 5. The first 24-inch long section of pipe isolates the flow measuring venturi from the test chamber. The chamber is a standard 300 pound pipe cross. One leg of the cross contains a water cooled jacket which houses a 7.6 cm (3 inch) diameter, 1.27 cm (1/2 inch) thick quartz window. This window provides access for television camera coverage and also permits measuring the ultraviolet (UV) radiation emitted from the titanium flame. The UV radiation is of interest because it is a likely technique for detecting a titanium fire.

The other cross leg contains a water-cooled jacket which houses a 10.2 cm (4 inch) diameter, 4.4 cm (1.75 inch) thick tempered pyrex glass window. This window provides viewing access for high speed motion picture photography. The window jacket is cooled to prevent the glass from weakening at the higher temperatures. The cooling, however, causes a temperature gradient across the glass which results in the glass fracturing at a temperature near 399°C (750°F). The window was used satisfactorily for tests at 121°C (250°F) and 260°C (500°F). The glass window was replaced by a steel plate for the tests at 399°C (750°F). In these tests, the motion picture camera and TV camera both view through the smaller quartz window by the use of a partially reflecting mirror arrangement which is shown in Figure 6. This scheme proved adequate; however, alignment is more critical through the smaller window.

Figure 5. Test Chamber

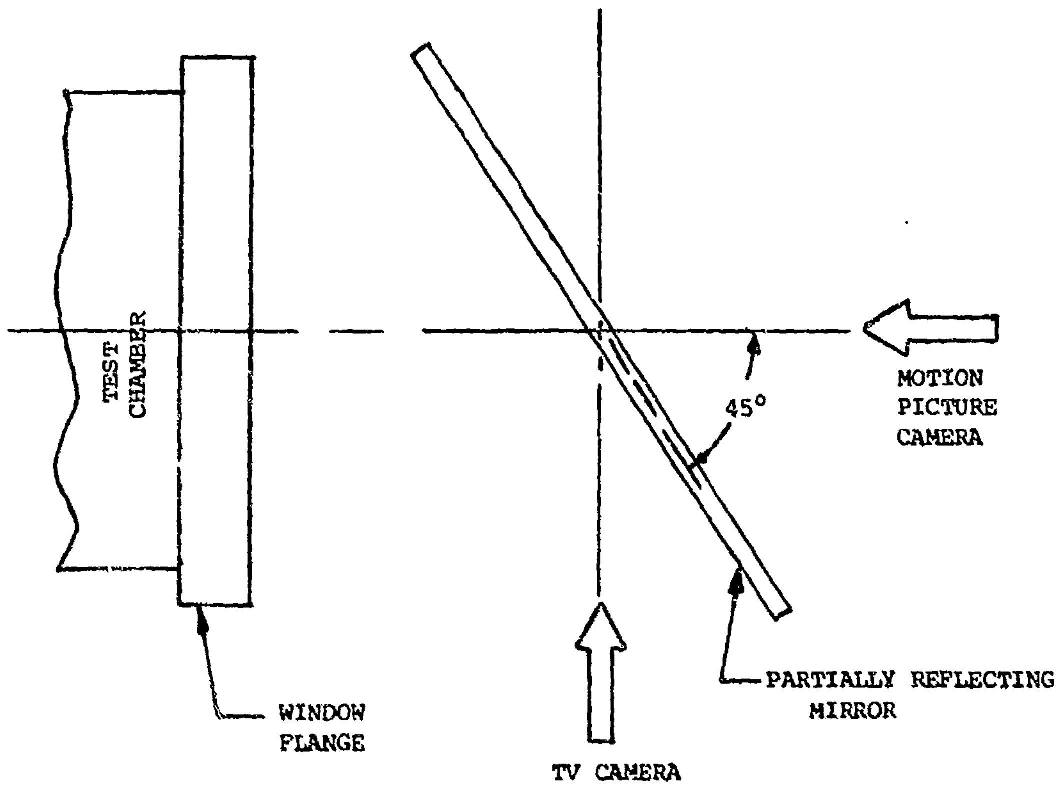


Figure 6. Mirror Arrangement for Visual Observation

The sample holder and igniter are mounted on a flange which bolts into the bottom center of the test section. This arrangement permits a fast change of test specimens. The sample holder and igniter are shown in Figure 7. The sample is held in place by boron nitride blocks which are fastened to the flange by stainless steel brackets. The boron nitride blocks keep the sample from burning past the holder. Since boron nitride is a high temperature material, it works satisfactorily at the high ambient temperature and is not significantly damaged by the molten titanium.

The igniter shown in Figure 7 is a 0.23 cm (0.090 inch) diameter titanium rod which is machined to 0.15 cm (0.060 inch) diameter at the center for 0.64 cm (0.25 inch) length. This forces the igniter to burn first at the center. Without the narrowed section, the igniter will usually burn first at one end or the other because of the strain produced at the connection point. This igniter proved to be unreliable at high air flow. Analysis of the high speed motion picture film revealed that the igniter was blowing over the top of the sample after becoming soft prior to melting.

The igniter was modified to a 6.3 mm x 1.6 mm x 7.62 cm long (0.25 inch x 0.062 inch x 3 inch) piece of titanium which is positioned evenly with the top edge of the sample, as shown in the illustration in Figure 8. This igniter is notched approximately 1.6 mm (1/16 inch) deep on both sides at the center. This igniter proved to be reliable and was used for the tests described in this report. Electric current from a 200 ampere, 16 volt, 60 Hertz transformer passes through the electrical fittings to the igniter holder. All conductors in the igniter circuit except the igniter are made from copper.

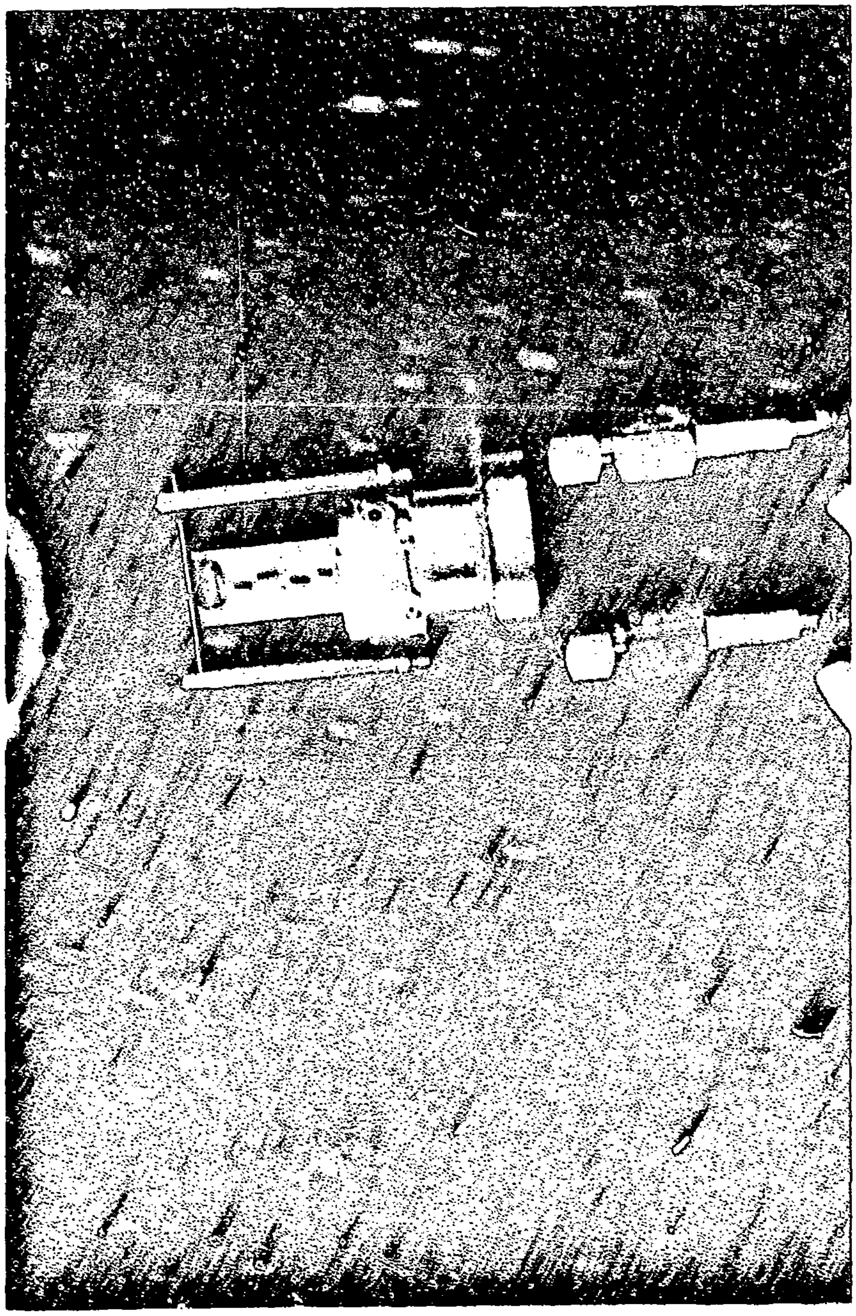


Figure 7. Sample Holder Flange

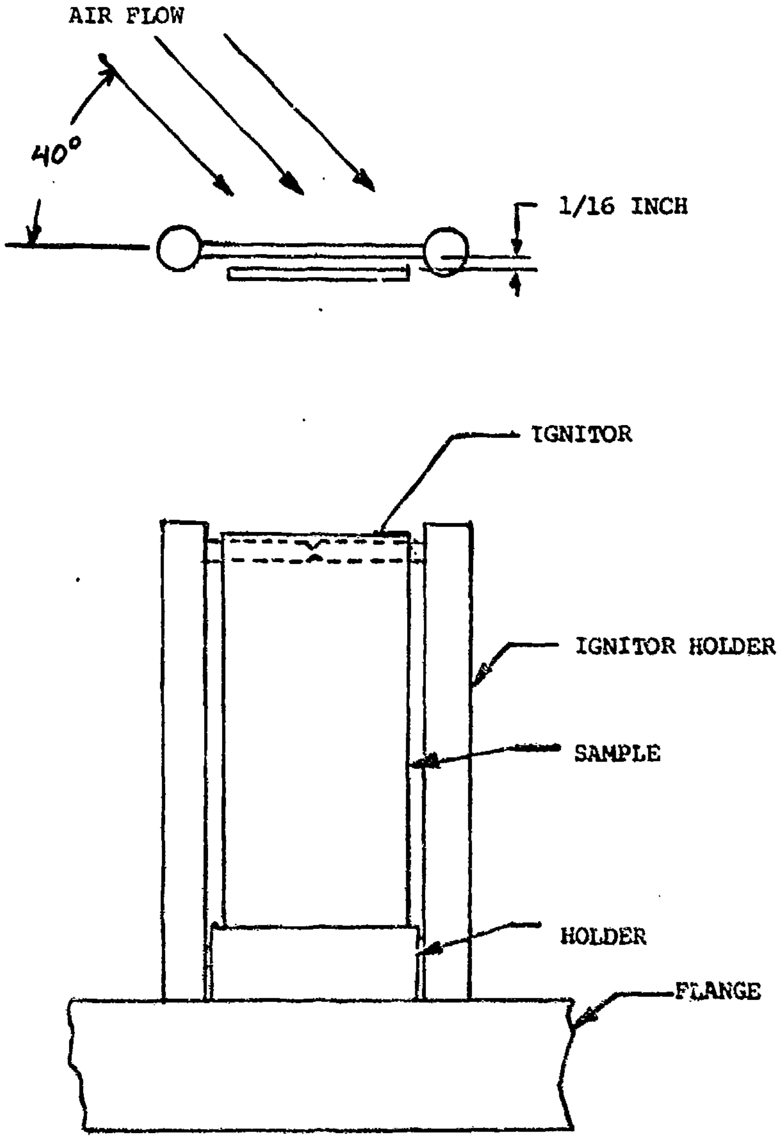


Figure 8. Sample and Ignitor Arrangement

C. SUPPRESSION HARDWARE

The suppression tests primarily involved injecting argon gas into the air flow upstream of the burning titanium sample and noting effects on the burning sample. CO_2 gas was also used in a few tests. The injection manifold is illustrated in Figure 9. This manifold injects the gas as illustrated in Figure 1. The manifold is pressurized up to the solenoid valve by a high capacity regulator which is manifolded to twelve, Size A argon cylinders. The complete argon injection system schematic is shown in Figure 10. The same hardware was also used for the CO_2 studies except that only six bottles were employed.

The argon temperature and pressure are measured in the injection manifold. The injection system was calibrated by sampling the flow stream near the sample. This procedure will be detailed later.

D. INSTRUMENTATION

The air system control instrumentation consists of a pressure gauge readout of the static wall temperature, a strip chart recorder output of the differential pressure (ΔP) across the venturi, and a thermocouple meter output of the air stream temperature. These instruments were used for adjusting the air flow conditions in the test chamber.

The test chamber parameters were recorded on a chart recorder (shown in Figure 11) so that changes and transients could be observed. The conditions during the burning tests were found to be stable and thus did not actually require time recording. The argon suppression tests, however, do involve rapid changes of temperatures and pressures and the recorded data is required for analyzing the test results.

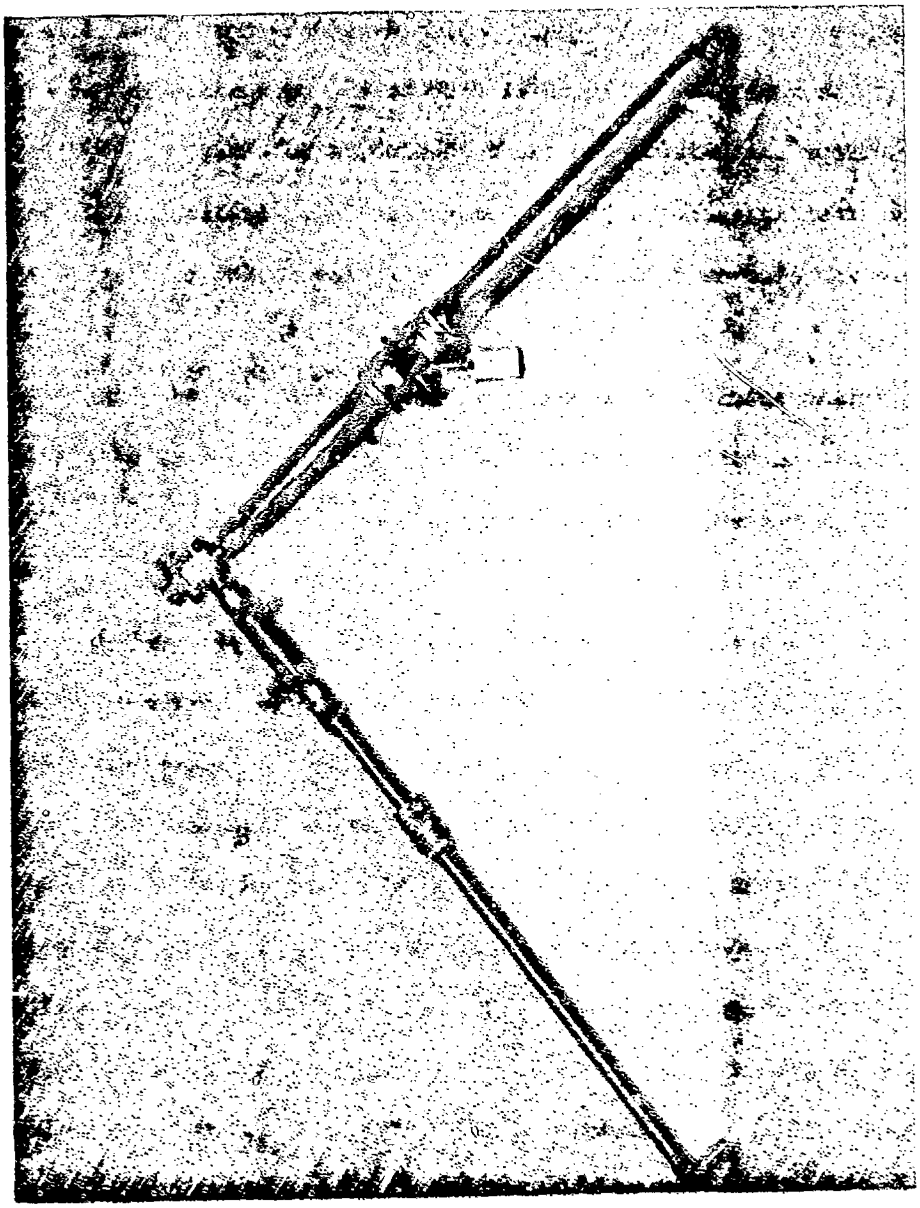


Figure 9. Argon and CO^2 Injection Manifold

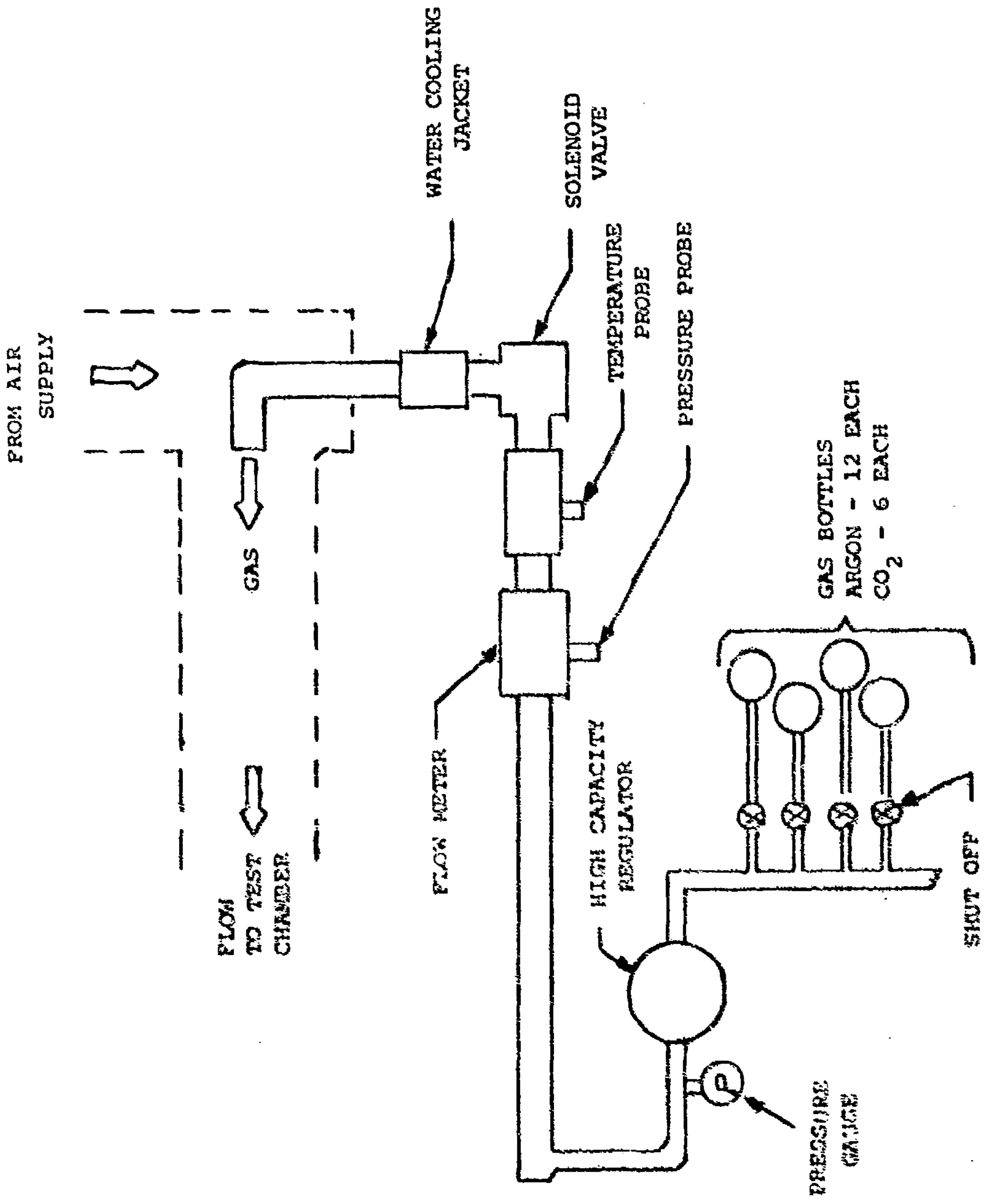


Figure 10. Argon and CO_2 Supply System Schematic

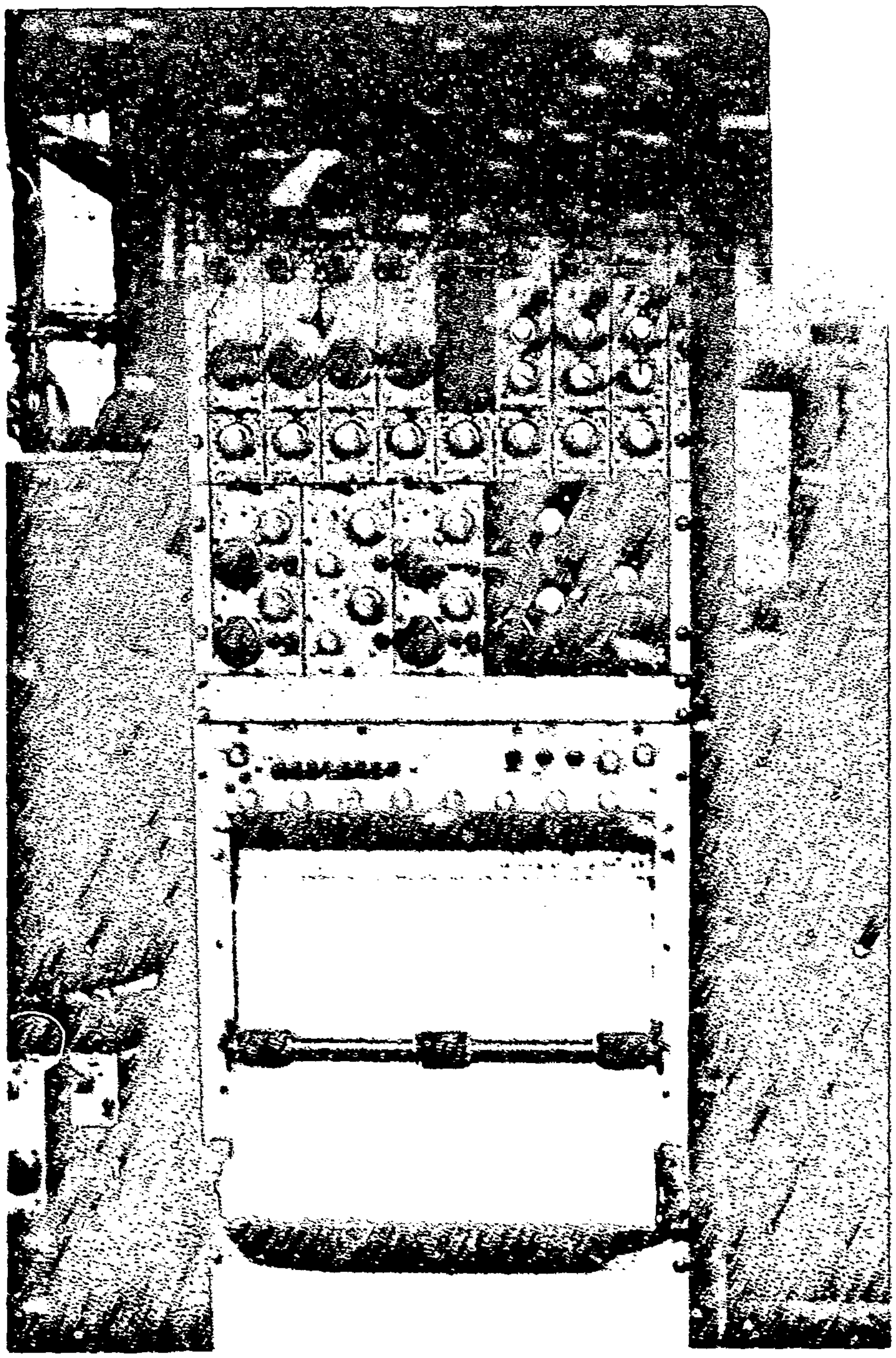


Figure 11. Data Chart Recorder

The air temperature is measured by an exposed junction Cr-Al thermocouple which is located about 6.4 mm (0.25 inch) from the wall in the nozzle just upstream of the sample. The exposed junction provides sufficient response during the argon injection tests.

The chamber static pressure is measured at the wall just upstream of the sample. The pressure transducer is located near the chamber and provides a sufficient frequency response to record transients in the pressure.

Two event markers are used so that both the time of ignition and the time of argon injection can be correlated with the pressure and temperature traces.

The argon temperature is measured near the exit of the flow meter. Measurement of the argon flow by using a turbine type flow meter proved to be unsuccessful because the readings were difficult to interpret. The actual argon concentration was determined by sampling the air stream near the sample and analyzing the mixture for oxygen, nitrogen, and argon. Samples were taken at the six required test conditions. The specific details of this procedure will be discussed in the section on extinguishing tests.

The ultraviolet emission tests were made with a spectroradiometer system that will be described in detail in Section VI.

The tests are properly sequenced by the use of a 12-step sequencing programmer which has a dwell time on each step that is adjustable from 0 to 10 seconds. This programmer (shown in Figure 12) is used to activate the motion picture camera, TV camera, sample igniter, argon injection valve, sample valves, and provide sync signals for the recorders and cameras. Once initiated, the test is automatic but does have manual override on some of the functions.

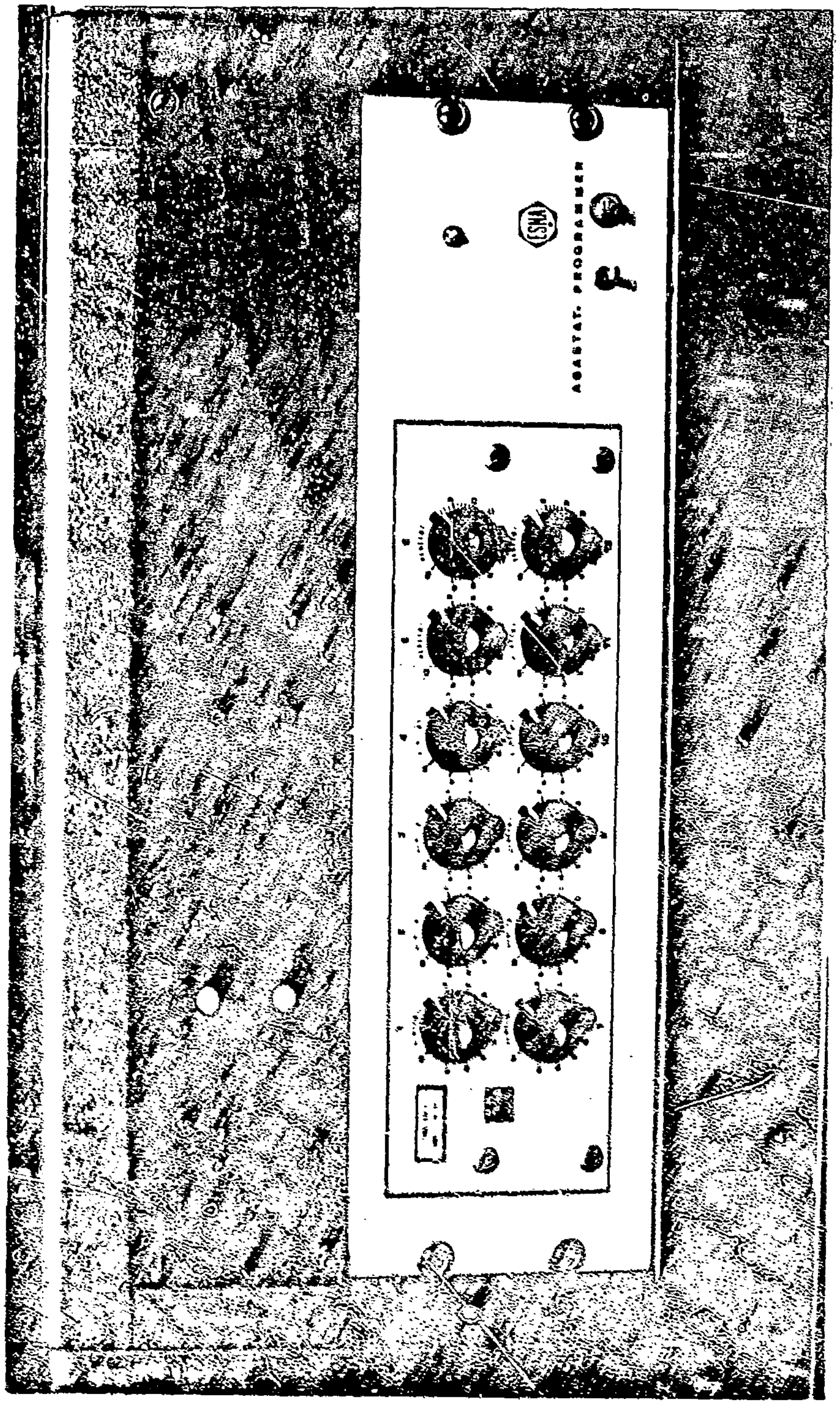


Figure 12. Test Sequence Programmer

SECTION III

COMBUSTION TESTS

A. TEST DESCRIPTION

The test procedure used was to first install a sample in the test chamber and then bring the air flow, pressure, and temperature to the desired values. The test was then initiated by starting the test sequencer. The test was monitored on the TV system and a determination made on whether the ignition was normal and whether sustained combustion occurred. In addition, the sample was analyzed visually after removal from the test chamber. These first hand procedures were successful in determining if the test was satisfactory for most tests. A more detailed analysis was later conducted by looking at the high speed motion pictures. This analysis showed that a few tests which were initially thought to be good were, in fact, not valid because of ignition difficulties. These tests were then excluded from the study.

If the TV viewing and sample analysis showed that the ignition was not normal, the test was repeated. If sustained combustion occurred, the air flow for the next test was increased and if non-sustained combustion occurred, the air flow was decreased. Eventually, the critical value of air flow was found that separated the non-sustained combustion and the sustained combustion regions. This sequence was repeated at all combinations of the three pressures (448, 793, 1138 kPa) and the three temperatures (121°C, 260°C, and 399°C).

Tests were conducted with two sample thicknesses (0.06 cm and 0.16 cm). In addition, compressor blades were tested at some of the pressures and temperatures. The limited number of blades and facility test time available did not permit testing the blades over the complete range of temperature and pressure. Enough tests were conducted, however, to allow some comparison of results.

The combustion tests were designed to define the air flow conditions that would support sustained combustion on a sample ignited on the edge by molten titanium. This is both a function of the air flow conditions around the sample and the ignition source. An insufficient amount of energy in the ignition source will fail to ignite a sample even though the airflow conditions are amenable for sustained combustion. The effect of the ignition source was not thoroughly studied in this test program, however, the high speed motion pictures of the ignition and sample were studied to determine the characteristics of the ignition source.

If the molten material ignited the sample along the top edge and the air flow was correct for sustained combustion, the sample would burn completely to the sample holder. Some burn patterns produced an even, horizontal burn down the sample. Other burn patterns were more complex and resulted in the flame burning down the leading or trailing edge first and then burning forward or rearward into the sample. This was more prevelant with the actual compressor blades because the blade edges are thin and burn more readily than the center portion.

As the air velocity on other tests was increased, a point would be reached such that the sample would start to burn at the point that the molten titanium from the igniter impinged on the sample but would soon stop burning (usually within a few mm, but occasionally as much as one-half cm). Since the sample would burn a short distance and then stop, it was assumed that sufficient energy was present to ignite the sample.

Several additional tests were conducted to establish the effectiveness of the ignition source. A steady burning was established on a sample by igniting it in air flow conditions that support sustained combustion. The air flow was then changed to a condition that had been established as a non-sustained burning condition. The sample stopped burning immediately after the air flow was changed. These tests further verify that the ignition source is sufficient to ignite the sample if the air flow is correct for sustained combustion.

The air flow required for sustained combustion is also a function of the angle of the sample relative to the direction of air flow. The angle used in these tests is 40 degrees, which is typical for a compressor blade. The effect of varying the angle between the sample and the air flow was not evaluated in this series of tests.

The following five samples were used in the combustion tests:

1. Sample A - Size: 2.54 cm x 7.62 cm x 0.06 cm
   (1" x 3" x 0.025")
   Material: Titanium Alloy
   6% Aluminum, 4% Vanadium
2. Sample B - Size: 2.54 cm x 7.62 cm x 0.16 cm
   (1" x 3" x .064")
   Material: Titanium Alloy
   6% Aluminum, 4% Vanadium
3. Sample C - Compressor Blade
   6% Aluminum, 4% Vanadium (thickness less than Sample D)
4. Sample D - Compressor Blade
   6% Aluminum, 4% Vanadium (thickness greater than Sample C)

5. Sample E - Size: 2.54 cm x 7.62 cm x 0.11 cm

Material: Titanium Alloy

β structure

B. TEST RESULTS AND DISCUSSION

The test results are tabulated in Table 1 through Table 9. The critical value of the air flow for supporting sustained combustion is tabulated in Table 10. The critical value is determined by looking at all tests of one sample at a fixed set of air flow conditions and estimating the break point between the sustained and non-sustained burning regions. This is not necessarily the midpoint between the data points, but is the result of analyzing the individual tests and considering factors such as ignition. It should be apparent that this value could vary somewhat due to the interpretive factors involved in making the determination. This value is, however, the best that can be obtained from this series of tests. The results are sufficient to establish trends in the burning characteristics over the temperature and pressure range of interest in this study.

Sample A generally burned at a higher air velocity than Sample B, which is expected because of the difference in thickness. The effect of an increase in air temperature is an increase in the air velocity at which sustained combustion can occur, as illustrated in Figure 13. The effect of pressure varies, as illustrated in Figure 14.

The data on Sample C is presented in Figure 15. It should be noted that two data points are not actual break points between non-sustained and sustained burning, but only measured data points in the sustained burning region. There were not sufficient tests conducted to determine the actual break point. The blade shows a definite effect of temperature and

TABLE 1

TITANIUM COMBUSTION TEST RESULTS, SAMPLE A

Test #	Pressure		Air Flow		Air Velocity		Burn Rate		Summary of Test
	kPa	(psia)	Kg/sec	(lbm/sec)	m/sec	(ft/sec)	cm/min	(inch/min)	
8AK01	455	66	0.36	0.8	32	107		6.26	Sustained combustion, entire sample burned
8AK02	448	65	0.68	1.5	62	203			Ignition was marginal, only slight combustion of sample
8AK03	448	65	0.54	1.2	49	162		7.0	Sustained combustion, sample burned about 75%
8AK04	448	65	0.54	1.2	49	162		3.67	Sustained combustion, sample burned about 85%
8AK05	448	65	0.59	1.3	54	176			Slight combustion on top edge
8AK06	786	114	0.91	2.0	47	154		7.23	Sustained combustion, entire sample burned
8AK07	786	114	1.36	3.0	71	231			Slight combustion on top edge
8AK08	786	114	1.13	2.5	59	193			Partial combustion on top edge
8AK09	779	113	1.04	2.3	55	179			Partial combustion on top edge
8AK10	779	113	0.91	2.0	47	156		7.26	Sustained combustion, entire sample burned
8AK11	1138	165	1.13	2.5	41	133	Not measured		Sustained combustion, entire sample burned
8AK12	1124	163	1.36	3.0	49	162			Partial combustion on top edge and leading edge
8AK13	1124	163	1.22	2.7	44	146			Marginal ignition, igniter positioned low on sample
8AK14	1117	162	1.22	2.7	45	147			Partial combustion on top edge
8AK15	1117	162	1.13	2.5	41	136			Marginal ignition, igniter positioned low on sample
8AK16	1117	162	1.13	2.5	41	136	Not measured		Sustained combustion, entire sample burned

Sample: 2.54 cm x 7.62 cm x 0.06 cm Titanium Temperature: 121°C

TABLE 2

TITANIUM COMBUSTION TEST RESULTS, SAMPLE A

Test #	Pressure kPa	Pressure (psia)	Air Flow Kg/sec	Air Flow (lbm/sec)	Air Velocity m/sec	Air Velocity (ft/sec)	Burn Rate cm/min	Burn Rate (inch/min)	Summary of Test
8AM01		61		2.5	110	360			Partial combustion on top edge
8AM02		62		2.0	86	284			Partial combustion on top edge
8AM03		65		1.5	62	203			Partial combustion on top edge
8AM04		66		1.0	41	133		5.17	Sustained combustion, entire sample burned
8AM05		65		1.0	41	135	Not measured		Sustained combustion, entire sample burned
8AM06		64		1.5	63	206			Partial combustion on top edge
8AM07		114		2.0	47	154			Marginal ignition, not considered a valid test
8AM08		115		1.5	35	115		6.6	Sustained combustion, entire sample burned
8AM09		115		1.75	41	134	Not measured		Sustained combustion, entire sample burned
8AM10		115		1.75	41	134		8.3	Sustained combustion, entire sample burned
8AM11		164		2.0	33	107		7.8	Sustained combustion, entire sample burned
8AM12		164		2.5	41	134		9.6	Sustained combustion, entire sample burned
8AM13		164		3.5	57	188			Partial combustion on top edge
8AM14		164		3.0	49	161		6.6	Sustained combustion, entire sample burned
8AM15		162		3.0	50	162			Partial combustion on top edge
8AN06	779	113	0.90	2.0	47.4	155.6	17	6.7	Sustained combustion, entire sample burned
8AN07	779	113	1.02	2.25	53.3	175			Partial combustion on top edge
8AN08	779	113	1.02	2.25	53.3	175			Partial combustion on top edge
8AO10	441	64	0.57	1.25	52.1	171			Slight combustion on top edge
8AO11	441	64	0.57	1.25	52.1	171			Slight combustion on top edge

Sample: 2.54 cm x 7.62 cm x 0.06 cm Titanium   Temperature: 260°C

TABLE 3

TITANIUM COMBUSTION TEST RESULTS, SAMPLE A

Test #	Pressure kPa	Pressure (psia)	Air Flow Kg/sec	Air Flow (lbm/sec)	Air Velocity m/sec	Air Velocity (ft/sec)	Burn Rate cm/min	Burn Rate (inch/min)	Summary of Test
8AP01	448	65	0.45	1.0	52	170.5			Sample failed, not a valid test
8AP02	448	65	0.45	1.0	52	170.5	15	5.9	Sustained combustion, entire sample burned
8AP03	441	64	0.23	0.5	26	85.2	20.8	8.2	Sustained combustion, entire sample burned
8AP04	779	113	0.91	2.0	59.7	196	Not measured		Sustained combustion, entire sample burned
8AP05	793	115	0.68	1.5	44	144.5			Sustained combustion, entire sample burned
8AP06	793	115	0.45	1.0	29.4	96.3	19	7.5	Sustained combustion, entire sample burned
8AP07	765	111	1.36	3.0	91.3	299.5			Slight combustion on top edge
8AP08	765	111	1.13	2.5	76	249.5			Partial combustion on top edge
8AP09	779	113	1.02	2.25	67	220.6			Partial combustion on top edge
8AP10	786	114	0.91	2.0	59	194.4	18.3	7.2	Sustained combustion, entire sample burned
8AP11	1131	164	1.13	2.5	51.5	169	16.3	6.4	Sustained combustion, entire sample burned
8AP12	1124	163	1.36	3.0	62.2	204			Partial combustion on top edge
8AP13	1117	162	1.25	2.75	57.3	188			Partial combustion on top edge
8AQ14	448	65	0.68	1.5	78	256	16.0	6.3	Sustained combustion, entire sample burned
8AQ15	448	65	0.91	2.0	104	341			Partial combustion on top edge
8AQ16	434	63	0.79	1.75	93.9	308			Slight combustion on top edge
8AQ17	434	63	1.02	2.25	120.7	396			Partial combustion on top edge
8AQ18	779	113	0.68	1.5	44.8	147	7.8	5.3	Sustained combustion, entire sample burned

Sample: 2.54 cm x 7.62 cm x 0.06 cm Titanium   Temperature: 399°C

TABLE 4

TITANIUM COMBUSTION TEST RESULTS, SAMPLE B

Test #	Pressure kPa	Pressure (psia)	Air Flow Kg/sec	Air Flow (lbm/sec)	Air Velocity m/sec	Air Velocity (ft/sec)	Burn Rate cm/min	Burn Rate (inch/min)	Summary of Test
8AH02	461	67	0.45	1.0	30	97			Slight combustion on top edge
8AH03	461	67	0.27	0.6	18	58			Slight combustion on top corners, however, igniter was 1/4" low
8AI01	448	65	0.27	0.6	18	60			Igniter fused to sample, not a good ignition
8AI02	448	65	0.23	0.5	15	50			Sustained combustion on leading edge; however, entire sample did not burn
8AI03	455	66	0.23	0.5	15	49	6.6	2.6	Sustained combustion, entire sample burned
8AI04	806	117	1.04	2.3	39	128			Partial combustion on top edge, however, igniter was 1/4" low
8AI05	800	116	0.91	2.0	34	112			Sustained combustion; however, entire sample did not burn
8AI06	806	117	0.91	2.0	34	111			Partial combustion on leading corner and top edge
8AI07	793	115	0.73	1.6	27	90			Sustained combustion; however, entire sample did not burn
8AI08	793	115	0.45	1.0	17	56			Igniter went over the top and did not ignite the sample
8AJ01	793	115	0.64	1.4	24	79	14.7	5.8	Sustained combustion, entire sample burned
8AJ02	793	115	0.64	1.4	24	79	9.9	3.9	Sustained combustion, entire sample burned
8AJ03	1138	165	1.36	3.0	36	118			Ignition was marginal, slight combustion on top edge
8AJ04	1136	165	1.36	3.0	36	118			Slight combustion on top edge
8AJ05	1131	164	1.13	2.5	30	99			Partial combustion on top edge
8AJ06	1138	165	0.91	2.0	24	79	10.7	4.2	Sustained combustion, entire sample burned
8AJ07	1138	165	0.91	2.0	24	79	8.4	3.3	Sustained combustion, entire sample burned
8AJ08	1136	165	1.13	2.5	30	98			Slight combustion on trailing edge; however, igniter was too low
8AS09	448	65	0.45	1.0	30	100			Igniter only burned partially
8AS10	448	65	0.36	0.8	24	80			Slight combustion on top edge
8AS11	448	65	0.27	0.6	18	60			Slight combustion on top edge; however, most of igniter did not hit the sample
8AS12	448	65	0.23	0.5	15	50	7.9	3.1	Sustained combustion, entire sample burned
8AS13	448	65	0.27	0.6	18	60			Partial combustion on top edge

Sample: 2.54 cm x 7.62 cm x 0.16 cm Titanium Temperature: 121°C ±2°C

TABLE 5

TITANIUM COMBUSTION TEST RESULTS, SAMPLE B

Test #	Pressure kPa	Pressure (psia)	Air Flow Kg/sec	Air Flow (lbm/sec)	Air Velocity m/sec	Air Velocity (ft/sec)	Burn Rate cm/min	Burn Rate (inch/min)	Summary of Test
8AE01	448	65	1.36	3.0	123	405			Slight combustion on top edge
8AE02	441	64	0.91	2.0	84	275			Slight combustion on top edge
8AE03	448	65	0.68	1.5	62	203			Slight combustion on top edge
8AE04	448	65	0.36	0.8	33	108	8.0	3.18	Sustained combustion, entire sample burned
8AE05	793	115	2.04	4.5	105	344			Ignition was marginal, sample did not burn
8AE06	793	115	0.91	2.0	47	153	11.1	4.38	Sustained combustion, entire sample burned
8AE07	793	115	2.04	4.5	105	344			Ignition was marginal, sample did not burn
8AE08	779	113	1.36	3.0	71	233			Slight combustion on top edge
8AE09	779	113	0.45	1.0	24	78	12.0	4.74	Sustained combustion, entire sample burned
8AE10	1124	163	1.59	3.5	57	189			Slight combustion on top edge
8AE11	1133	165	0.91	2.0	32	107	13.6	5.34	Sustained combustion, entire sample burned
8AF01	448	65	0.45	1.0	41	135			Ignition was marginal, sample did not ignite
8AF02	448	65	0.18	0.4	16	54			Sample installed in reverse direction
8AF03	448	65	0.18	0.4	16	54	7.3	2.88	Sustained combustion, entire sample burned
8AF04	607	88	0.68	1.5	46	150			Slight combustion on top edge
8AF05	621	90	0.45	1.0	30	98			Slight combustion on top edge
8AF06	621	90	0.45	1.0	30	98			Slight combustion on top edge
8AF07	621	90	0.23	0.5	15	49	13.2	5.18	Sustained combustion, entire sample burned
8AF08	621	90	0.45	1.0	30	98			Slight combustion on top edge
8AF09	807	117	1.13	2.5	57	188	Not measured		Sustained combustion, entire sample burned
8AF10	965	140	1.36	3.0	57	188			Bad ignition
8AF11	972	141	1.13	2.5	48	159			Bad ignition
8AF12	979	142	1.13	2.5	48	159			Slight combustion on top leading edge
8AF13	965	140	0.92	2.0	38	126	12.0	4.73	Sustained combustion, entire sample burned
8AG01	965	140	1.13	2.5	48	157			Slight combustion on top edge

Sample: 2.54 cm x 7.62 cm x 0.16 cm Titanium   Temperature: 260°C

TABLE 5 (Cont'd)

Test #	Pressure kPa	Pressure (psia)	Air Flow Kg/sec	Air Flow (lbm/sec)	Air Velocity m/sec	Air Velocity (ft/sec)	Burn Rate cm/min	Burn Rate (inch/min)	Summary of Test
8AG02	1138	165	1.13	2.5	41	133	13.3	5.22	Sustained combustion
8AG03	1138	165	1.36	3.0	49	160			Slight combustion on top edge
8AG04	1151	167	1.36	3.0	48	158			Slight combustion on top edge
8AN01	793	115	0.91	2.0	47	153			Slight combustion on trailing edge
8AN02	786	114	0.45	1.0	24	77	10.2	4.01	Sustained combustion, entire sample burned
8AN03	793	115	0.68	1.5	35	115	11.9	4.7	Sustained combustion, entire sample burned
8AN04	779	113	0.79	1.75	41	136			Partial combustion
8AN05	772	112	0.91	2.0	48	157			Slight combustion on top edge
8AS06	448	65	0.36	0.8	33	108	7.6	3.0	Sustained combustion, 80% of sample burned
8AS07	448	65	0.45	1.0	41	135	5.1	2.0	Sustained combustion, 80% of sample burned
8AS08	448	65	0.50	1.1	45	149			Slight combustion on trailing edge

TABLE 6

TITANIUM COMBUSTION TEST RESULTS, SAMPLE B

Test #	Pressure		Air Flow		Air Velocity		Burn Rate		Summary of Test
	KPa	(psia)	Kg/sec	(lbm/sec)	m/sec	(ft/sec)	cm/min	(inch/min)	
8AG01	448	65	0.45	1.0	41	135			Partial combustion on trailing edge top corner
8AG05	1158	168	1.36	3.0	48	157			Slight combustion on top edge
8AG06	1165	169	1.13	2.5	40	130			Partial combustion on top edge
8AQ01	1124	163	1.13	2.5	42	138	12.2	4.8	Sustained combustion, entire sample burned
8AQ02	1103	160	1.36	3.0	50	165			Partial combustion on top edge
8AQ03	1117	162	1.25	2.75	45	149	15.2	6.0	Sustained combustion, entire sample burned
8AQ04	1117	162	1.25	2.75	45	149			Partial combustion on top edge and trailing edge
8AQ05	779	113	0.68	1.5	36	117	11.8	4.65	Sustained combustion, entire sample burned
8AQ06	786	114	0.91	2.0	47	154			Partial combustion on top edge
8AQ07	793	115	0.79	1.75	41	134	12.4	4.9	Sustained combustion, entire sample burned
8AQ08	779	113	0.91	2.0	95	156			Partial combustion on top edge and trailing edge
8AQ09	455	66	0.34	0.75	30	100	8.9	3.5	Sustained combustion, entire sample burned
8AQ10	448	65	0.45	1.0	41	135	9.1	3.6	Sustained combustion, entire sample burned
8AQ11	469	65	0.68	1.5	62	203			Slight combustion on top edge
8AQ12	448	65	0.57	1.25	52	169	8.1	3.2	Sustained combustion, entire sample burned
8AQ13	434	63	0.68	1.5	64	209			Partial combustion on top edge and trailing edge

Sample: 2.54 cm x 7.62 cm x 0.16 cm Titanium   Temperature: 399°C

TABLE 7

TITANIUM COMBUSTION TEST RESULTS, SAMPLE C

Test #	Pressure kPa	Pressure (psia)	Air Flow Kg/sec	Air Flow (lbm/sec)	Air Velocity m/sec	Air Velocity (ft/sec)	Burn Rate cm/min	Burn Rate (inch/min)	Summary of Test
BAL01	448	65	0.45	1.0	30	100			Slight combustion on top edge
BAL02	449	65	0.36	0.8	24	80			Partial combustion on leading edge
BAL03	449	65	0.23	0.5	15	50			Ignition failure
BAL04	441	64	0.23	0.5	15	50			Partial combustion on leading edge
BAL05	793	115	0.45	1.0	17	57	11.7	4.6	Sustained combustion, sample completely burned
BAL06	786	114	0.91	2.0	35	114	11.2	4.4	Sustained combustion, sample completely burned
BAL07	779	113	1.13	2.5	44	134	12.7	5.0	Sustained combustion, sample completely burned
BAL08	779	113	1.[illegible]	3.5	61	201			Slight combustion on trailing and top edges
BAL09	772	112	1.42	3.0	53	174	15.2	6.0	Sustained combustion, sample completely burned
BAL10	449	65	0.22	0.4	12	40	Not measured		Sustained combustion, sample completely burned

Sample: TF-39 6th Stage Compressor Blade Temperature: 121°C (250°F)

TABLE 8

TITANIUM COMBUSTION TEST RESULTS, SAMPLE C

Test #	Pressure		Air Flow		Air Velocity		Burn Rate		Summary of Test
	kPa	(psia)	Kg/sec	(lbm/sec)	m/sec	(ft/sec)	cm/min	(inch/min)	
8A001	441	64	0.45	1.0	42	137			Sample incorrectly installed
8A002	441	64	0.45	1.0	42	173			Not a good ignition
8A003	469	68	0.23	0.5	20	65	12.4	4.9	Sustained combustion, sample completely burned
8A004	793	115	0.68	1.5	35	115	13.7	5.4	Sustained combustion, sample completely burned
8A005	786	114	0.91	2.0	47	154	20.0	7.9	Sustained combustion
8A006	779	113	1.1	2.5	59	195			Slight combustion on trailing and top edges
8A007	779	113	1.1	2.5	59	195	11.9	4.7	Sustained combustion, sample completely burned
8A008	772	112	1.4	3.0	72	235	7.6	3.0	Sustained combustion, sample burned about 50%
8A009	772	112	1.4	3.0	72	235			Slight combustion on trailing edge
8A018*	779	113	0.66	1.5	45	147	13.5	5.3	Sustained combustion, sample completely burned

Sample: TF-39 6th Stage Compressor Blade

Temperature: 260°C (500°F) except * which was 399°C (750°F)

TABLE 9

TITANIUM COMBUSTION TEST RESULTS, SAMPLE D

Test #	Pressure kPa	Pressure (psia)	Air Flow Kg/sec	Air Flow (lbm/sec)	Air Velocity m/sec	Air Velocity (ft/sec)	Burn Rate cm/min	Burn Rate (inch/min)	Summary of Test
Temperature = 149°C (300°F)									
8AR05	517	75	0.45	1.0	28	93			Ignition on leading edge, only small amount of burning
8AR06	531	77	0.45	1.0	27	90	10.4	4.1	Ignition on trailing edge, sample burned completely
8AR07	531	77	0.45	1.0	27	90			Ignition was not good
8AR08	531	77	0.34	0.75	10	68	12.2	4.6	Ignition on leading edge, sample burned completely
Temperature = 260°C (500°F)									
8AR09	517	75	0.64	1.4	50	164	11.4	4.5	Ignition on trailing edge, sample burned completely
8AR10	517	75	0.64	1.4	50	164			Ignition was not good, molten Ti did not hit sample
8AR11	517	75	0.45	1.0	36	117			Ignition on leading edge, only small amount of burning
8AS01	517	75	0.64	1.4	50	164	10.4	4.1	Ignition on trailing edge, sample burned completely
8AS02	524	76	0.34	0.75	26	87	15.2	6.0	Ignition on leading edge, sample burned completely
Temperature = 371°C (700°F)									
8AS03	855	124	0.77	1.7	44	146	13.5	5.3	Ignition on trailing edge, sample burned completely
8AS04	857	125	0.77	1.7	44	144	10.2	4.0	Ignition on leading edge, sample burned completely
8AS05	862	125	0.77	1.7	44	144	Not measured		Ignition on leading edge, sample burned completely

Sample: TF-30 6th Stage Compressor Blade   Temperature: As indicated above Test No.

TABLE 10

MAXIMUM AIR VELOCITY FOR SUSTAINED COMBUSTION

PRESSURE kPa	(psia)	SAMPLE	MAXIMUM VELOCITY FOR SUSTAINED COMBUSTION 121°C m/sec	(250°F) ft/sec	260°C m/sec	(500°F) ft/sec	399°C m/sec	(750°F) ft/sec
448	(65)	A (.06 cm)	52	(170)	47	(153)	80	(262)
793	(115)	A	51	(167)	50	(165)	63	(207)
1138	(165)	A	43	(141)	49	(161)	54	(178)
484	(65)	B (.16 cm)	17	(55)	43	(142)	52	(169)
798	(115)	B	34	(112)	40	(131)	44	(144)
1138	(165)	B	27	(89)	44	(145)	45	(149)
448	(65)	C (TF-39 6th)	14	(45)	>20	(>65)	Not Tested	
793	(115)	C	57	(188)	66	(215)	45	(>147)
1138	(165)	E (β alloy)	Not Tested		20	(66)	Not Tested	

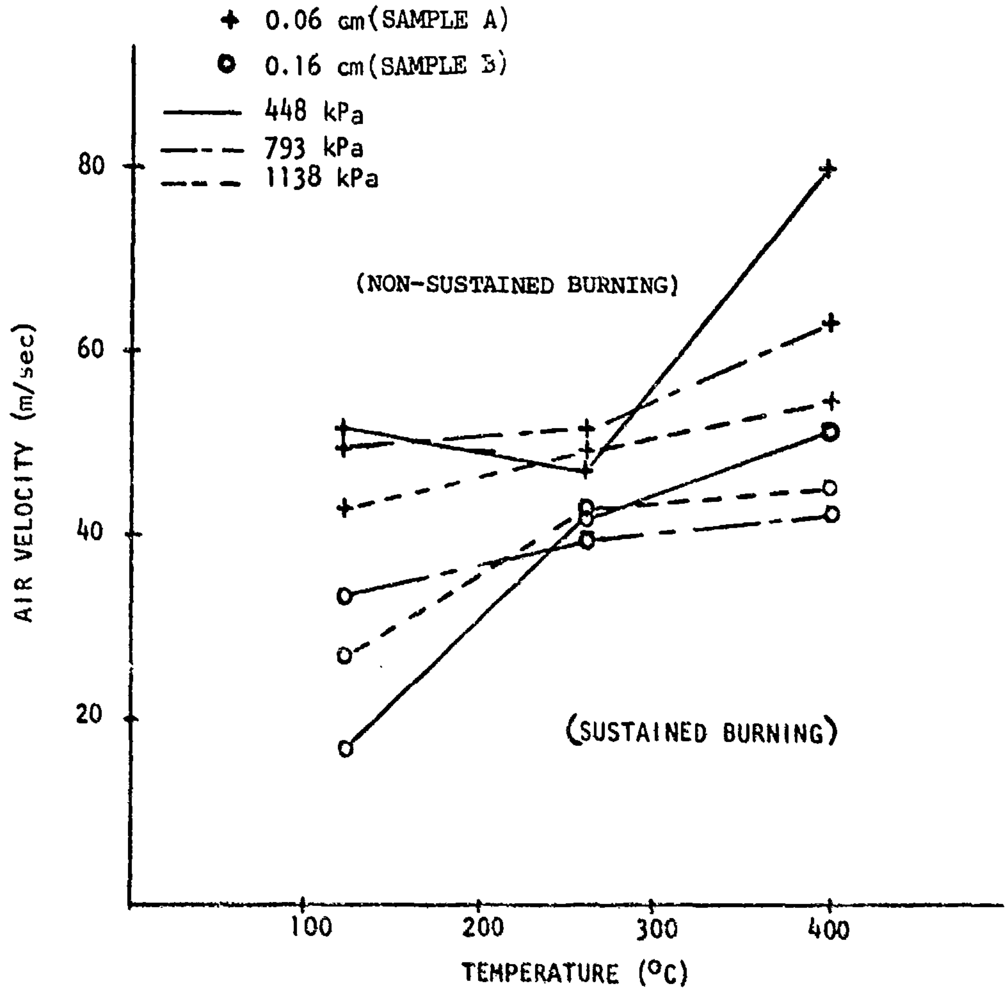


Figure 13. Sustained, Non-Sustained Burning Data for Samples A and B

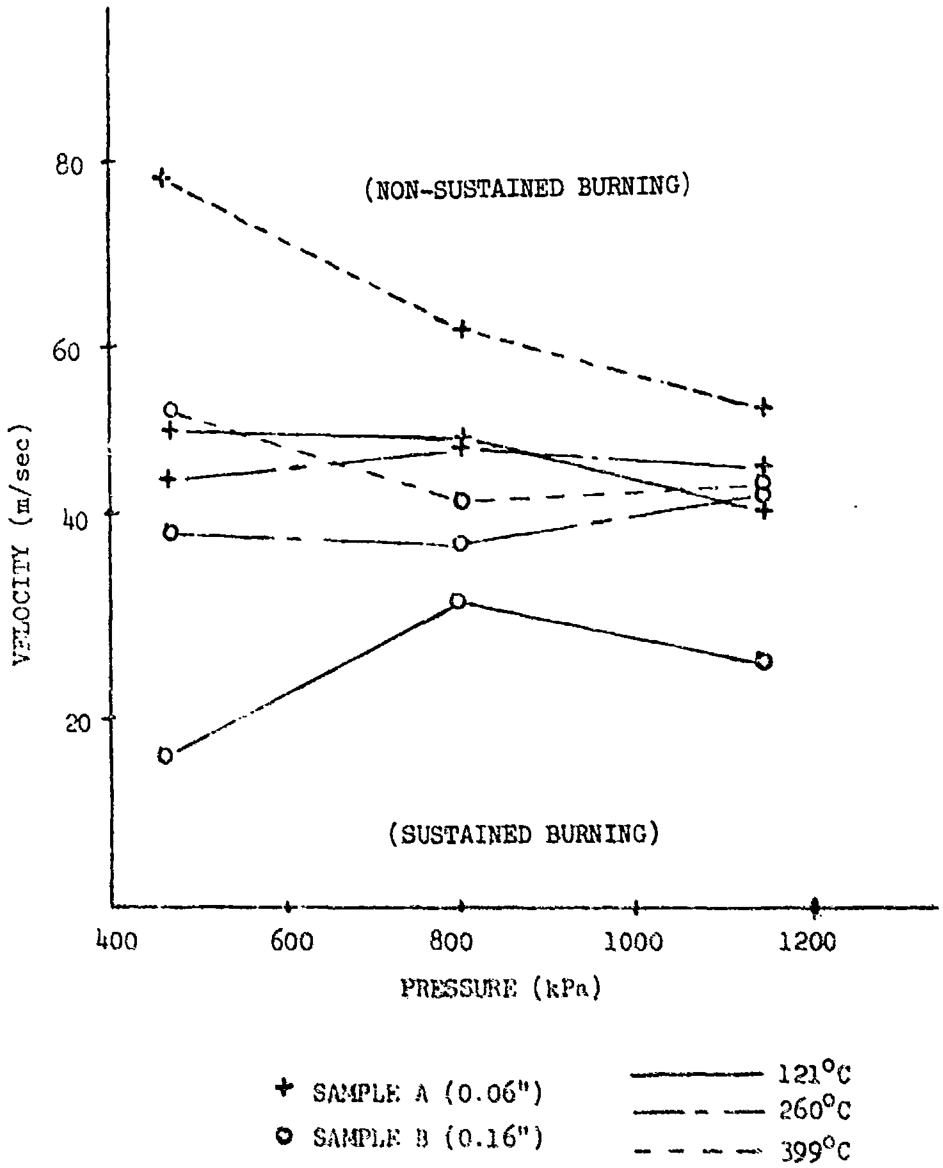


Figure 14. Sustained, Non-Sustained Burning Data for Samples A and B

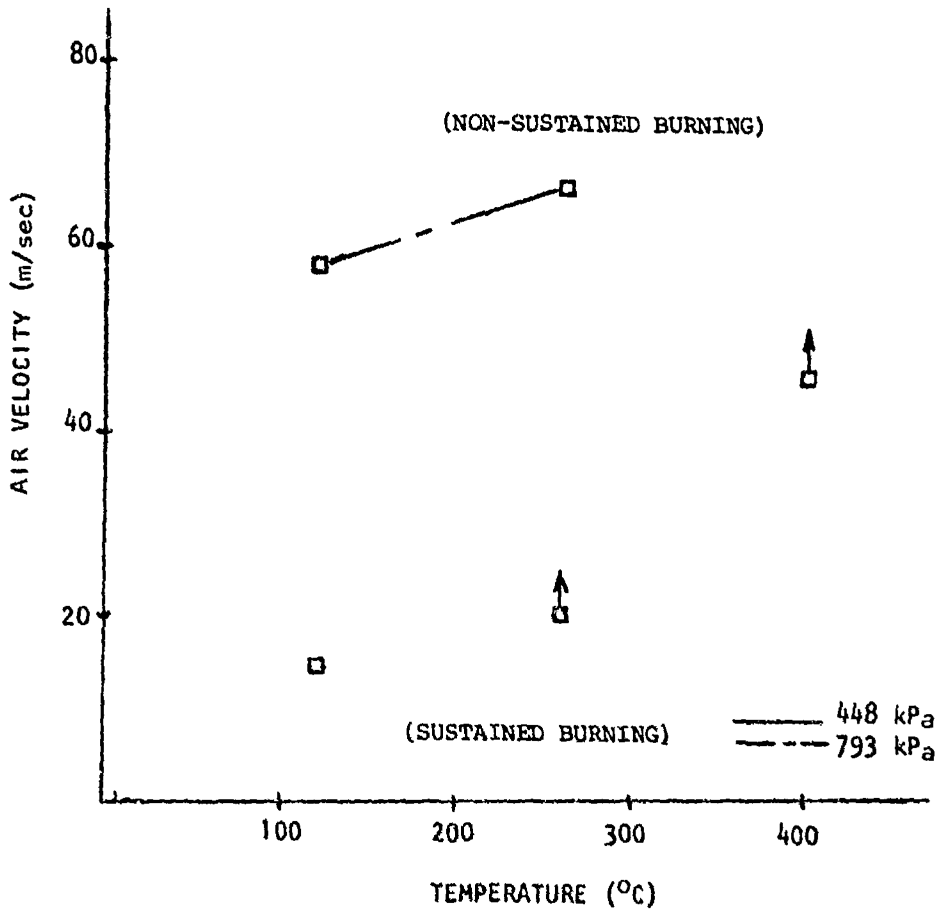


Figure 15. Sustained, Non-Sustained Burning Data for Sample C

also pressure. The pressure effect may be caused by a change in the air flow across the sample at higher pressures.

There are not sufficient data points with Sample D to establish any trends in the burning characteristics. The data on both types of blades indicate that the blades will burn generally in the same air flow conditions as the flat surface samples.

A few tests were conducted with a β structure titanium alloy (Sample E). The thickness of this sample was between that of Sample A and Sample B. It was not possible to achieve sustained burning with this sample at an air velocity that supported sustained combustion with Samples A and B. In addition, the burn rate of this sample at 260°C, 1138 kPa, and 20 m/sec air velocity is 10 cm/min, which is somewhat less than the burn rate measured for Samples A and B at the same air flow conditions. The burn rate of the other samples is discussed in the next section.

These limited test results indicate that the alloy and structure of titanium have a definite effect on the burning characteristics.

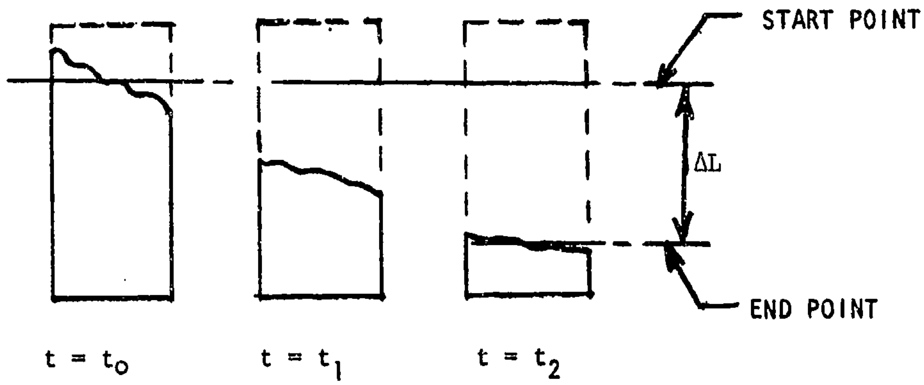
SECTION IV

BURN RATE ANALYSIS

A. ANALYSIS DESCRIPTION

The burning rate for samples which exhibited sustained burning is determined by analyzing the high speed motion pictures. Each test was photographed at 60 frames per second. Burning rate can be expressed in several ways, such as weight change or volume change. The speed of the burning edge as it burned down the sample is used for this analysis. Difficulties occur, however, with this approach because the sample often does not burn at a constant rate over the whole sample. What is described here is a determination of an average burn rate on the portion of the sample which did experience a fairly steady and even burn rate. The top edge near the igniter and the bottom edge near the sample holder were excluded. As illustrated in Figure 16, the burn rate is determined by measuring the time it takes the sample to burn between two points on the sample. The end points were varied somewhat from test to test to exclude variations such as an unusually slow initial burn rate or a burn pattern which developed an odd shape. If less than 2 cm length of sample burning could not be approximated by a straight line burn pattern, the burn rate was not determined for that specific test.

Analysis of the motion picture film reveals some general characteristics of the burning. If the sample ignites across the entire top edge, it generally burns from top to bottom. Sometimes the sample will burn faster down the front edge and then burn back toward the trailing edge. Other



$$\text{BURN RATE} = \frac{\Delta L}{t_2 - t_o}$$

Figure 16. Burn Rate Measurement Technique

tests result in the sample burning faster down the trailing edge and then forward into the sample.

B. RESULTS AND DISCUSSION

The burn rate data are tabulated in Tables 11 through 14. Although the burn rate varies considerably even at the same air flow conditions, it is possible to establish trends and the lack of trends from these data.

The temperature effect on the burn rate is too small to be determined. Not much effect is expected because the ambient temperature change is small compared to the temperature at the burning surface.

A definite trend due to pressure is apparent with Sample B and somewhat apparent with Sample A. The samples burn faster at higher pressure. The air is more dense at the higher pressure and thus more oxygen is available for combustion.

In general, Sample A burned faster than Sample B under the same test conditions.

The burn rate of the compressor blades (Samples C and D) does not show a trend due to pressure or temperature. Since the blades were not tested over the full temperature and pressure range, it is difficult to determine a trend. The blades appear to generally burn at a rate between the rates of Samples A and B. The blade thickness varies from the thin edges, which are approximated by Sample A, to the thick center, which is approximated by Sample B. The measured burn rate for the blades is an average rate over the complete blade, and thus would be expected to be within this range. In a few tests, a blade edge burned several times faster than the center portion.

TABLE 11

AVERAGE BURN RATE DATA SUMMARY, SAMPLE A

TEMPERATURE		PRESSURE		AIR VELOCITY		AVERAGE BURN RATE	
°C	°F	KPa	psia	m/sec	ft/sec	cm/min	inch/min
121	250	448	65	33	107	16	6.3
121	250	448	65	49	162	18	7.0
121	250	448	65	49	162	9	3.7
121	250	793	115	47	154	18	7.2
121	250	793	115	48	156	18	7.2
260	500	448	65	62	203	13	5.2
260	500	793	115	35	115	17	6.6
260	500	793	115	41	134	21	8.3
260	500	793	115	48	156	17	6.7
260	500	1138	165	33	107	20	7.8
260	500	1138	165	41	134	24	9.6
260	500	1138	165	49	161	17	6.6
399	750	448	65	52	170	15	5.9
399	750	448	65	26	85	21	8.2
399	750	448	65	78	256	16	6.3
399	750	793	115	29	96	19	7.5
399	750	793	115	59	194	18	7.2
399	750	793	115	45	147	14	5.3
399	750	1138	165	52	169	16	6.4

SAMPLE A (.06 CM thick)

TABLE 12

AVERAGE BURN RATE DATA SUMMARY, SAMPLE B

TEMPERATURE °C	TEMPERATURE °F	PRESSURE KPa	PRESSURE psia	AIR VELOCITY m/sec	AIR VELOCITY ft/sec	AVERAGE BURN RATE cm/min	AVERAGE BURN RATE inch/min
121	250	448	65	15	49	7	2.6
121	250	448	65	15	50	8	3.1
121	250	793	115	24	79	15	5.8
121	250	793	115	24	79	10	3.9
121	250	1138	165	24	79	11	4.2
121	250	1138	165	24	79	8	3.3
260	500	448	65	33	108	8	3.2
260	500	448	65	16	54	7	2.9
260	500	448	65	33	108	8	3.0
260	500	448	65	41	135	5	2.0
260	500	793	115	47	15[illegible]	11	4.4
260	500	793	115	24	78	12	4.7
260	500	793	115	24	77	10	4.0
260	500	793	115	35	115	12	4.7
260	500	1138	165	33	107	14	5.3
260	500	1138	165	41	133	13	5.2
399	750	448	65	31	100	9	3.5
399	750	448	65	41	135	9	3.6
399	750	448	65	52	169	8	3.2
399	750	793	115	36	117	12	4.7
399	750	793	115	41	134	12	4.9
399	750	1138	165	42	138	12	4.8
399	750	1138	165	45	149	15	6.0

SAMPLE B (0.16 CM thick)

TABLE 13

AVERAGE BURN RATE SUMMARY, SAMPLE C

TEMPERATURE		PRESSURE		AIR VELOCITY		AVERAGE BURN RATE	
°C	°F	kPa	psia	m/sec	ft/sec	cm/min	inch/min
121	250	448	65	12	40	16.5	6.5
121	250	793	115	17	57	12	4.6
121	250	786	114	35	114	11	4.4
121	250	779	113	[illegible]	114	13	5.0
121	250	772	112	53	174	15	6.0
260	500	469	68	20	65	13	5.0
260	500	793	115	35	115	14	5.4
260	500	786	114	47	154	20	7.9
260	500	779	113	59	195	12	4.7
260	500	772	112	72	235	7.6	3.0
399	750	779	113	45	147	13.5	5.3

SAMPLE C: (TF-39 6th Stage Blade)

TABLE 14

AVERAGE BURN RATE SUMMARY; SAMPLE D

TEMPERATURE		PRESSURE		AIR VELOCITY		AVERAGE BURN RATE	
°C	°F	kPa	psia	m/sec	ft/sec	cm/min	inch/min
149	300	531	77	27	90	10.4	4.1
149	300	531	77	10	68	11.7	4.6
260	500	517	75	50	164	11.4	4.5
260	500	517	75	50	164	10.2	4.1
260	500	524	76	26	87	15	6.0
260	500	786	114	47	153	9.1	3.6
371	700	855	124	44	146	13.5	5.3
371	700	86	125	44	144	10.2	4.0

SAMPLE D: (TF-30 6th Stage Blade)

SECTION V

FLAME SUPPRESSION TESTS

A. TEST DESCRIPTION

The titanium flame extinguishing tests were conducted to determine what concentration of argon gas is required to extinguish a titanium fire. Argon is believed to be inactive in the presence of the high temperature titanium flame and can thus be used to decrease the oxygen concentration to a level below that required to support combustion. The tests were conducted at air flow conditions of 260°C (500°F) and 1138 kPa (165 psia). The air velocity past the blade prior to argon injection was 24 m/sec (80 ft/sec). The temperature and density of the mixture changed the velocity in the test chamber after injection of the argon gas, but these changes were not sufficient to cause the flame to extinguish. The mixture velocity after argon injection dropped to 19 m/sec (61 ft/sec) for the worst case (100% argon).

Attempts to calibrate the concentration of argon by using a rotary vane flow meter did not prove successful because the meter output did not change sufficiently over the range of use in these tests and thus caused inaccurate data. With a sufficiently higher pressure in the argon manifold than in the test chamber, the flow is held constant by a critical orifice located after the solenoid operated injection valve. After a short transient upon opening the valve, the flow is controlled by the argon manifold pressure which also experiences a short transient (less than 0.1 sec) and then reaches a steady state.

The following procedure was used to calibrate the argon injection system. The test chamber was operated at the air flow conditions required for the flame extinguishment tests. Argon was injected at six different values of manifold pressure, and the argon-air mixture was sampled near the test sample at these six values. The values of pressure required were estimated from calculations of critical orifice flow. The range of argon concentration of interest was between 50% and 100%. The six gas mixture samples were analyzed for composition. The percent argon mixture can thus be determined from the argon manifold pressure. The calibration data are illustrated in Figure 17. The amount of argon injected is assumed to be linear with respect to the manifold pressure. The highest pressure data point does not fall in line with the other points. Most likely, an excess of the 100% argon is actually injected at this pressure and the excess is bled off through the pressure regulating bleed valve.

The argon-air mixture reaches a quasi steady-state temperature within a few seconds following injection of the argon. The argon cools after expansion through the critical orifice. The pipe between the injection point and the test chamber is, however, at the initial air flow temperature and contains a large mass which heats the argon air mixture. The temperature of the mixture did not change significantly after reaching the steady-state value.

B. RESULTS AND DISCUSSION

The test results are tabulated in Table 15. Four tests were conducted with Sample B, and the flame was extinguished in each test. Seven tests were conducted with the thinner sample (Sample A) with the argon concentration ranging from 45% to 100%.

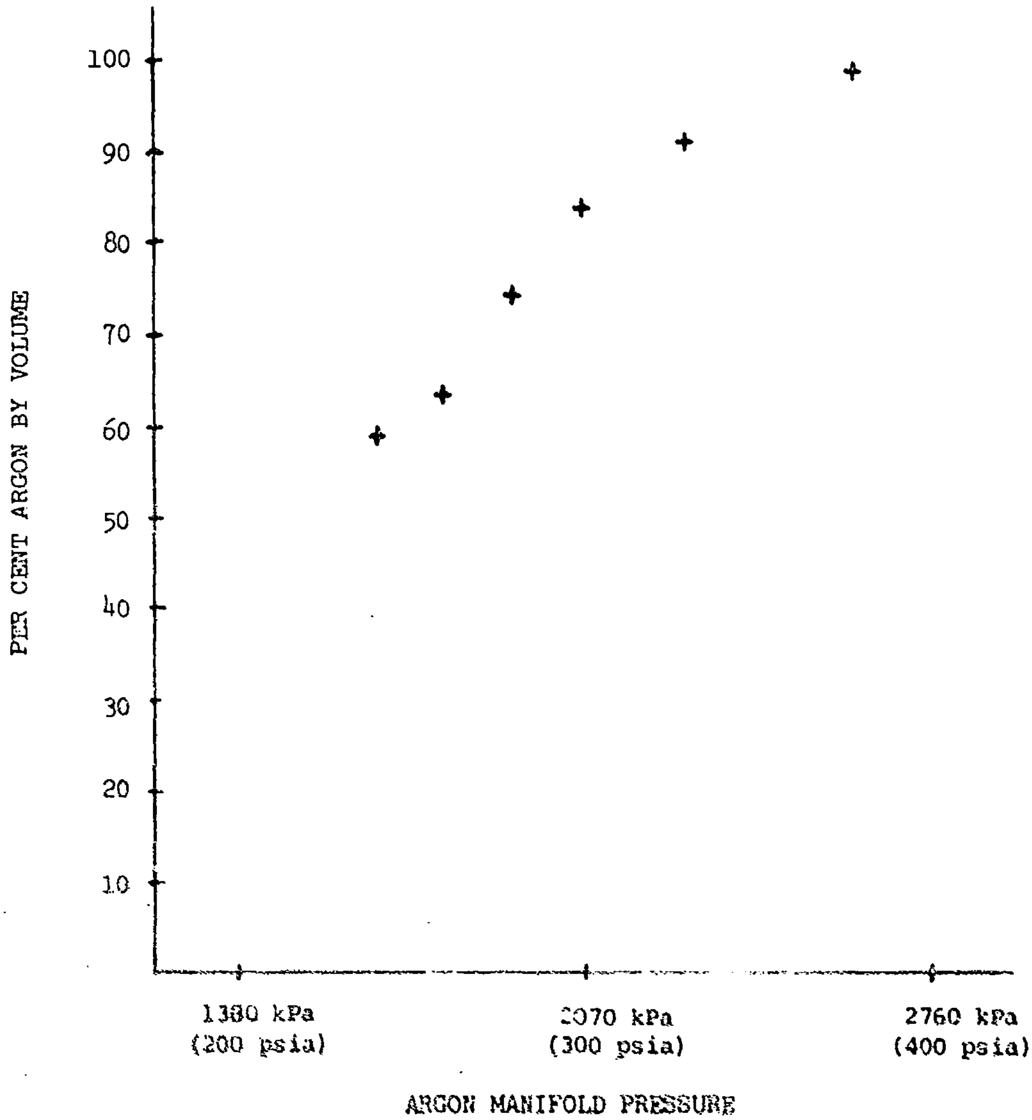


Figure 17. Argon Injection Calibration Curve

TABLE 15

ARGON GAS EXTINGUISHING DATA

TEST	SAMPLE	% ARGON	TIME TO EXTINGUISHMENT
8AZ01	B	90	< 0.1 sec
8AZ02	B	98	< 0.1 sec
8AZ04	B	100	< 0.1 sec
8AZ04	B	100	< 0.1 sec
8AV08	B	48	1.0 sec
8AV10	B	62	0.5 sec
8AV11	B	50	0.5 sec
8AZ05	A	100	< 0.1 sec
8AZ06	A	90	< 0.1 sec
8AZ07	A	73	0.15 sec
8AZ08	A	66	0.15 sec
8AZ09	A	55	7 sec (See text)
8AZ10	A	45	Continued to burn
8AZ12	A	100	< 0.1 sec

Pressure 113[illegible] kPa (165 psia)

Temperature 260°C (500°F)

Air Velocity 24m/sec (80 ft/sec) prior to argon injection

It is somewnat difficult to determine exactly when the flame is extinguished since the material remains hot for a period of time. The argon arrival time at the sample was calculated by assuming that the argon and air were completely mixed at the injection point and that steady state conditions were reached immediately after the valve opened. The flame was considered extinguished when all molten material stopped leaving the sample surface and activity on the surface slowed considerably. On the tests with high argon concentration, this effect took place within 0.1 second after the argon mixture reached the sample; however, the time to extinguishment listed in Table 15 can only be considered accurate to within 0.1 second due to the interpretive nature of the data analysis.

Concentrations of argon above 65% effectively extinguished the flame, although slightly longer times are required for the tests at 66% and 73% than for the tests with 90% and above. The test conducted at 55% concentration showed a different characteristic. A definite slowing of the combustion took place within 0.1 second after arrival of the argon; however, the sample continued to burn for another 8 seconds before surface activity stopped and the sample cooled. The test conducted with Sample A at 45% argon concentration showed the same initial decrease in burning activity; but in this test, the burning continued for considerable time and the sample almost completely burned.

Additional tests were conducted to determine what would happen if the argon concentration was decreased after initially extinguishing a burning sample but prior to the sample cooling. In these tests, the chamber air flow conditions were the same as shown in Table 15. The test sample (Sample A) was ignited and allowed to achieve a steady burn. The flame was then extinguished with 75% argon air mixture, which was maintained in the chamber for 3 seconds. The argon was then turned off and the chamber returned to the initial conditions within 1 second. At this point, the sample which was still hot re-ignited immediately and started to burn. When the argon concentration was maintained for a sufficient time to allow the sample to cool to a dull red glow, the sample did not reignite after removal of the argon. The time required for the sample to cool was as great as ten seconds for these tests.

These tests point out a definite design requirement on such a technique utilized for protection of a test facility. In a large scale test, a large amount of molten titanium and other materials would be present following a fire. Sufficient argon would need to be supplied until the ignition sources cooled (possibly a long time) or until the air flow changed to a condition that will not support combustion. Most likely a combination of both these techniques would be used to effectively protect a facility.

Several tests were conducted with CO_2 gas, which is a common fire extinguishing agent for hydrocarbon-type fires. The CO_2 gas was injected and calibrated with the same hardware that was described for the argon extinguishing tests. In these tests, the sample was ignited and achieved steady burning as previously described. The test data are shown in Table 16. In general, the burn rate increased considerably after the CO_2 was injected. The tests with 23% CO_2 show about a 50% increase in burn rate, while the tests with nearly 100% CO_2 show an increase in burn rate of about 300%.

TABLE 16

CO_2 EXTINGUISHING TEST DATA

TEST NR.	PRESSURE kPa	PRESSURE (psia)	AIR VELOCITY m/sec	AIR VELOCITY (ft/sec)	BURN RATE cm/min	BURN RATE (inch/min)	CO_2 CONCENTRATION
8BA01	1138	165	24	80	18	7	23%
8BA02	1138	165	24	80	18	7	23%
8BA03	448	65	62	203	NOT MEASURED		
8BA04	448	65	62	203	30	12	100%

SAMPLE: B (0.16 cm thick)

TEMPERATURE: 260°C (500°F)

SECTION VI

ULTRAVIOLET (UV) EMISSION ANALYSIS

A. TEST DESCRIPTION AND DISCUSSION OF RESULTS

A good method for detecting the occurrence of a titanium fire is to sense the ultraviolet (UV) radiation emitted from the burning titanium. Spectral emission data from metal fires are available and indicate that energy is emitted from 2000 Å and 3000 Å (Reference 1). This spectral region is of interest because solar blind ultraviolet detection systems that operate in this wavelength region are available (Reference 2). These systems are presently used for fire detection of hydrocarbon fuel-type fires.

The tests conducted were designed to determine if these developed detection systems are applicable to titanium fire detection. Actual spectral lines are not measured with the spectroradiometer equipment used in the tests. The test equipment set up is shown in Figure 18. The spectroradiometer was set at one of five wavelengths and the incident UV power on the detector measured as a function of time while a sample burned. The UV emission from a typical test is shown in Figure 19. The initial peaks are caused by the igniter burning. As illustrated, the output varies considerably with time due to the fluctuations in the burning. The measured spectroradiometer detector output current is averaged after the initial ignition and prior to the trailing off as the sample is consumed. This average value is then used to calculate the UV power at that specific wavelength, as shown in Table 17.

Although spectral peaks are not measured, the average power available in the solar blind UV spectral region can be used to approximate the

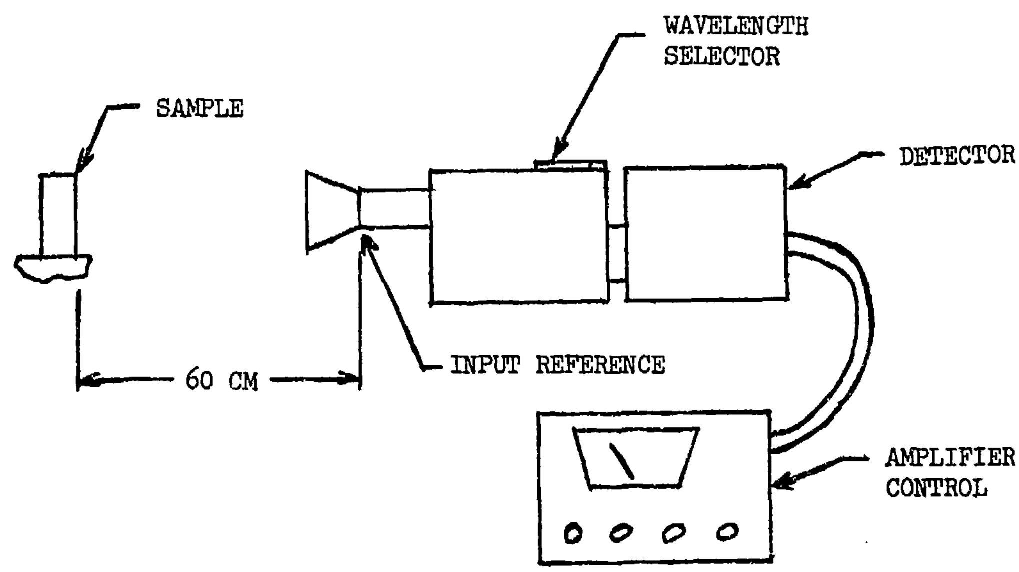


Figure 18. Ultraviolet Measurement Instrumentation

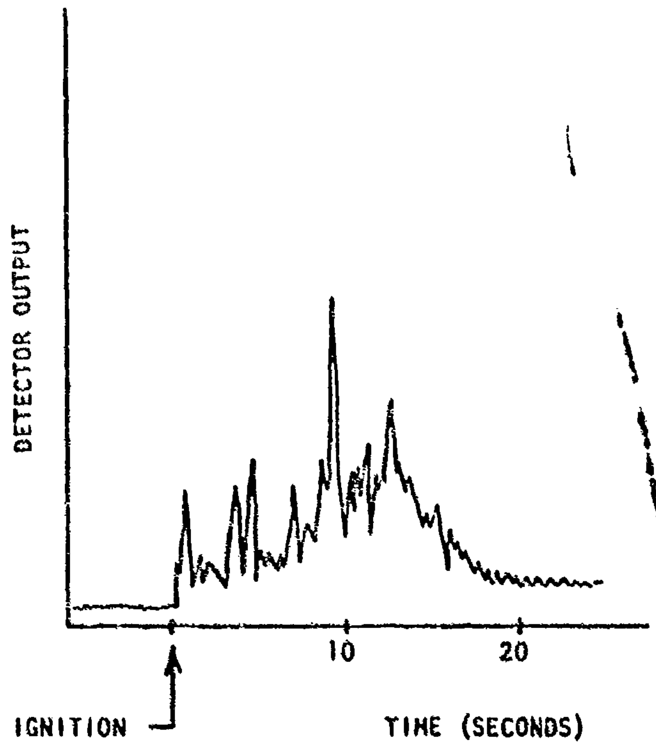


Figure 19. Typical Ultraviolet Emission Measurement

TABLE 17

ULTRAVIOLET EMISSION FROM TITANIUM FLAME

Test Nr	Wavelength (Angstroms)	Detector Signal (Ampere)	*Calculated Emitted Power (watts/sq cm-nm)	Typical Power Emitted from 5 Inch Diameter JP-4 Pan Fire at 140 cm (watts/sq cm-nm)
8AY08	2000	0.6×10^{-8}	4.2×10^{-8}	10×10^{-10}
8AY09	2250	0.8×10^{-8}	1.1×10^{-8}	2.2×10^{-10}
8AY13	2500	0.6×10^{-8}	5.0×10^{-9}	1.4×10^{-10}
8AY11	2750	0.8×10^{-8}	4.5×10^{-9}	1.1×10^{-10}
8AY12	3000	1.0×10	5.5×10^{-9}	1.3×10^{-10}

Air Temperature	$260^{\circ}C$	$(500^{\circ}F)$
Air Pressure	793 kPa	(115 psia)
Air Flow Velocity	23.3 m/s	(76.4 feet/sec)

* Detector surface located 60 cm from flame
(See text for discussion of results)

sensitivity of a UV detector to a titanium flame. This calculation requires knowing the spectral response of the detector, the spectral output of the source, and the distance between the source and detector. The UV emission from the 2.5 x 7.6 cm titanium sample is compared to the UV emission from a 5 inch diameter pan fire of JP-4 fuel in Table 17. A typical hydrocarbon flame UV detector can detect the pan fire at a distance of 10 feet. This comparison shows that existing UV detectors can be adapted to detect titanium fires, since they have adequate sensitivity. The detector is, however, limited to a line of sight operation. The UV detector cannot distinguish between sparking, which might occur as a result of rubbing, and an actual flame because both generally have the same spectral output, however the signal level might be used to discriminate between sparking and a titanium fire.

An engine test facility can be protected by the installation of detectors at key locations where a titanium fire might occur.

Further analysis with equipment capable of measuring emission over the UV spectrum and capable of resolving the narrow spectral lines would be required to determine if selective wavelength-detectors can be used to distinguish a titanium flame from a hydrocarbon type flame. The extinguishing technique for the two types of flames may be different and thus discrimination between the two flames may be required.

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