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STUDY OF THE CHEMICAL INTEGRITY OF RADIOISOTOPE CONTAINMENT MATERIALS IN LAUNCH ABORT ENVIRONMENTS

(Summary Technical Report)
Phase II

Prepared by
J. L. Blumenthal
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TRW Systems

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(Summary Technical Report)
Phase II

Prepared by
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Redondo Beach, California
for
Sandia Corporation
under
Contract 48-2534

April 1966

ABSTRACT

This report describes the experimental investigation of the chemical integrity of radioisotope containment materials in launch-abort environments. The materials include cobalt-based "superalloys," nickel-based "superalloys," stainless steels, and coated and uncoated refractory metals.

Prepared for
Sandia Corporation
Under Contract No. 48-2534

Prepared J L Blumenthal

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SUMMARY

This report is the Summary Technical Report describing the work performed by TRW Systems for the Sandia Corporation under Phase II of Contract 48-2534. The investigation was initiated in order to answer critical questions concerning the chemical behavior of radioisotope containment materials when exposed to a launch pad abort fire environment.

The first phase of the program which was described in a previous report (Reference 1) envolved a detailed search and analysis of the available data from the literature to establish in as quantitative a fashion as possible what is known about the high temperature chemical interaction of radioisotope containment materials with launch pad abort combustion gas species.

In the second phase of the program, which is the subject of the present report, high temperature experimental screening tests on a number of combinations of containment materials and launch abort environments were conducted. The specific combinations of materials and environments which were chosen for the screening studies were those for which there was either no information or insufficient information in the literature to establish their chemical reactivity. Both quantitative reaction kinetics experiments and qualitative observations of the behavior of materials in selected flame environments were conducted. The specific combinations of materials and environments which were investigated were the following:

Static Reaction Kinetics Experiments — $T > 2000^{\circ}F$

- Haynes 25 — O_2
- Hastelloy C — O_2
- Hastelloy X — O_2
- 316 Stainless Steel — O_2
- Haynes 25 — Nitric Oxide

- Flame Experiments—H_2-O_2 Flame System
  - Haynes 25
  - Hastelloy C
  - Hastelloy X
  - 316 Stainless Steel
  - 304 Stainless Steel
  - Tungsten
  - Tantalum - 10% Tungsten
  - Pfaudler Silicide Coated Tungsten
- Flame Experiments—CO-O_2 Flame System
  - Haynes 25
  - Tantalum - 10% Tungsten
  - Pfaudler Silicide Coated Tungsten

The objective of this phase of the program was to determine, as a function of temperature and time, the extent of chemical reaction which would occur with the above-mentioned combinations of materials and environments.

Based on the experimental results of this program, the following conclusions regarding the behavior of containment materials in launch abort environments are presented:

1) In pure oxygen at temperatures up to 2200°F, 316 Stainless Steel, Haynes 25, Hastelloy C, and Hastelloy X, all oxidize at a rate which is too slow to be of concern from a safety point view.* At temperatures from 2200°F up to the melting range of the alloys (2400° to 2600°F), however, the oxidation rate was sufficiently rapid that a significant fraction of a sample of any of the above alloys was oxidized in a period of 1 or 2 hours.

2) The reaction of Haynes 25 with pure nitric oxide was somewhat slower than the reaction of this alloy with pure oxygen under identical conditions of temperature and pressure. Hence, it would seem likely that flame environments containing high concentrations of nitric oxide would be no more reactive with Haynes 25 than flame environments which contain high concentrations of oxygen.

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*A reaction was considered to be "of Concern from a Safety Point of View" if a significant fraction of a sample was oxidized in a period of minutes.

3) Well designed radioisotope capsules fabricated from 304 Stainless Steel, 316 Stainless Steel, Haynes 25, Hastelloy C, or Hastelloy X should be able to withstand (chemically) short term (period of minutes) exposure to abort flame environments containing oxygen, nitrogen, hydrogen, water, carbon monoxide, and carbon dioxide at capsule temperatures up to about 2300°F.

4) In flame environments containing high concentrations of water vapor and/or oxygen, capsules fabricated from 304 or 316 Stainless Steel are likely to ignite and react rapidly and exothermically with the flame environment if the surface temperature of the capsules reaches the melting range of the alloys (~2400 to 2600°F).

5) In flame environments containing high concentrations of both water vapor and oxygen, the uncoated refractory metals tungsten and tantalum - 10% tungsten react exceedingly rapidly. Ignition temperatures for these two refractory metals in oxygen-rich hydrogen-oxygen flames was of the order of 2200°F. Indeed, reaction rates in this type of flame environment were much faster than would be expected from the literature data for the static reactions of these metals with oxygen and water. Based on the experimental flame tests, it would seem unlikely that uncoated tantalum or tungsten-based refractory capsules (at temperatures in excess of 2200°F) could withstand an abort flame environment containing high concentrations of both water and oxygen for periods of time in excess of a few seconds.

6) In flame environments containing high concentrations of water, carbon dioxide, and carbon monoxide, but no appreciable oxygen; the oxidation of uncoated tantalum and tungsten-based alloys was considerably slower than in the oxygen-rich flames. However, the reaction between the uncoated refractory alloys and this flame environment was still sufficiently rapid to indicate that extensive oxidation of refractory capsules would take place when they were exposed to this type of abort flame for periods of minutes at temperatures in excess of 2000°F.

7) The Pfaudler silicide coating can provide short term (period of minutes) oxidation protection to tungsten capsules exposed to flame environments containing water, oxygen, hydrogen, carbon monoxide and carbon dioxide provided the capsule surface temperature does not exceed about 2900°F. It must be kept in mind, however, that if even a small portion of the thin silicide coating is abraded or scraped off of the capsule during an abort, then the coating system will no longer be effective in protecting the tungsten substrate.

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1. INTRODUCTION

This report is the summary technical report covering the work performed by TRW Systems for the Sandia Corporation under Phase II of Contract 48-2534. The primary objective of this study is to determine the chemical integrity of radioisotope containment materials when subjected to a booster vehicle abort environment.

The increasing usage of radioisotopes in aerospace applications has produced a need for an understanding of the behavior of radioisotope containment materials in launch pad abort environments. In particular, it is essential, for reasons of safety, that materials which are used to contain radioisotopes be compatible with launch pad abort fire environments. That is to say, radioisotope containment materials must maintain their chemical integrity when exposed to high temperature abort fire conditions. The recent work at Sandia Corporation on characterizing launch pad abort fire environments has indicated that the most probable event involves an initial fireball at temperatures ranging from 5500°* to 3000°F followed by a sustained fire at temperatures of 2500° to 1800°F. The initial fireball may exist for a period of seconds and the sustained fire may persist for as long as an hour. Depending on the type of rocket system which aborts, any or all of the following chemical species may be present in high concentrations in the abort environment: O_2, N_2, H_2, CO, CO_2, H_2O, NO, F_2, and HF. Thus, radioisotope containment materials should be compatible with the above combustion species for a period of a few seconds at 3000° to 5500°F and for a period of up to an hour at 1800° to 2500°F.

The first phase of the program, which was presented in a previous report (Reference 1) involved a scoping study in which a detailed investigation of the available information on the high temperature chemical interaction of radioisotope containment materials and abort environments (or combustion gas species) was conducted. The materials which were considered included both presently used containment materials and materials

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*Flame environments caused by hydrogen-fluorine combustion can be at somewhat higher temperatures.

which are being evaluated for possible future use as radioisotope containment materials. These materials include cobalt-based "superalloys," nickel-based "superalloys," stainless steels, coated and uncoated refractory metals, and noble metal claddings. The objective of Phase I of the program was to determine as much as possible from the available literature about which combinations of containment materials and launch abort environments are likely to react rapidly with each other, and hence, will be of concern from a safety point of view.

The second phase of the program, which is the subject of the present report, involved high temperature experimental screening tests on a number of combinations of containment materials and launch abort environments. The specific combinations of materials and environments which were chosen for the screening studies were those for which there was either no information or insufficient information in the literature to establish their chemical reactivity. Both quantitative reaction kinetics experiments and qualitative observations of the behavior of materials in selected flame environments were conducted. The specific combinations of materials and environments which were investigated were the following:

- Static Reaction Kinetics Experiments — $T > 2000^{o}F$
  - Haynes 25 — O_2
  - Hastelloy C — O_2
  - Hastelloy X — O_2
  - 316 Stainless Steel — O_2
  - Haynes 25 — NO
- Flame Experiments — H_2-O_2 Torch
  - Haynes 25
  - Hastelloy C
  - Hastelloy X
  - 316 Stainless Steel
  - 304 Stainless Steel
  - Tungsten
  - Tantalum - 10% Tungsten
  - Pfaudler Silicide Coated Tungsten

- Flame Experiments—$CO-O_2$ Torch
  - Haynes 25
  - Tantalum - 10% Tungsten
  - Pfaudler Silicide Coated Tungsten

The objective of this phase of the program was to determine, as a function of temperature and time, the extent of chemical reaction which would occur with the above-mentioned combinations of materials and environments.

This report is divided into five main sections and one Appendix:

- The introduction comprises the first section.
- In the second section is presented a description of the experimental facilities and techniques which were utilized in the program.
- The third section summarizes the major experimental results of the screening investigation.
- The fourth section presents the conclusions of the study.
- The fifth section introduces suggestions for additional work.
- In the appendix are presented a tabular summary of all the temperature-time data generated in the flame studies.

2. EXPERIMENTAL FACILITIES AND TECHNIQUES

2.1 REACTION KINETICS STUDIES

A static, constant volume, reaction kinetics apparatus (Reference 2) was used to investigate the reactions of containment materials with pure combustion gas species such as oxygen or nitric oxide. Figure 1 shows a schematic diagram of the system and Figure 2 shows a photograph of the experimental apparatus. In this apparatus, the combustion species (which comprised the gas phase) reacted with the solid containment material to form a solid phase product, so that, as reaction proceeded, the gas pressure continually dropped. Thus, the rate of reaction was measured by monitoring the pressure drop in the calibrated, constant volume system as a function of time. The total sample weight gain from the beginning to the end of an experiment, in general, compared very favorably with the weight gain calculated from the measured pressure drop in the constant volume system. An Astro high-temperature furnace and temperature control system was utilized to maintain the samples at a constant temperature throughout an experiment. A Texas Instrument ultra-sensitive Bourden Gage was used to monitor the system pressure in the range from 1 mm Hg to 760 mm Hg. This gage had a sensitivity of 0.01 mm Hg over the range from 1 to 1000 mm Hg.

Samples of Haynes 25, 316 stainless steel, Hastelloy-C and Hastelloy-X were tested with pure oxygen. The reaction of Haynes 25 with pure nitric oxide was also investigated. Table 1 gives the compositions of the alloys which were studied. All of the test samples were in the form of cylinders (3/16 inch diameter and 1/2 inch long) in the "as-worked" condition.

Table 1. Composition of the Alloys Investigated in the Static Reaction Kinetics System

	Composition (percent by weight)							
Alloy	Fe	Ni	Co	W	C	Mn	Cr	Mo
316 Stainless Steel	68.4	11.0	--	--	0.10	--	18.0	2.5
Haynes 25	1.5	10.2	51.6	14.9	0.10	1.4	20.1	--
Hastelloy C	5.9	56.8	1.0	3.3	0.05	0.5	15.4	15.9
Hastelloy X	17.8	48.5	1.1	0.6	0.10	0.6	21.4	9.0

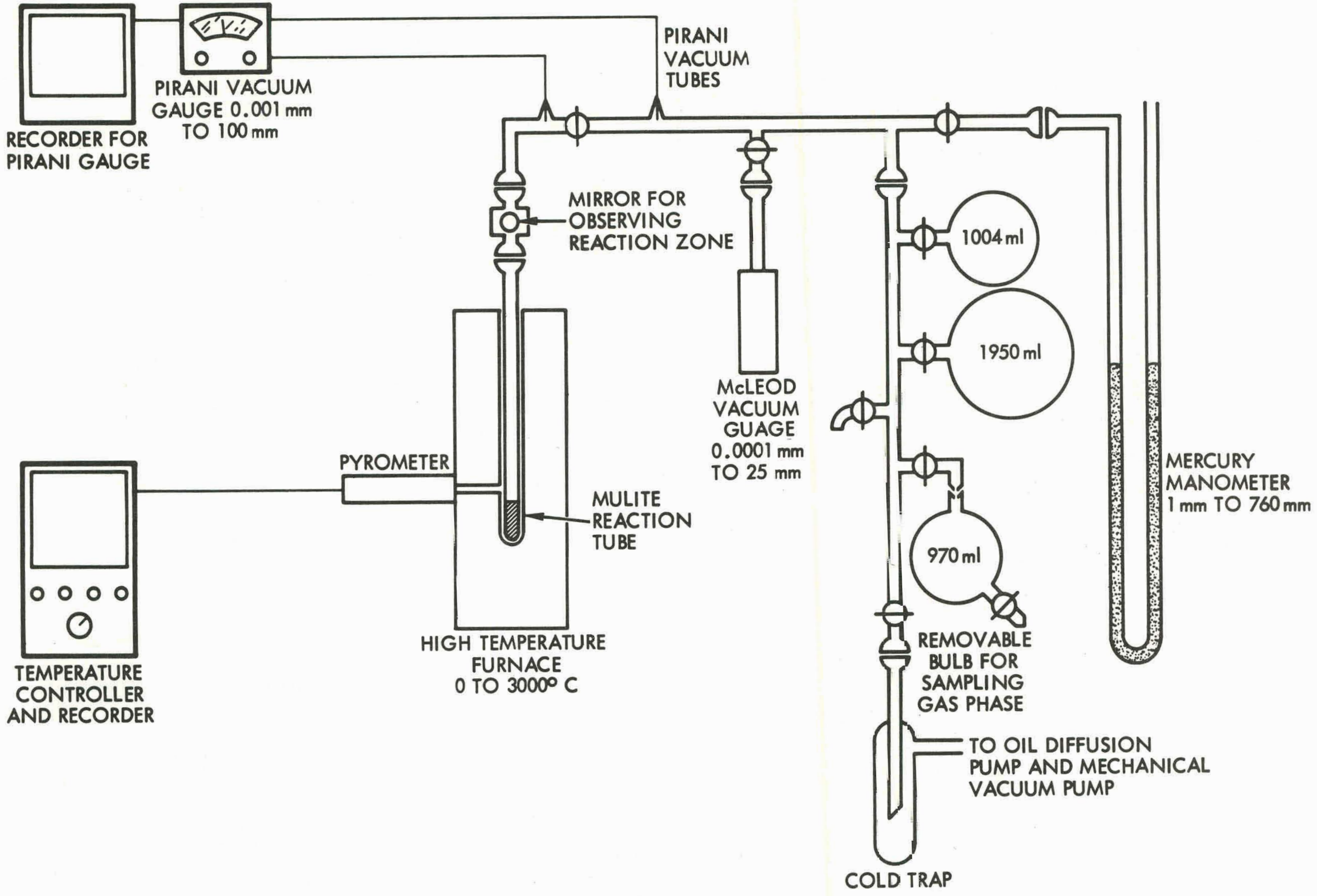

Figure 1. Schematic Diagram of the Static Reaction Kinetics System

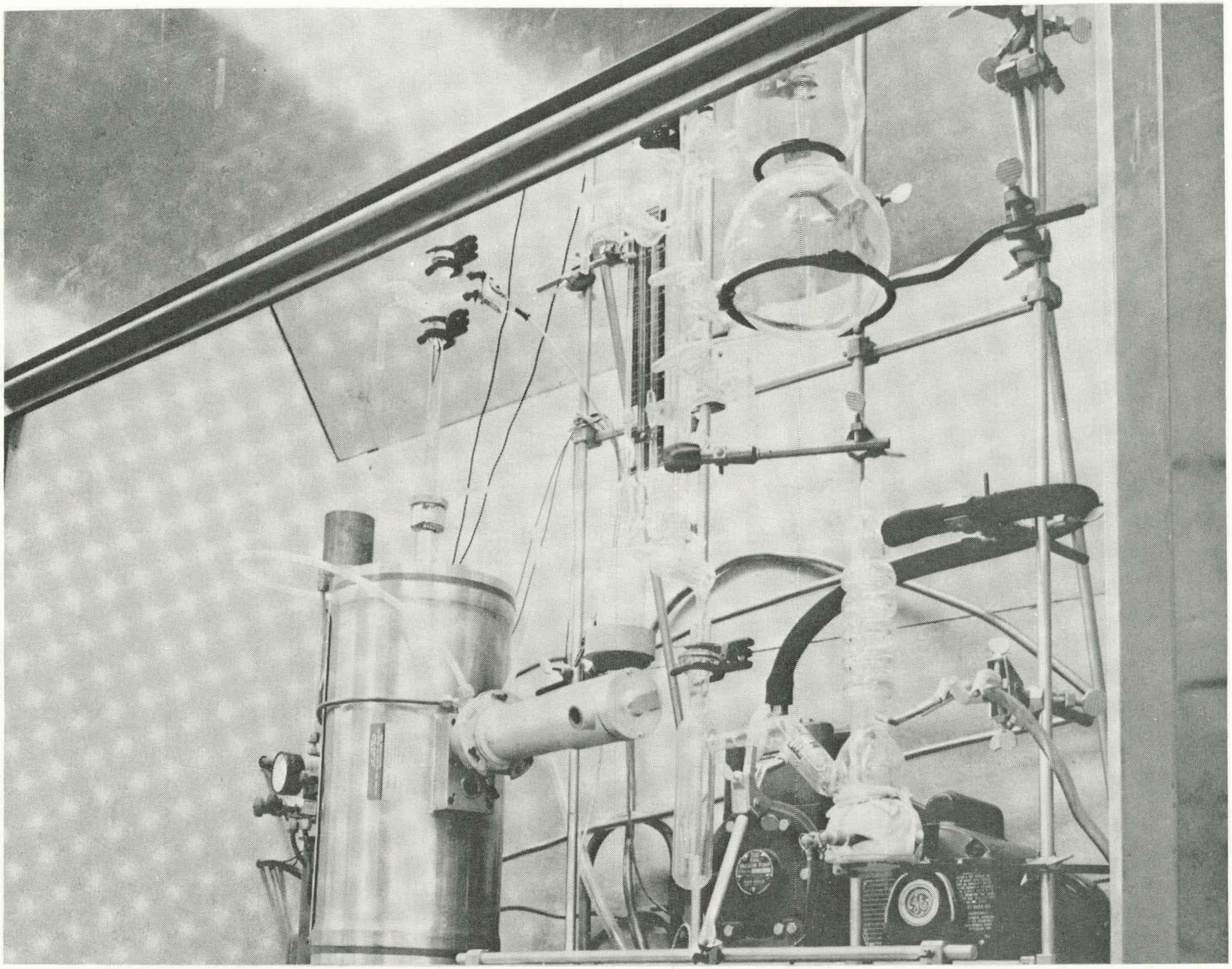

Figure 2. Static Reaction Kinetics System

All of the reaction kinetics data are reported on the basis of reaction per unit area of sample surface. The sample surface was taken as the initial geometric surface area which was exposed to the reacting atmosphere.

Prior to each experiment the samples were out-gassed for four hours at 500°C (932°F) under a vacuum of 0.1 micron. This treatment was sufficient to remove from the sample any adsorbed gases which might interfere with the pressure drop measurements during an experiment.

Experiments were conducted in the temperature range from 1100° to 1300°C (2000° to 2380°F) and at pressures ranging from 25 mm Hg to 760 mm Hg.

2.2 EXPERIMENTAL FLAME STUDIES

An experimental flame system (Reference 2) was utilized to investigate, by photographic and pyrometric techniques, the behavior of nuclear containment materials exposed to flame environments. This system, which is shown schematically in Figure 3 and photographically in Figure 4, was used in conjunction with a generalized thermochemical computer program to produce high temperature flame environments which were fully determined thermochemically and contained high concentrations of the most reactive combustion species. The system consisted of a sealed 36-ft^3 chamber for complete containment of all reaction products, and a controllable torch apparatus for producing the desired flame environment. All operations were controlled from outside the sealed chamber. The samples were mounted on a transite plate in such a way that half of the sample was embedded in a 1/4 inch deep hole in the transite and half of the sample protruded above the transite plate. The portion of the sample above the plate was completely enveloped by the flame during the experiment. In each experiment the flow rate of oxidizer and fuel was carefully metered so that the equilibrium flame temperature and chemical composition could be calculated. Studies were conducted with two different oxidizer-fuel combinations; oxygen-hydrogen, and oxygen-carbon monoxide.

Experiments were run at a variety of different initial heat fluxes, and hence, at a number of different steady state sample temperatures. The initial heat flux to the sample in each experiment was determined by a calibration experiment utilizing a copper calorimeter having the same

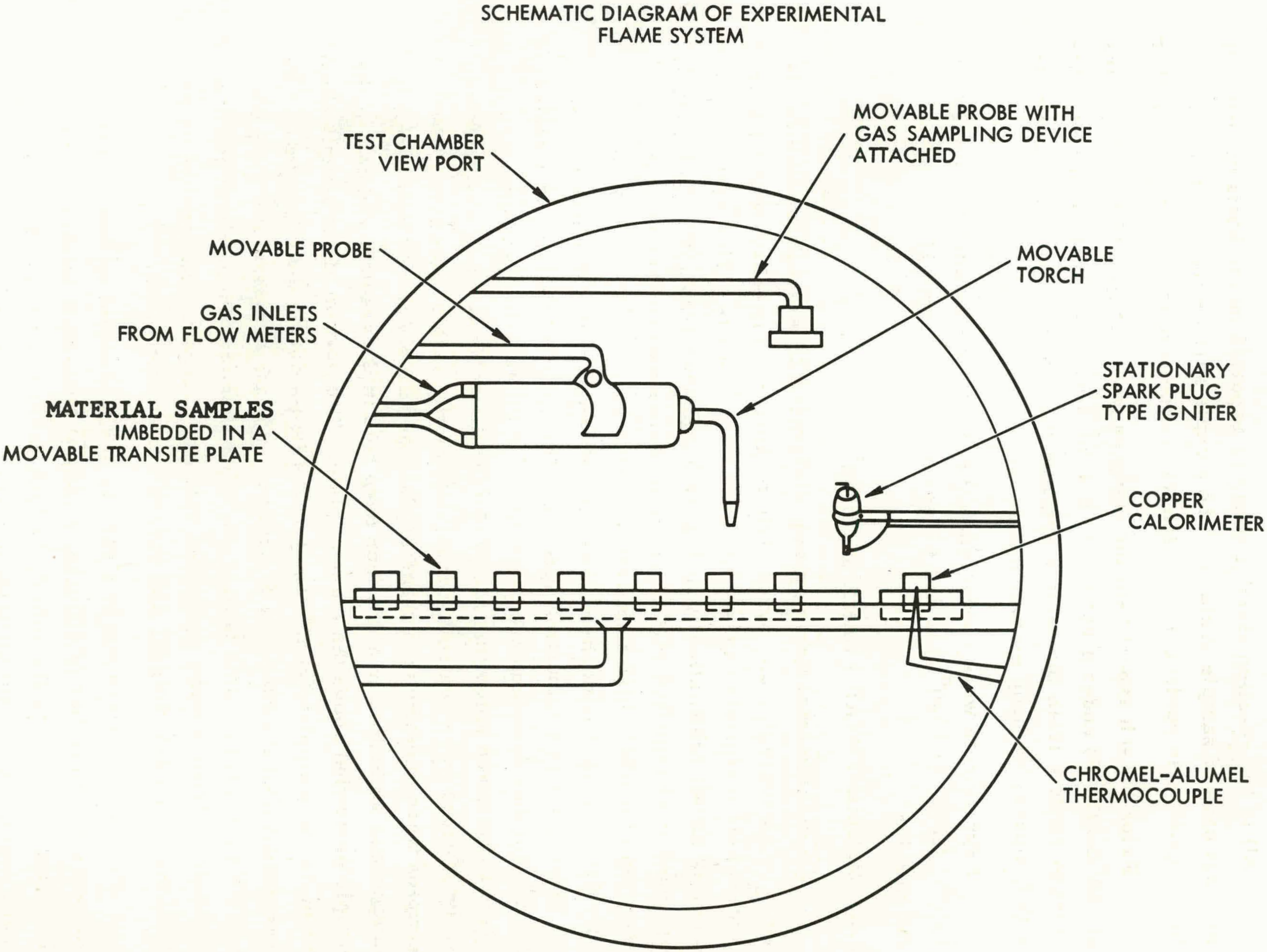

Figure 3. Schematic Diagram of the Experimental Flame System

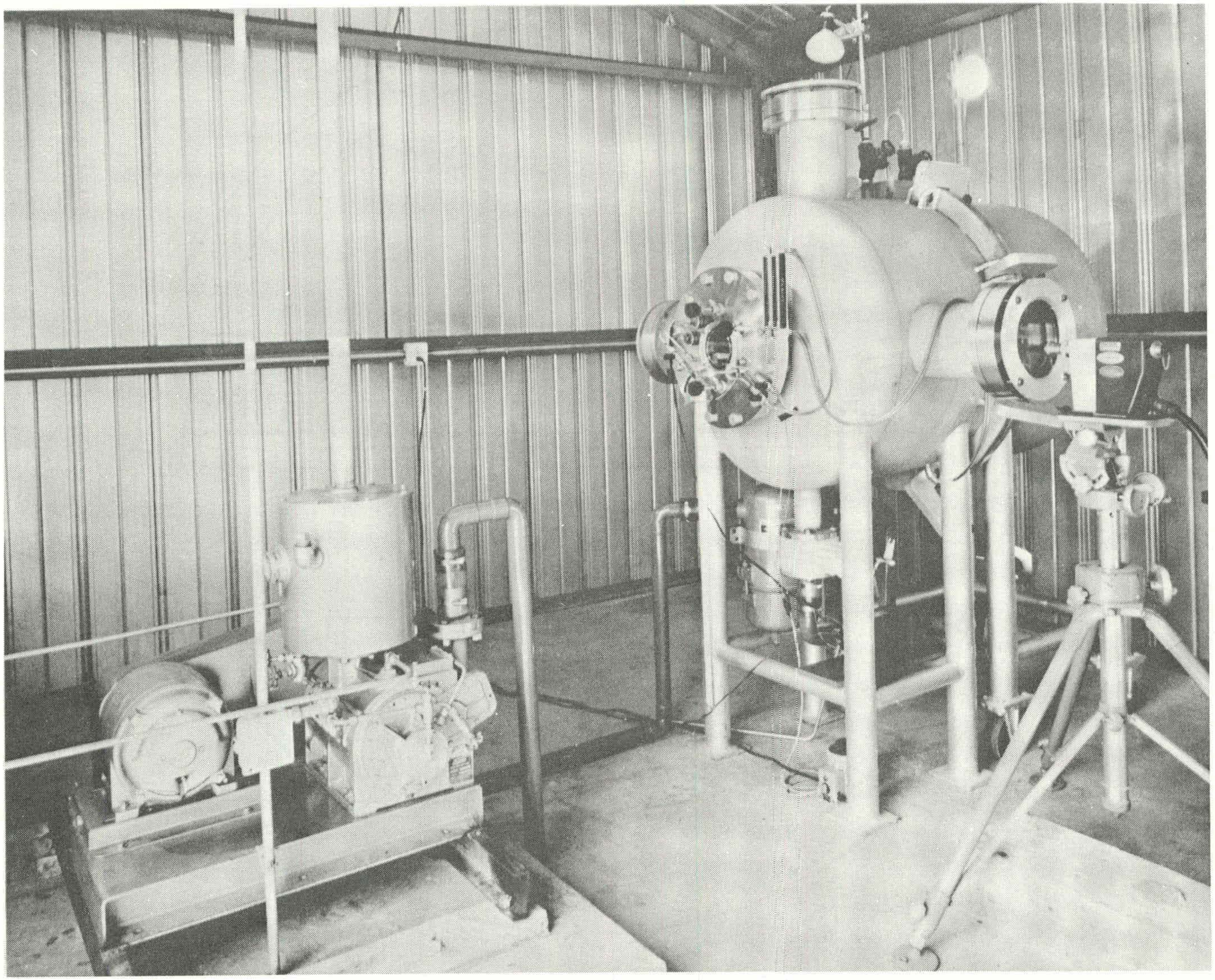

Figure 4. Experimental Flame Facility

shape, size, and physical orientation as the sample. It was found that for a nonreacting sample, the temperature-time curve could be computed fairly accurately from the initial heat flux data utilizing the equation:

$$m\bar{C}_p \frac{dT_s}{dt} = hA\,(T_f - T_s) - \epsilon\sigma A T_s^4 \qquad (1)$$

where

m = mass of sample
$\bar{C}_p$ = average sample heat capacity
σ = Stefan-Boltzmann constant
T_s = sample temperature, ^oR
T_f = flame temperature, ^oR
t = time, seconds
ϵ = total emissivity of oxidized sample
h = heat transfer coefficient calculated from the initial heat flux data
= q initial/$(T_f - 560^oR)$
q initial = initial heat flux at 560^oR
A = sample surface area

Thus, the actual temperature-time data as measured with a recording two-color pyrometer could be compared with the calculated temperature-time curve which assumes no heat generation due to reaction. Differences between the measured and calculated curves gave a qualitative measure of the heat generation due to reaction (and hence, rate of reaction).

Both a recording two-color pyrometer and a micro-optical pyrometer were used to measure the temperature of the surface of the samples. The two-color pyrometer tended to measure the temperature of the hottest spot on the sample, and hence gave an indication of the temperature of those portions of the surface which were reacting most rapidly. The micro-optical pyrometer could be sighted in on a very small portion of the sample surface, and hence was useful in determining temperature gradients between hot reaction zones and cooler parts of the sample surface.

Sixteen millimeter, color motion pictures of the behavior of the samples in the flame environments were taken during several experiments. Pictures were taken at sixty-four frames per second, which was found to be a good speed for photographing the relatively long duration experiments.

Samples of 304 stainless steel, 316 stainless steel, Haynes 25, Hastelloy C, Hastelloy X, tungsten, tantalum - 10% tungsten and Pfaudler silicide coated tungsten were all investigated in the H_2-O_2 flame system. Experiments were conducted in both fuel-rich flames in which water vapor was the only reactive specie, and in oxygen-rich flames in which both water and oxygen were present in appreciable concentrations. The test specimens consisted of cylinders (3/16 inch diameter, 1/2 inch long) and coupons (1 by 1/4 by 0.030 inch). The stainless steels and superalloys were tested as cylinders, while the refractory metals were investigated in the form of coupons.

Samples of Haynes 25, tantalum - 10% tungsten and Pfaudler silicide coated tungsten were tested in the CO-O_2 flame system. Experiments were conducted in both fuel-rich and oxygen-rich flames.

3. DISCUSSION OF THE EXPERIMENTAL RESULTS

The major experimental results of the program are summarized and discussed in this section. A complete tabular presentation of all of the temperature-time data for the flame studies are presented in an appendix.

3.1 REACTION KINETICS STUDIES

3.1.1 The 316 Stainless Steel-Oxygen System

The reactions of 316 stainless steel with pure oxygen were studied at temperatures of 1100°, 1200°, and 1300°C and at pressures near atmospheric. Figure 5 shows a plot of the milligrams of oxygen reacted as a function of time for measurements at the three experimental temperatures. Nonprotective oxidation appeared to take place at temperatures of 1100°C and above. The rate of reaction increased rapidly with increasing temperature. As the temperature was raised from 1100° to 1300°C the average reaction rate increased by a factor of twelve. Although the reaction was essentially nonprotective at temperatures of 1100°C and above in the sense that the reaction rate did not decrease with time, the actual rates of reaction were slow within the context of our criteria (massive corrosion in a period of minutes) until temperatures in excess of 1200°C were reached.

3.1.2 The Hastelloy C-Oxygen System

Figure 6 shows the reactions of Hastelloy C with oxygen as a function of time. The data is plotted for experiments at 1100°, 1200°, and 1300°C. At 1100°C the reaction appears to be slow and protective. At 1200°C, however, a "breakaway" takes place and the rate of oxidation is twenty times faster than at 1100°C.

3.1.3 The Hastelloy X-Oxygen System

The oxidation of Hastelloy X in pure oxygen was investigated at 1100°, 1193°, and 1325°C in the pressure range from 715 to 581 mm Hg. Figure 7 presents the experimental data in terms of oxygen reacted as a function of time. As can be seen from Figure 7, the oxidation of Hastelloy X at 1100° and 1193°C was extremely slow. Indeed, the reaction does not become rapid enough to be of interest in this program until a temperature of 1300°C or greater is reached.

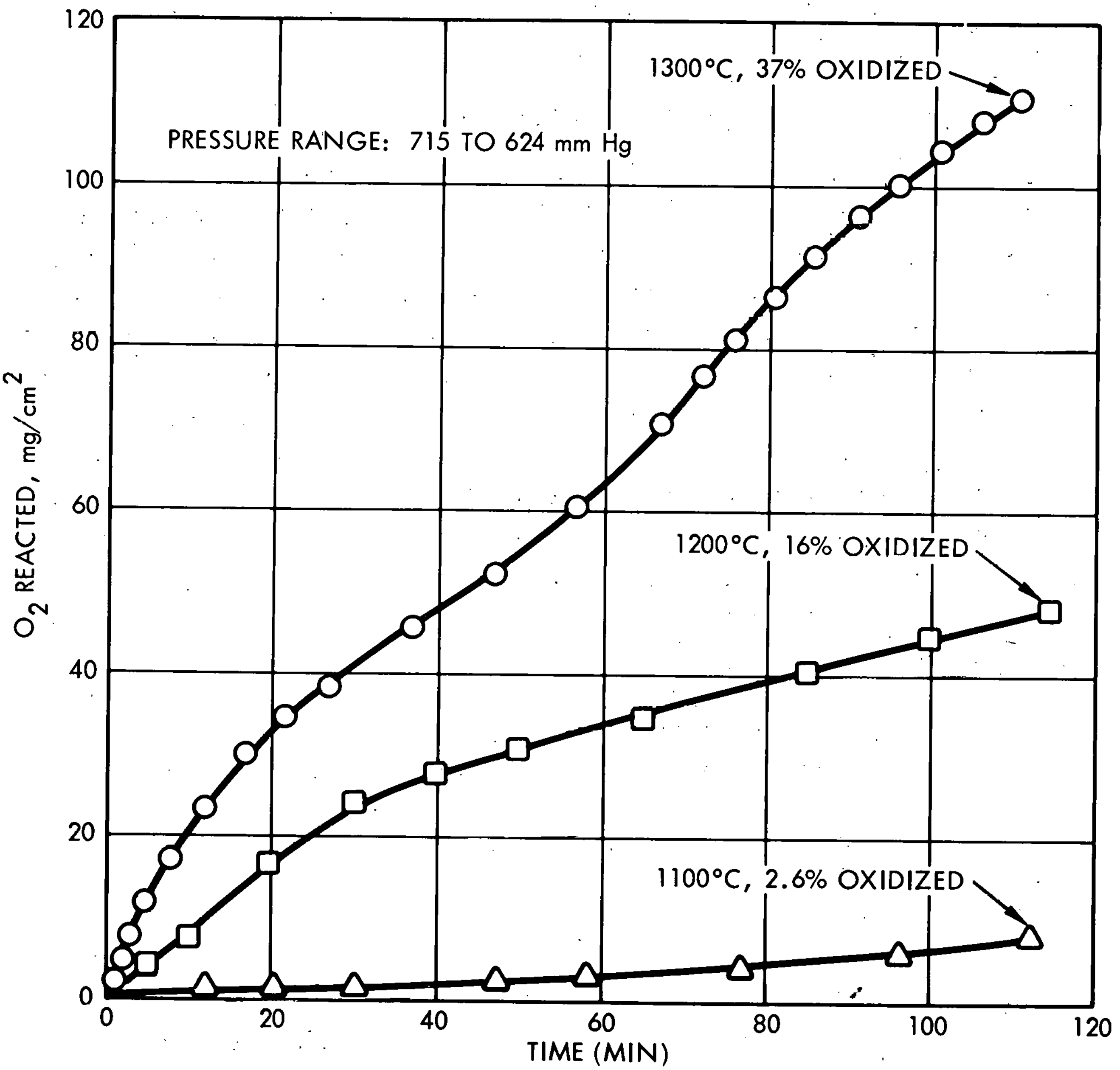

Figure 5. Oxidation of Type 316 Stainless Steel in Pure Oxygen

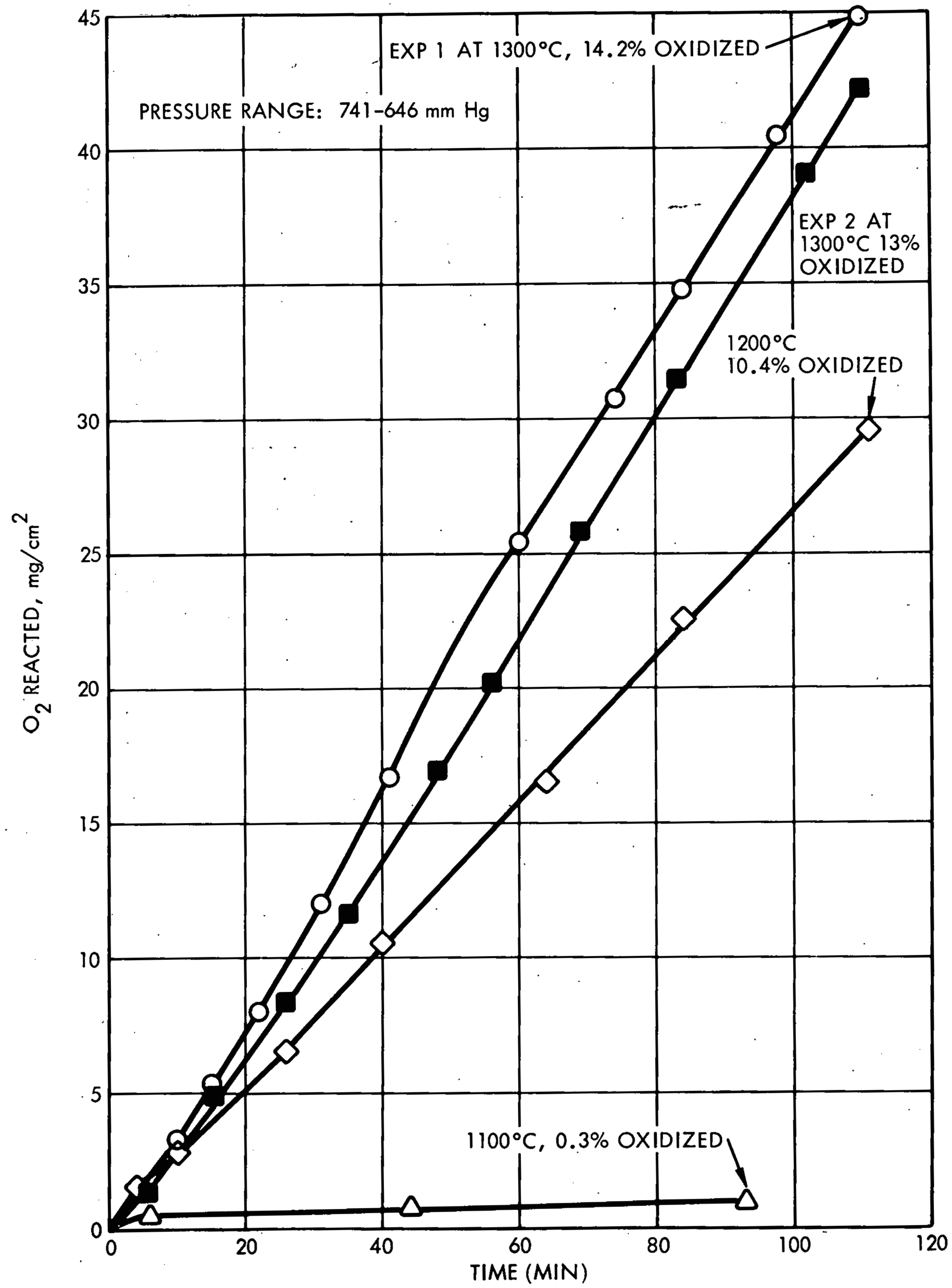

Figure 6. Oxidation of Hastelloy C in Pure Oxygen

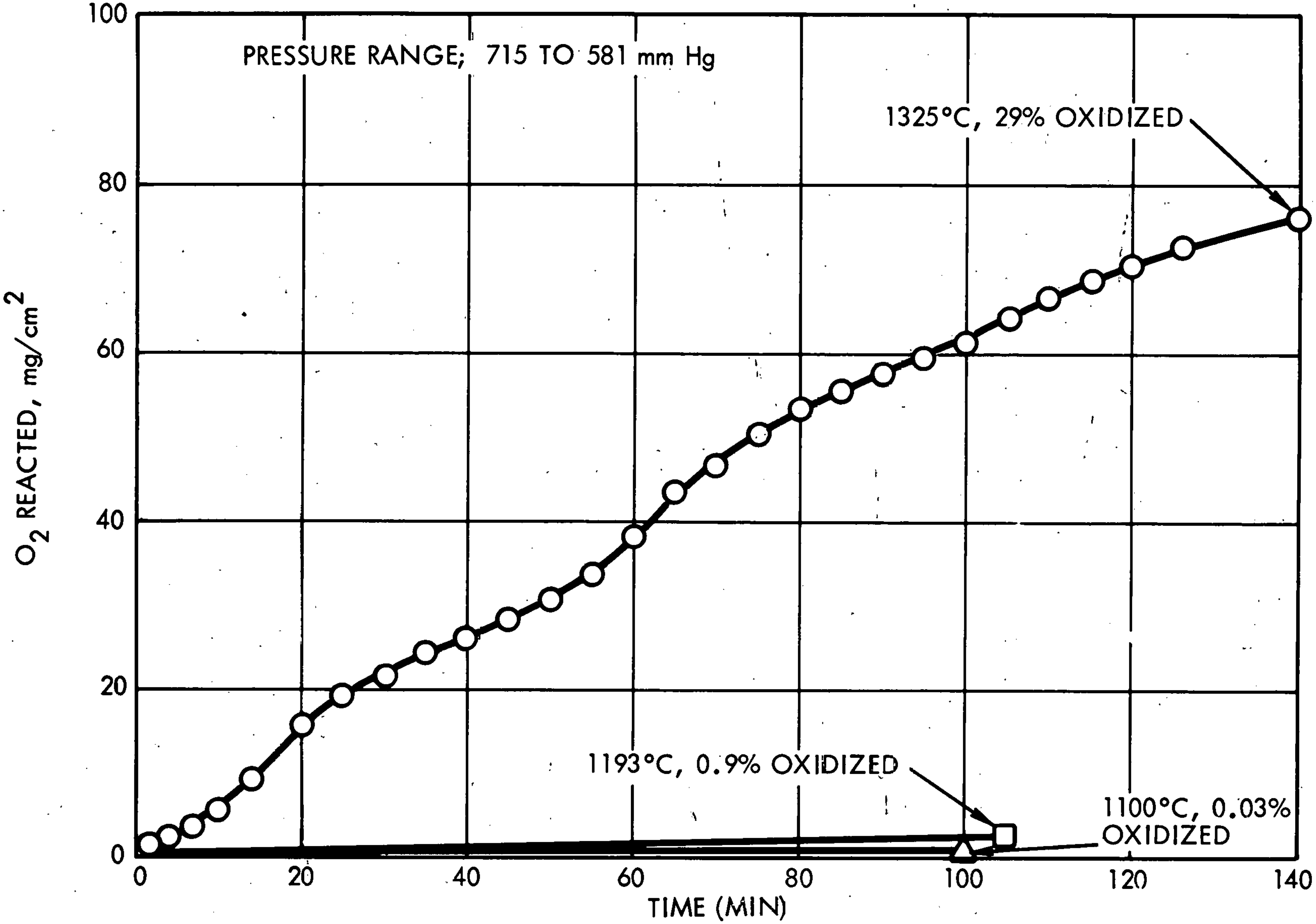

Figure 7. Oxidation of Hastelloy X in Pure Oxygen

3.1.4 The Haynes 25-Oxygen System

The oxidation of Haynes 25 in pure oxygen was investigated over the temperature range from 1100 to 1300°C at pressures near atmospheric. Figure 8 presents the experimental data plotted in terms of oxygen reacted as a function of time. Although the oxidation was essentially linear over the temperature range investigated, the reaction rates were not fast enough to be of any real interest from a launch abort safety viewpoint until temperatures in excess of 1200°C were reached. As can be seen from Figure 8, the reaction rate increases very rapidly with increasing temperature.

3.1.5 The Haynes 25-Nitric Oxide System

A number of experiments were carried out in which Haynes 25 was exposed to nitric oxide gas and the overall reaction followed as a function of time. The measured sample weight change from the beginning to the end of an experiment agreed very well with the weight change calculated from system pressure drop measurements assuming the following reaction to take place:

$$M + NO \rightarrow MO + 1/2\ N_2 \qquad M = \text{metal}$$

Figure 9 shows a plot of reaction versus time for experiments at 1100°, 1200°, and 1300°C and at a pressure of 500 mm Hg. As is apparent from this figure, there was relatively little difference between the experiment at 1200°C and the experiment at 1300°C. It would seem possible that at 1300°C the overall reaction was no longer controlled by surface kinetics but rather by the rate of diffusion of nitric oxide to the sample surface through the nitrogen gas which was formed as a product of reaction. From a comparison of Figure 8 and 9, it would appear that the oxidation of Haynes 25 in nitric oxide was somewhat slower than the oxidation of Haynes 25 in pure oxygen.

Figure 10 shows the results of several experiments run at 1200°C and at different nitric oxide pressures. The Haynes 25-nitric oxide reaction was found to be slightly pressure dependent at 1200°C. A 25-fold increase in the nitric oxide pressure resulted in about a 3.5-fold increase in the reaction rate.

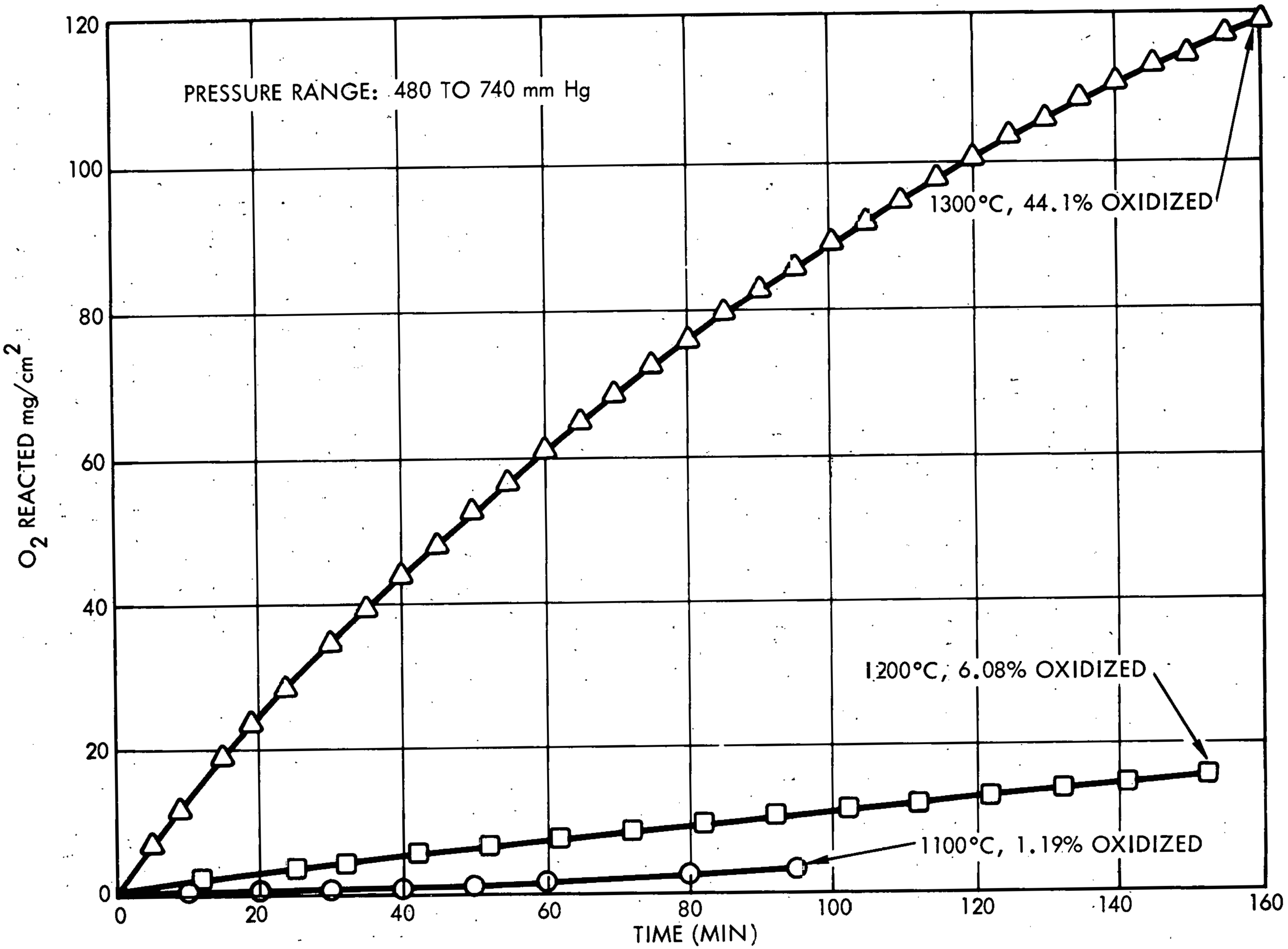

Figure 8. Oxidation of Haynes Alloy 25 in Pure Oxygen

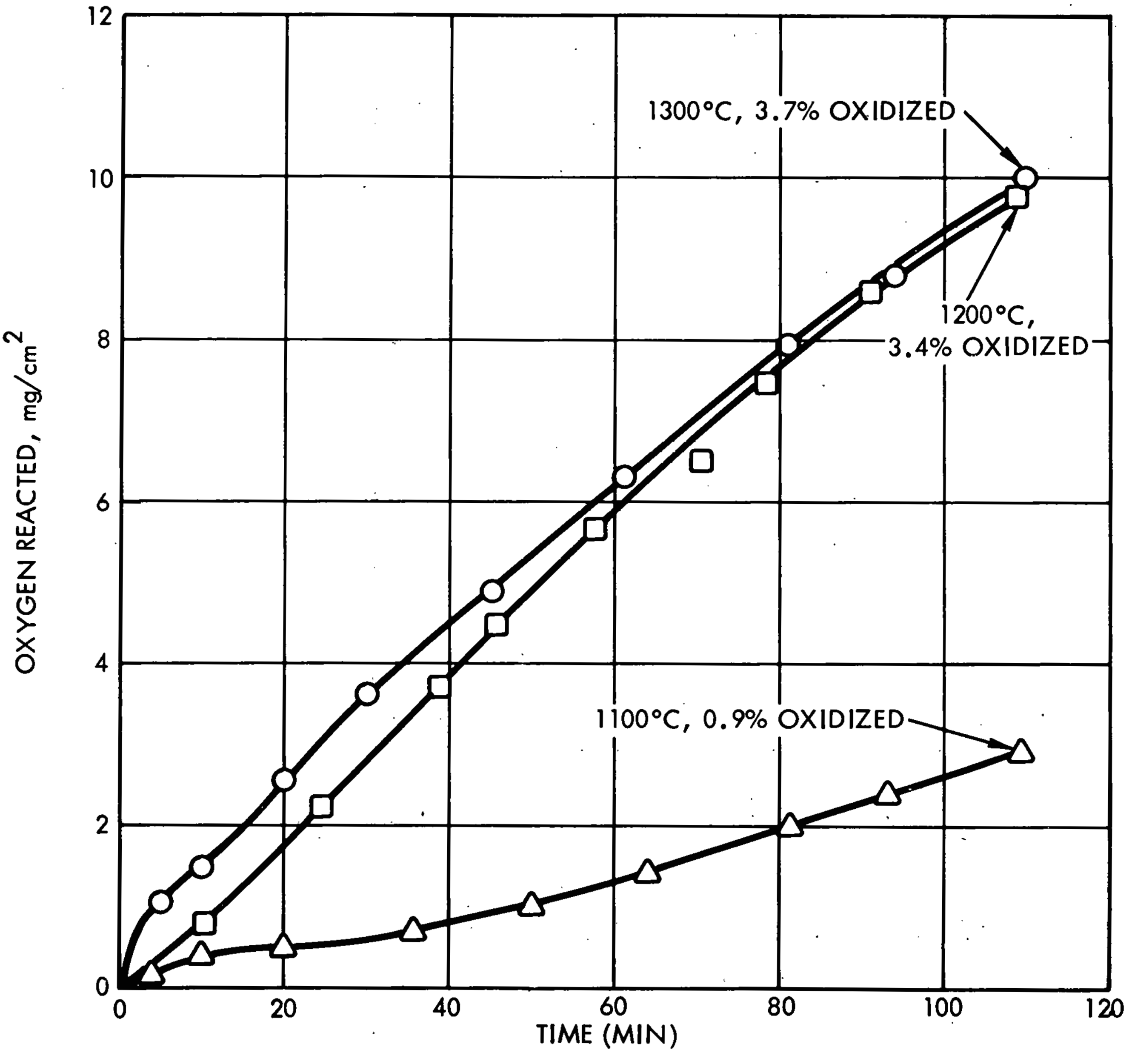

Figure 9. Oxidation of Haynes Alloy 25 in Nitric Oxide at 500 MM Hg. Pressure

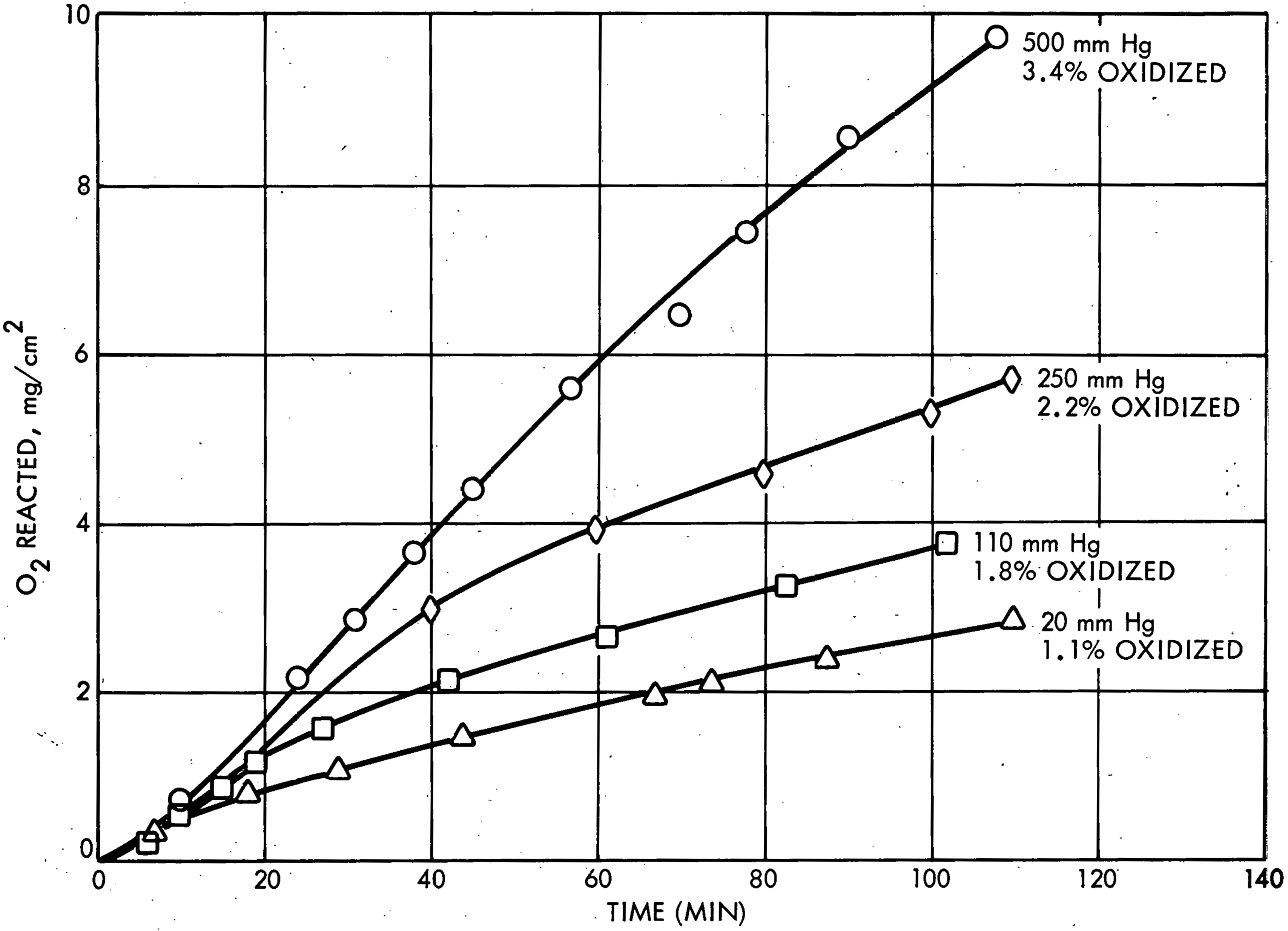

Figure 10. Oxidation of Haynes Alloy 25 in Nitric Oxide at 1200°C (Effect of Pressure)

3.1.6 Comparison of the Oxidation of 316 Stainless Steel, Hastelloy C, Hastelloy X, and Haynes 25

Figure 11, 12, and 13 compare the results of the oxidation in pure oxygen of 316 stainless steel, Hastelloy C, Hastelloy X and Haynes 25 at 1100°, 1200°, and 1300°C respectively. At 1100°C Hastelloy X oxidized much slower than any of the other alloys, while 316 stainless steel oxidized considerably faster than the other three alloys. Indeed, there was almost a factor of 100 difference between the rates of oxidation of Hastelloy X and 316 stainless steel at 1100°C. In general, it appeared that 316 stainless steel was less oxidation resistant at temperatures of 1100°C and above than the nickel or cobalt-based superalloys.

3.2 EXPERIMENTAL FLAME STUDIES

3.2.1 The Behavior of Type 304 Stainless Steel in the H_2-O_2 Flame System

A number of experiments were conducted in which type 304 stainless steel was exposed to thermochemically defined H_2-O_2 flame environments for periods of time of up to 20 minutes. Experiments were conducted at a variety of initial heat fluxes (and hence a number of different steady state sample temperatures) and at two different mixture ratios ($O_2/H_2 = 0.98$ and $O_2/H_2 = 0.33$). The oxygen-rich mixture ratio ($O_2/H_2 = 0.98$) contained high concentrations of both oxygen and water vapor.

Table 2 summarizes the test conditions used in each of the experiments with type 304 stainless steel. The table lists for each experiment the computed adiabatic flame temperature and chemical composition, the initial heat flux to the sample, the calculated steady state sample temperature, the total run time, and oxidizer and fuel flow rates.

Tables A-1 to A-19 of the Appendix present the detailed temperature-time data for each experiment. Both the two-color pyrometer measurements and the micro-optical pyrometer measurements are included. Initial and final sample weights are also included in these tables. An apparent corrosion rate was calculated from the weight change and the total time of an experiment, and is presented in the tables. The apparent corrosion rates calculated from measured weight changes, at best, give only a very crude measure of the rate of corrosion. At temperatures above the alloy melting

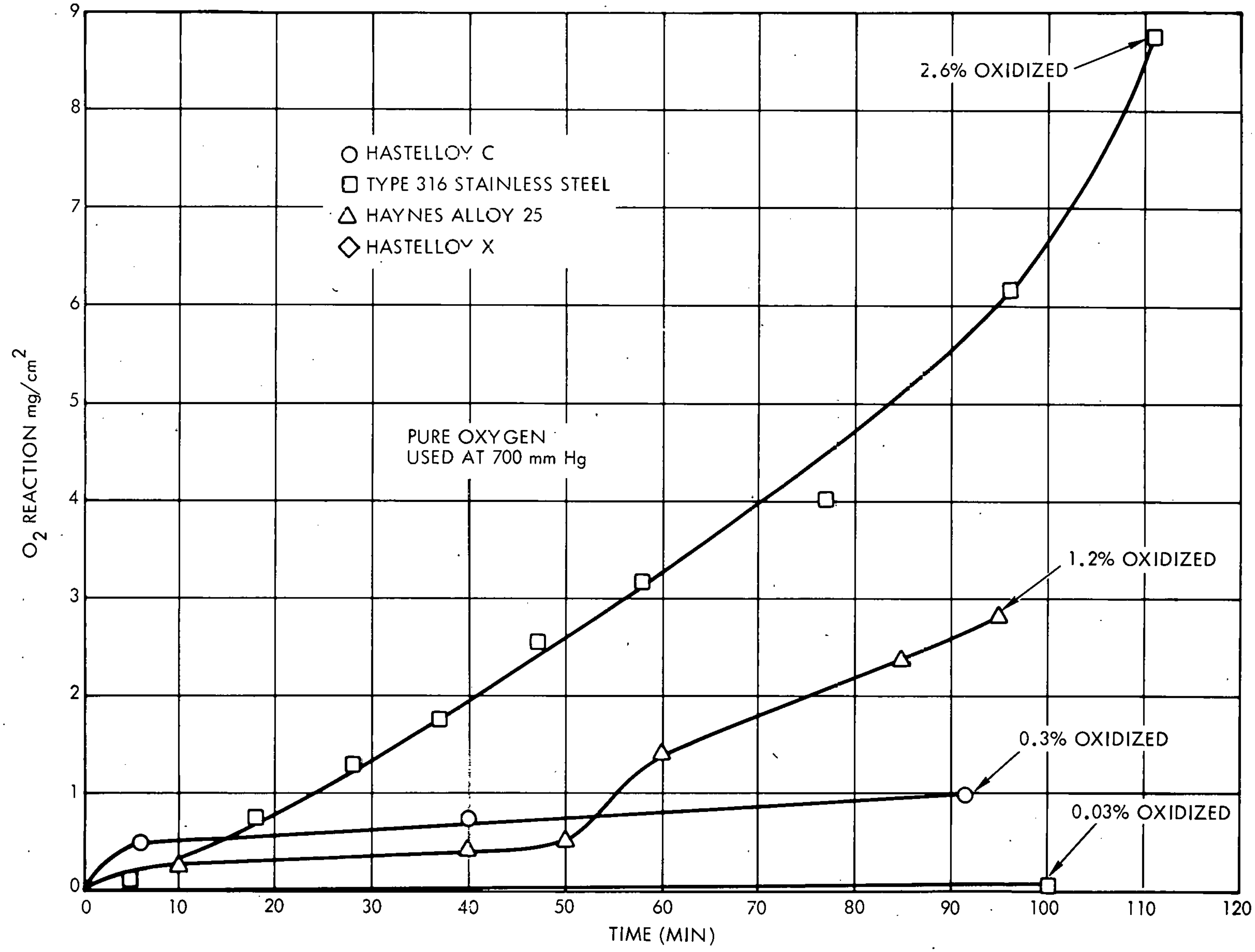

Figure 11. Oxidation at 1100°C

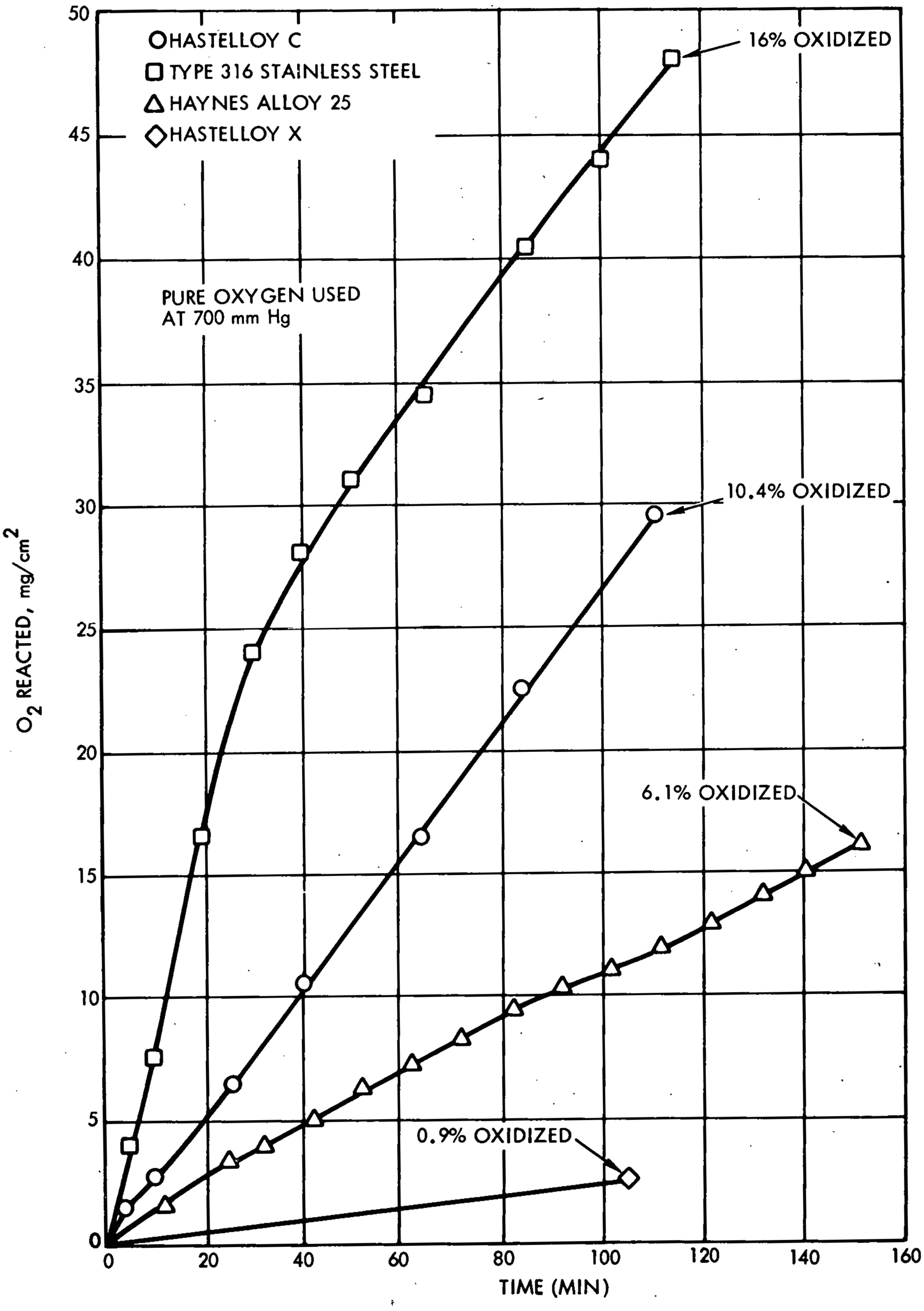

Figure 12. Oxidation at 1200°C

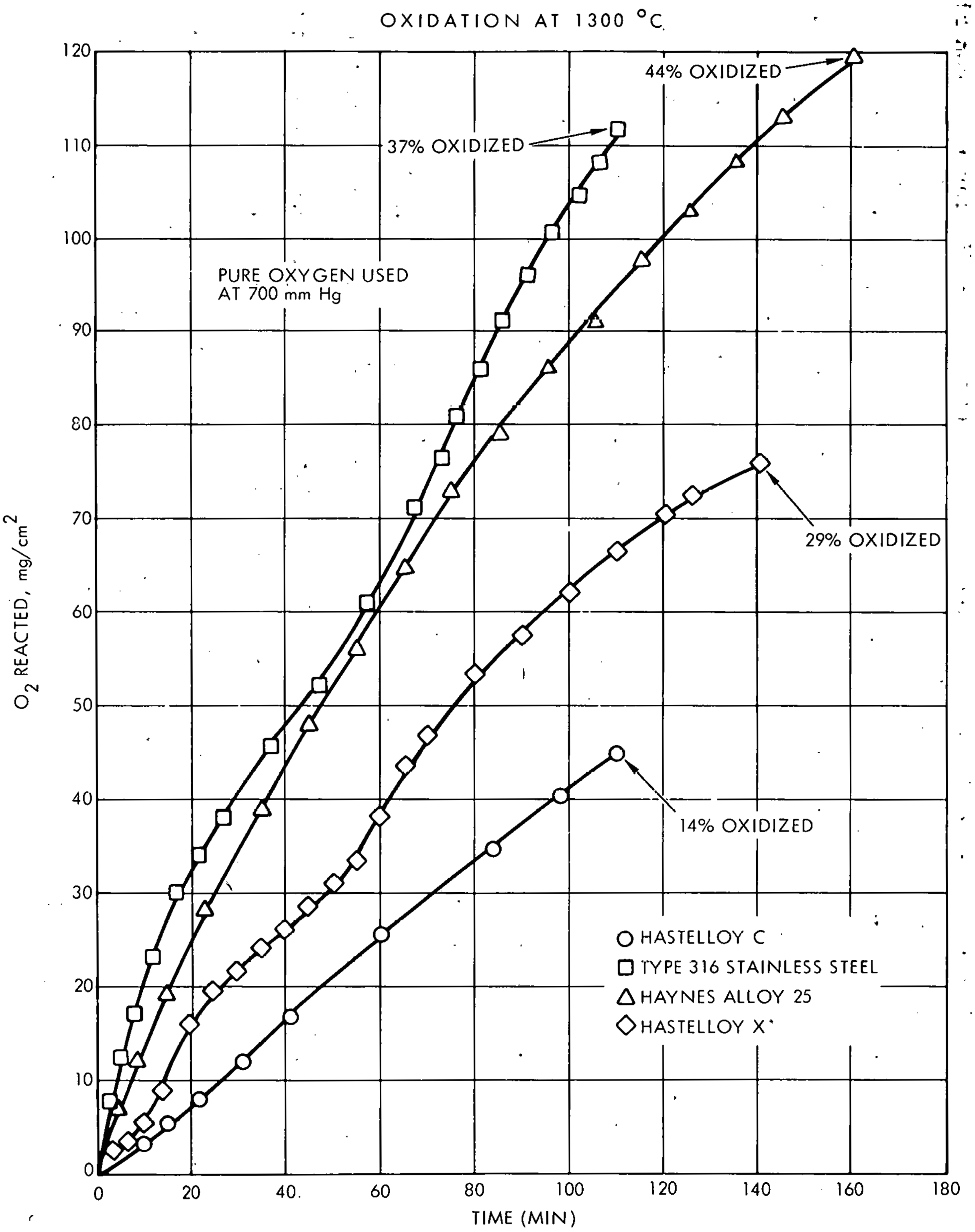

Figure 13. Oxidation at 1300°C

Table 2. Conditions of Type 304 Stainless Steel Torch Experiments—Hydrogen-Oxygen Flame

Experiment Number	1	2	3	4	5	6	7	8	9	10
Adiabatic Flame Temperature, °F	4790	4790	4790	4790	4840	4840	4840	4840	4840	4840
Calculated Steady State Temperature, °F	2770	2670	3000	3000	2805	2495	2340	2920	2045	2340
O_2 Flow liters/min	5.88	4.90	8.80	8.80	2.00	1.30	1.00	2.64	0.75	1.00
H_2 Flow, liters/min	6.00	5.00	9.00	9.00	6.00	4.00	3.00	8.00	2.27	3.00
O_2/H_2 Ratio	0.98	0.98	0.98	0.98	0.33	0.33	0.33	0.33	0.33	0.33
Initial Heat Flux, Btu/ft^2-sec	93.5	79.5	137.2	137.2	99.6	59.2	44.0	119.7	25.6	44.0
Total Run Time, sec	364	300	21	12	94.5	213	354	41	480	375
Surrounding Atmosphere	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air
Equilibrium Flame Composition										
X_{O_2}*	0.270	0.270	0.270	0.270	0.006	0.006	0.006	0.006	0.006	0.006
X_{H_2}	0.034	0.034	0.034	0.034	0.312	0.312	0.312	0.312	0.312	0.312
X_{H_2O}	0.516	0.516	0.516	0.516	0.533	0.533	0.533	0.533	0.533	0.533
X_{OH}	0.110	0.110	0.110	0.110	0.052	0.052	0.052	0.052	0.052	0.052
X_H	0.022	0.022	0.022	0.022	0.088	0.008	0.008	0.008	0.008	0.008
X_O	0.044	0.044	0.044	0.044	0.009	0.009	0.009	0.009	0.009	0.009

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*X = Mole Fraction

Table 2. Conditions of Type 304 Stainless Steel Torch Experiments—Hydrogen-Oxygen Flame (Continued)

Experiment Number	11	12	13	14	15	32	33	34	35
Adiabatic Flame Temperature, °F	4790	4840	4790	4840	4840	4790	4790	4790	4840
Calculated Steady State Temperature, °F	1810	2135	3000	2495	2920	2670	2215	2320	2135
O_2 Flow, liters/min	0.75	0.82	8.80	1.30	2.64	4.90	1.67	2.30	0.82
H_2 Flow, liters/min	0.76	2.46	9.00	4.00	8.00	5.0	1.70	2.35	2.46
O_2/H_2 Ratio	0.98	0.33	0.98	0.33	0.33	0.98	0.98	0.98	0.33
Initial Heat Flux, Btu/ft^2-sec	16.5	29.7	137.2	59.2	119.7	79.5	34.3	41.8	29.7
Total Run Time, sec	360	920	11	71	15.5	30	1200	1200	1200
Surrounding Atmosphere	Air	Air	Air	Air	Air	Air	Air	Air	Air
Equilibrium Flame Composition									
X_{O_2}*	0.270	0.006	0.270	0.006	0.006	0.270	0.270	0.270	0.006
X_{H_2}	0.034	0.312	0.034	0.312	0.312	0.034	0.034	0.034	0.312
X_{H_2O}	0.516	0.533	0.516	0.533	0.533	0.516	0.516	0.516	0.533
X_{OH}	0.110	0.052	0.110	0.052	0.052	0.110	0.110	0.110	0.052
X_H	0.022	0.088	0.022	0.008	0.008	0.022	0.022	0.022	0.008
X_O	0.044	0.009	0.044	0.009	0.009	0.044	0.044	0.044	0.009

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*X = Mole Fraction

range some material may be removed by ablation. At temperatures below the alloy melting range, oxide scales can spall from the sample during cooldown. Thus, the reported corrosion rates in the flame experiments only give a rough estimate of the amount of oxidation.

Figure 14 shows a plot of the temperature-time data for experiments in both oxygen-rich and hydrogen-rich flames. Both the experimental points and the calculated steady state sample temperatures are shown.

The temperature-time response of experiments 34 and 35 (Figure 14) were typical of the results obtained in all experiments at sample temperatures below the melting range of 304 stainless steel (~2500°F). The measured sample temperatures were just slightly above the calculated temperatures. There did not appear to be any appreciable difference between exposing samples to fuel-rich flames ($O_2/H_2 = 0.33$) and exposing samples to oxygen-rich flames ($O_2/H_2 = 0.98$).

There was no evidence of a significant heat input due to rapid surface reaction in any of the experiments where samples remained at temperatures below the alloy melting range. That is, there was no tendency for the samples to ignite at temperatures below the melting range.

When the 304 stainless steel samples were exposed to hydrogen-oxygen flame environments under conditions where the samples were heated to temperatures in excess of 2500°F there was evidence of considerable surface heating due to reaction. This can be seen from the temperature-time data for experiment number 3 where the measured temperatures were as much as 500°F above the calculated steady state temperature (which assumes no heat input due to reaction). It would appear that, at least in some of the higher heat flux experiments (sample temperatures in excess of 2500°F), the 304 stainless steel ignited.

Figure 15 shows a photograph of an unreacted test specimen and Figure 16 shows a photograph of the 304 stainless steel sample after experiment 34. This sample was exposed to the oxygen-rich flame for 20 minutes under conditions which left the peak sample temperature at about 2400°F. A considerable oxide scale had formed on the sample. This sample was sectioned and examined microscopically to determine to what extent internal oxidation had taken place. Figure 17 shows a photomicrograph of an unreacted specimen and Figure 18 shows the sectioned sample

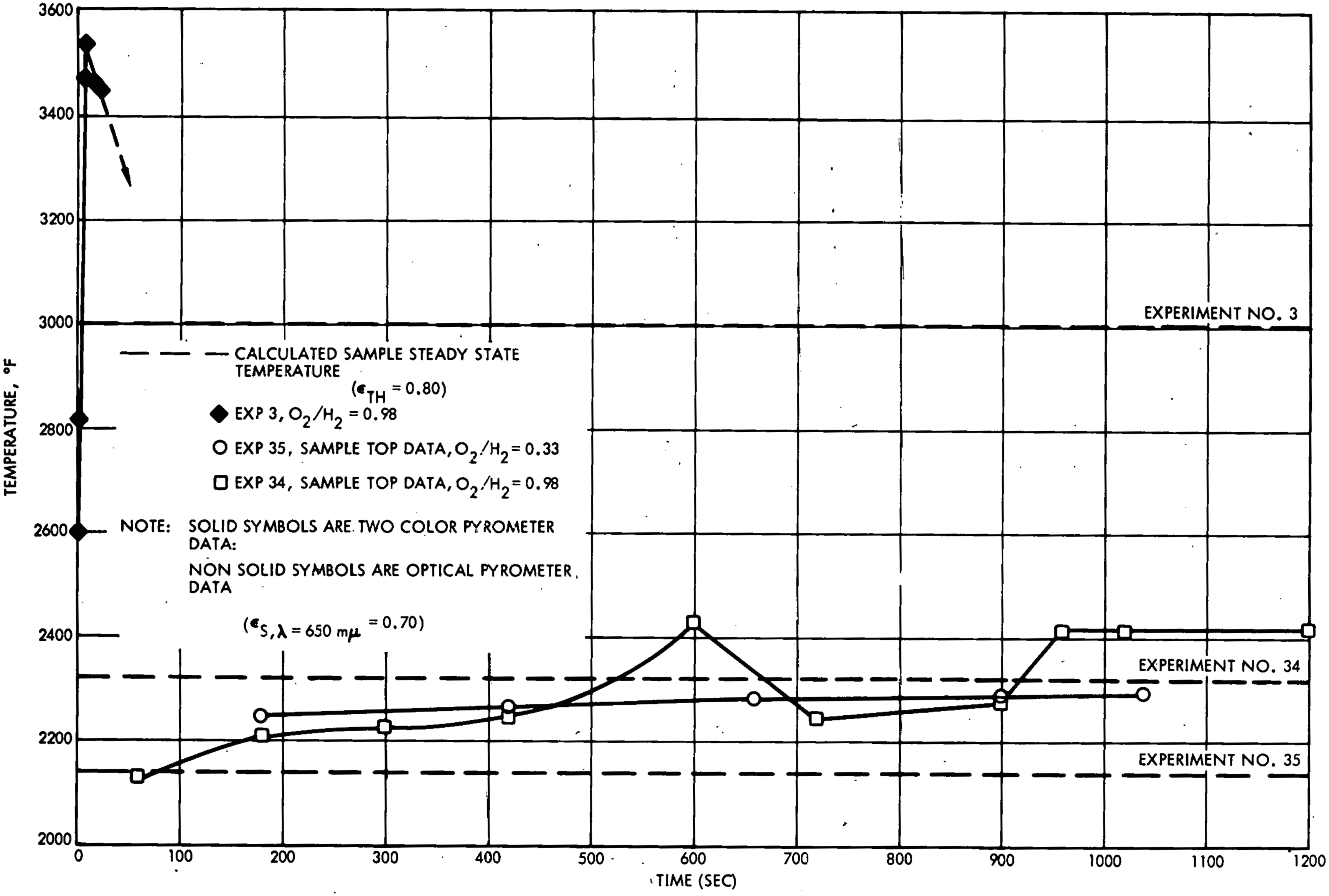

Figure 14. Temperature Time Data for Type 304 Stainless Steel in a Hydrogen-Oxygen Flame Environment

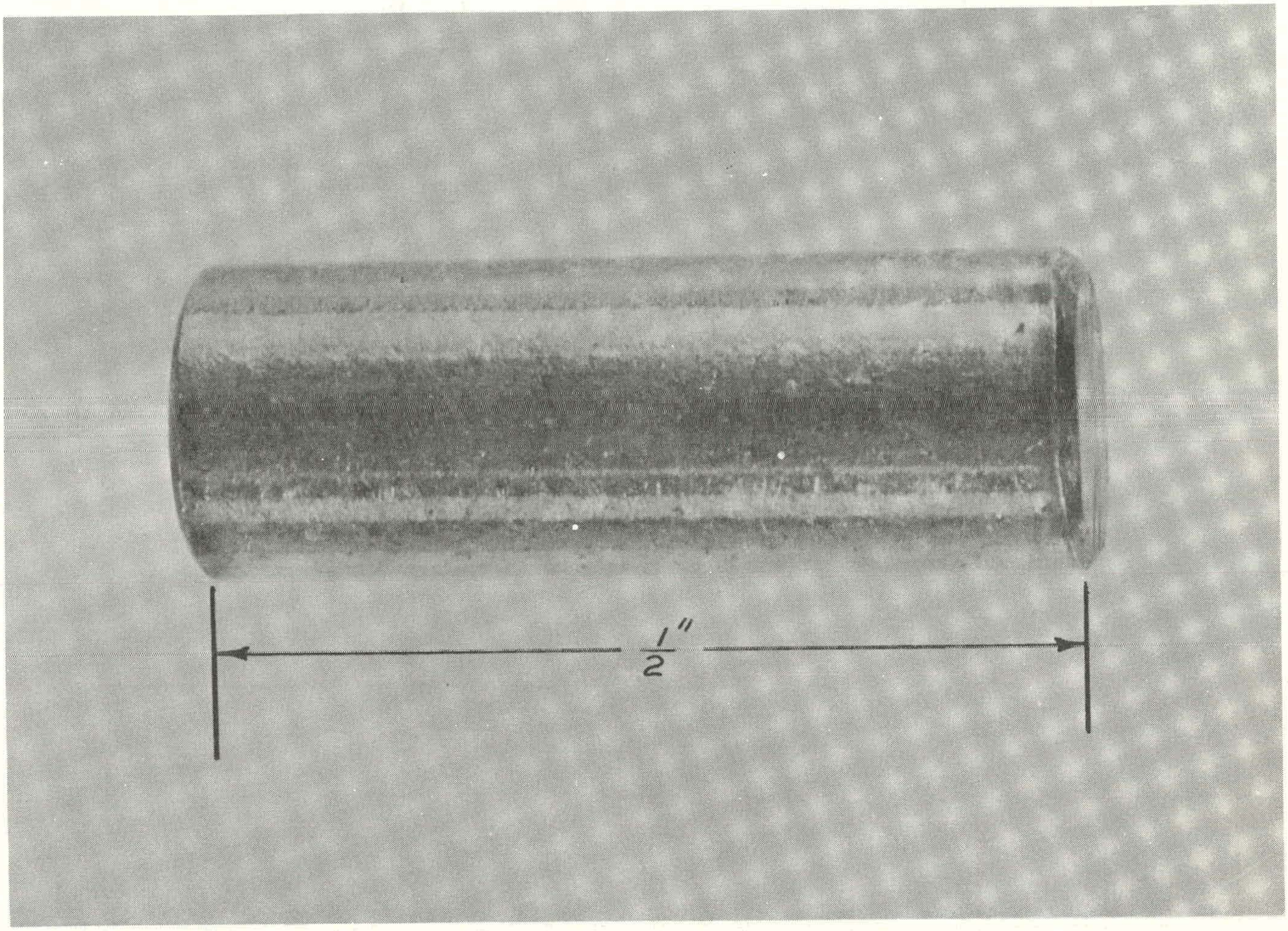

Figure 15. Unreacted Cylindrical Sample

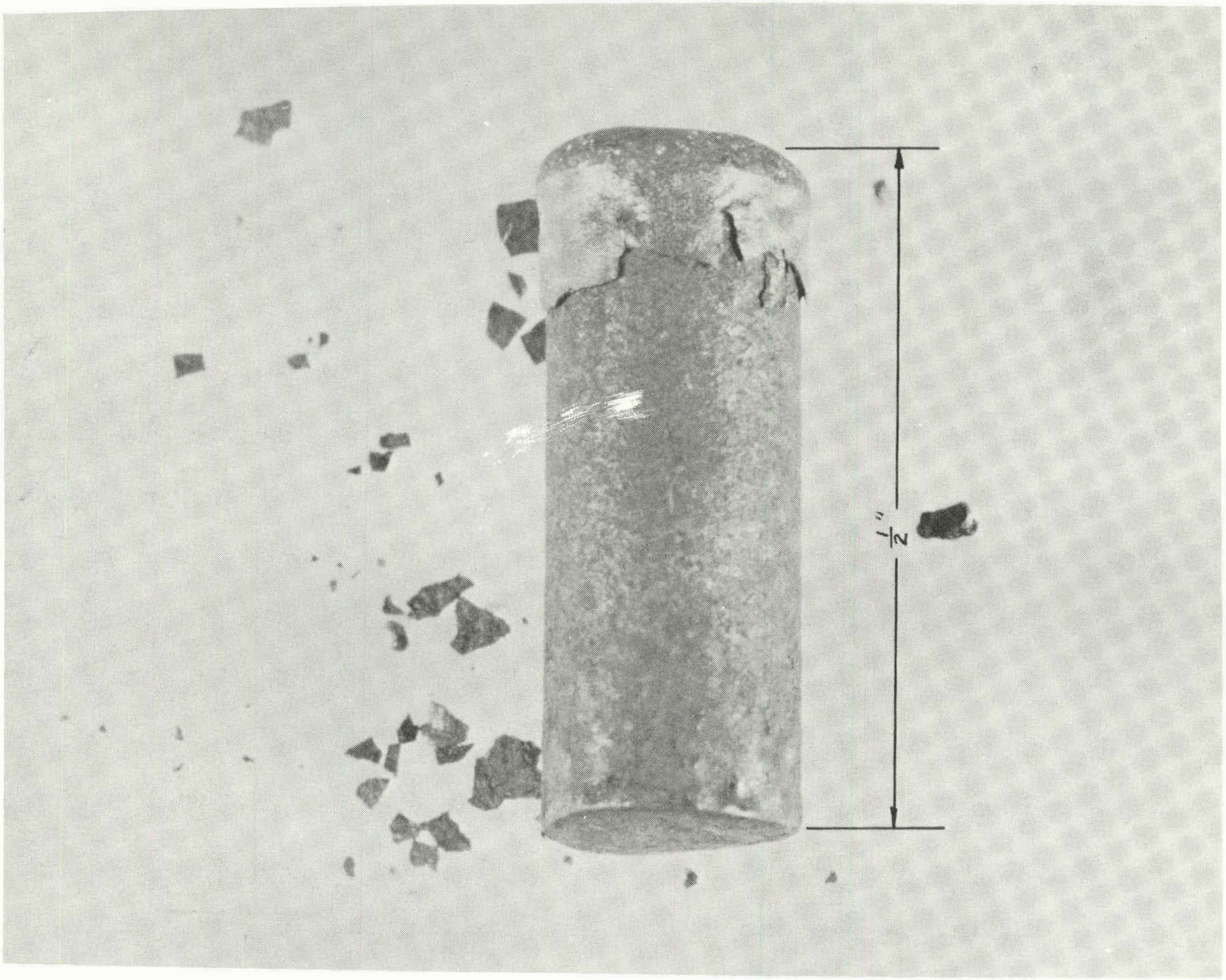

Figure 16. Experiment Number 34

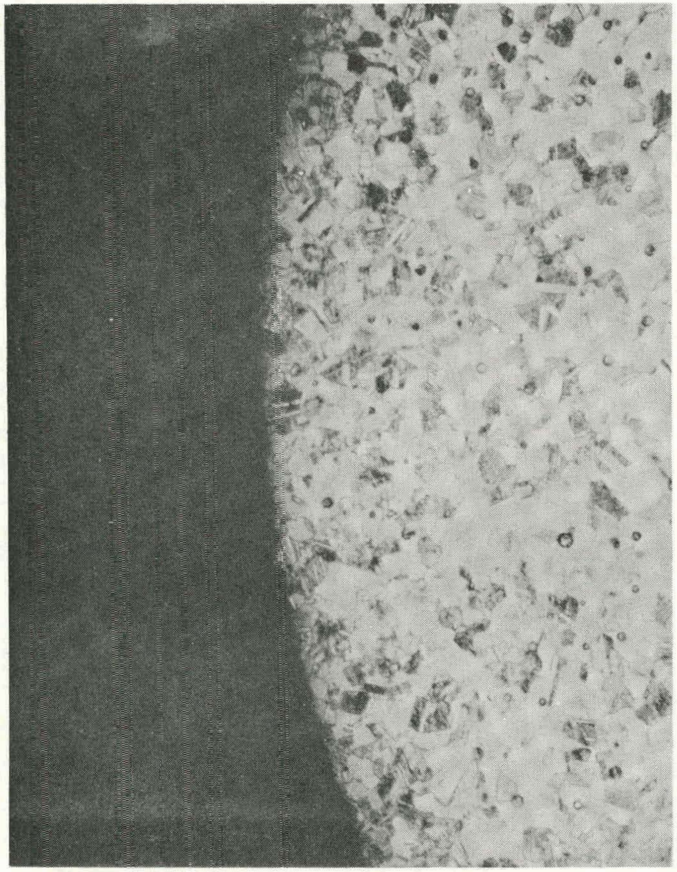

Figure 17. Unreacted 304 Stainless Steel Sample 80 X

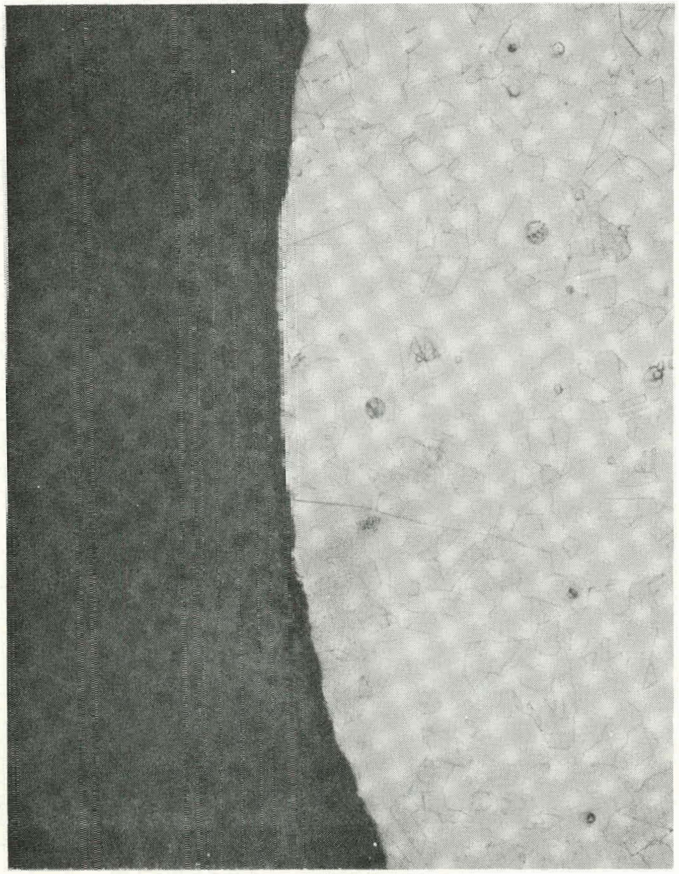

Figure 18. Sectioned 304 Stainless Steel Sample Experiment 34

from experiment 34. From a comparison of those two photomicrographs it was apparent that there was no appreciable internal oxidation of the experiment 34 test specimen, and that oxidation was limited to scaling of the external surface.

Figure 19 shows a photograph of a sample after exposure to the oxygen-rich flame at temperatures up to 3300°F. When the sample melted, reaction became quite vigorous and there was considerable sparking and evolution of volatile material through bubbling.

3.2.2 The Behavior of Type 316 Stainless Steel in the H_2-O_2 Flame System

The behavior of type 316 stainless steel in hydrogen oxygen flame environments was investigated in a manner analogous to the previously described (section 3.2.1) experiments with type 304 stainless steel. Table 3 details the test conditions for each experiment and Tables A-20 to A-31 of the appendix tabulate the measured temperature-time data for each experiment. The results obtained were very similar to those obtained with type 304 stainless steel and are summarized briefly below:

Figure 20 shows the measured and calculated temperature versus time data for typical experiments in both hydrogen-rich and oxygen-rich flames. The results of two experiments at relatively low heat fluxes (experiments 36 and 37) and one experiment at a high heat flux (experiment 16) are shown. In experiments at low heat fluxes, such as 36 and 37, where the sample did not obtain temperatures higher than about 2500°F the calculated steady state temperature agreed fairly well with the measured sample temperature. Hence, under these conditions, there was very little surface heating due to reaction and no tendency towards sample ignition. At higher heat fluxes, where the sample temperature exceeded the melting range of the 316 stainless steel (~2500°F), the measured sample temperatures were as much as 700°F greater than the calculated temperatures which indicated a considerable amount of sample heating due to surface reaction. Thus, as illustrated by experiment 16 shown in Figure 20, it would appear that, like type 304 stainless steel, type 316 stainless steel can be ignited at temperatures above its melting range in a hydrogen-oxygen flame. There was no real evidence to indicate that either the fuel-rich or oxygen-rich flame was more reactive with 316 stainless steel at any of the sample temperatures investigated.

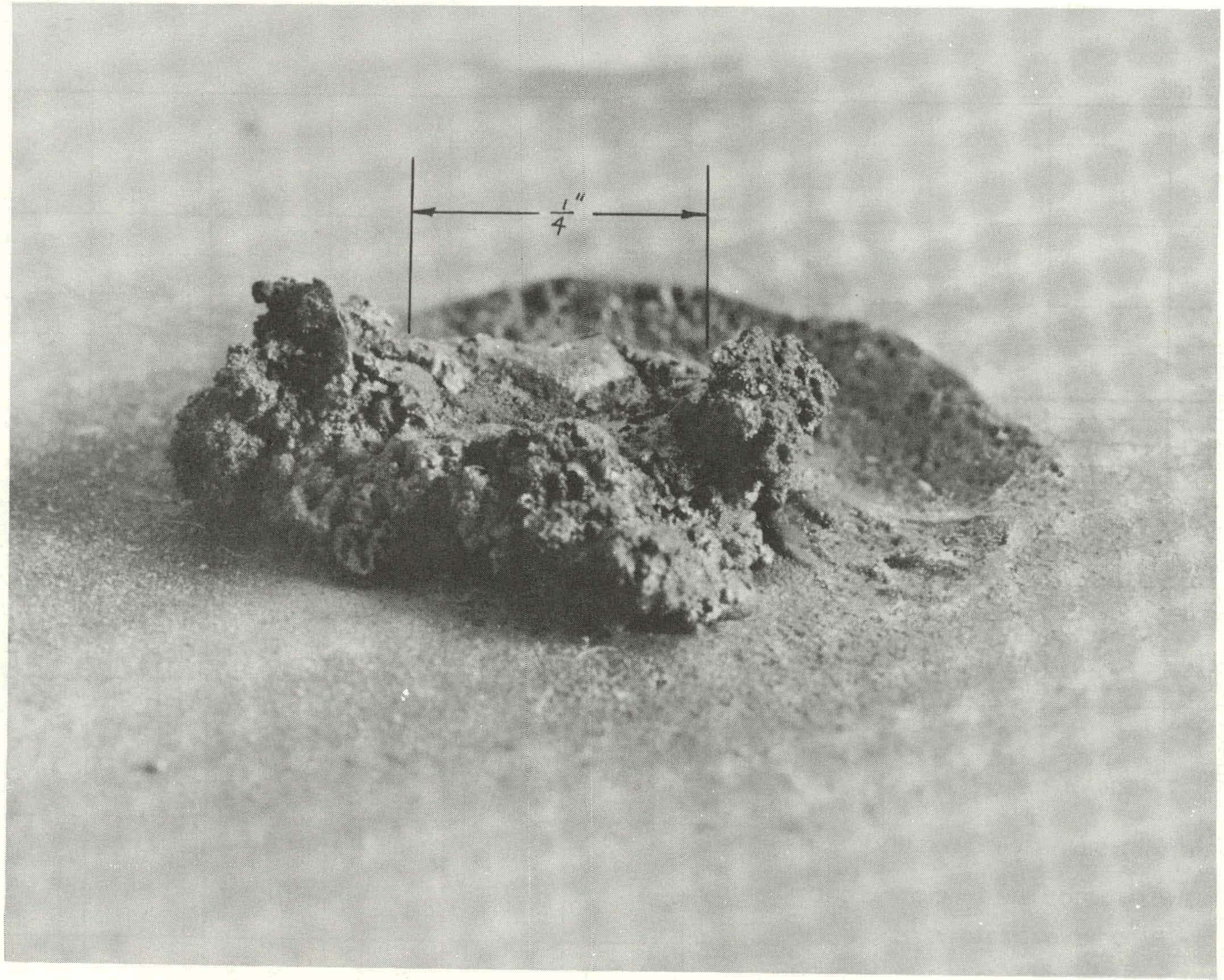

Figure 19. Experiment No. 13

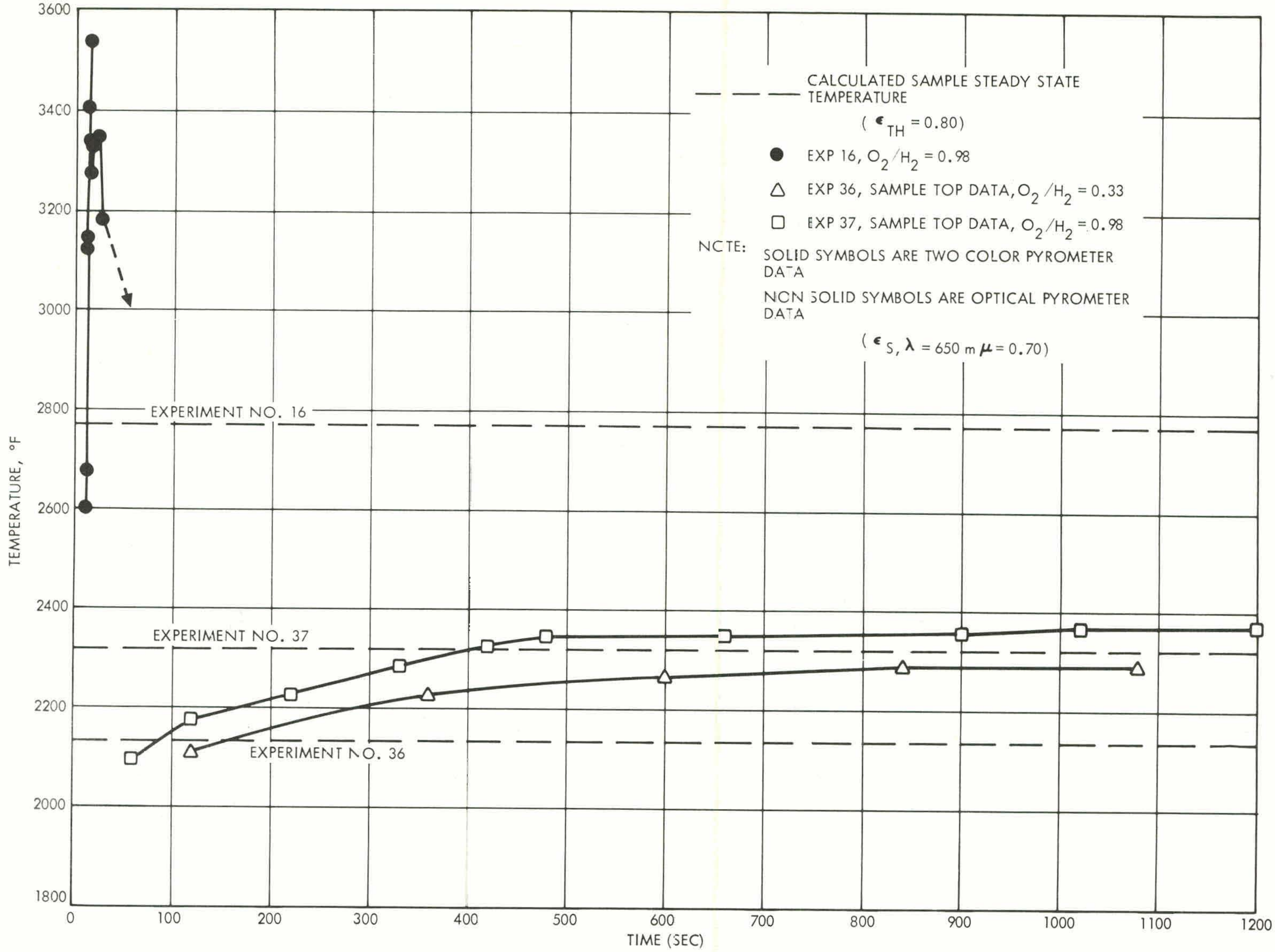

Figure 20. Temperature Time Data for Type 316 Stainless Steel in a Hydrogen-Oxygen Flame Environment

Table 3. Conditions of Type 316 Stainless Steel Torch Experiments — Hydrogen-Oxygen Flame

Experiment Number	16	17	18	19	20	21	22	23	24	25	36	37
Adiabatic Flame Temperature, °F	4790	4790	4790	4790	4790	4840	4840	4840	4840	4840	4840	4790
Calculated Steady State Temperature, °F	2770	2770	2670	2540	2380	2805	2495	2920	2340	2045	2135	2320
O_2 Flow, liters/min	5.88	5.88	4.90	3.90	2.90	2.00	1.30	2.64	1.00	0.75	0.82	2.3
H_2 Flow, liters/min	6.00	6.00	5.00	4.00	3.00	6.00	4.00	8.00	3.00	2.27	2.40	2.35
O_2/H_2 Ratio	0.98	0.98	0.98	0.98	0.98	0.33	0.33	0.33	0.33	0.33	0.33	0.98
Initial Heat Flux, Btu/ft^2-sec	93.5	93.5	79.5	63.8	47.5	99.0	59.2	119.7	44.0	25.6	29.7	41.75
Total Run Time, sec	27.5	30.5	211	360	360	182	336	31	360	360	1200	1200
Surrounding Atmosphere	Air	Oxygen	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air
Equilibrium Flame Composition												
X_{O_2}*	0.270	0.270	0.270	0.270	0.270	0.006	0.006	0.006	0.006	0.006	0.006	0.270
X_{H_2}	0.034	0.034	0.034	0.034	0.034	0.312	0.312	0.312	0.312	0.312	0.312	0.034
X_{H_2O}	0.516	0.516	0.516	0.516	0.516	0.533	0.533	0.533	0.533	0.533	0.533	0.516
X_{OH}	0.110	0.110	0.110	0.110	0.110	0.052	0.052	0.052	0.052	0.052	0.052	0.110
X_H	0.022	0.022	0.022	0.022	0.022	0.088	0.088	0.088	0.088	0.088	0.088	0.022
X_O	0.044	0.044	0.044	0.044	0.044	0.009	0.009	0.009	0.009	0.009	0.009	0.044

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*X = Mole Fraction

Figure 21 shows the 316 stainless steel test sample after the completion of experiment 36. The test specimen was exposed to the fuel-rich hydrogen-oxygen flame environment for 20 minutes at a temperature of approximately 2250°F. The specimen was coated with a fairly heavy oxide scale. Figure 22 shows a photomicrograph of a polished and etched sample of unreacted 316 stainless steel, and Figure 23 shows a photomicrograph of a polished and etched cross section of the test specimen from experiment 36. It was apparent that there was no appreciable internal corrosion of this test specimen and that the majority of the oxidation took place on the external surface.

Figure 24 shows the test specimen after completion of a high heat flux experiment (experiment 21) in which peak sample temperatures reached 3500°F. The craters in the sample probably represent areas where sparking or violent bubbling took place during the test.

3.2.3 The Behavior of Haynes Alloy 25 in the H_2-O_2 Flame System

The behavior of Haynes 25 in hydrogen-oxygen flame environments which were fully determined thermochemically was investigated in a number of experiments. Samples were tested in both fuel-rich and oxygen-rich flames at a variety of initial heat fluxes (and hence at a number of different steady state temperatures). The experimental test matrix was very similar to the ones conducted with 316 and 304 stainless steels (sections 3.2.1 and 3.2.2). Table 4 lists the experimental conditions for each of the hydrogen-oxygen flame tests. Tables A-32 to A-45 present the measured temperature-time data, initial and final sample weights, and calculated steady state sample temperature (assuming no heat generation due to reaction and an emissivity of 0.8) for each experiment.

Figure 25 compares the calculated and measured temperature versus time data for several experiments in both oxygen-rich and fuel-rich flames. In experiments in which the Haynes 25 samples remained at temperatures below the melting range of the alloy (~2600°F) there was rather good agreement between calculated and experimental sample temperatures indicating no appreciable surface heating due to reaction and no tendency to ignite. There did not appear to be any real difference between the behavior of

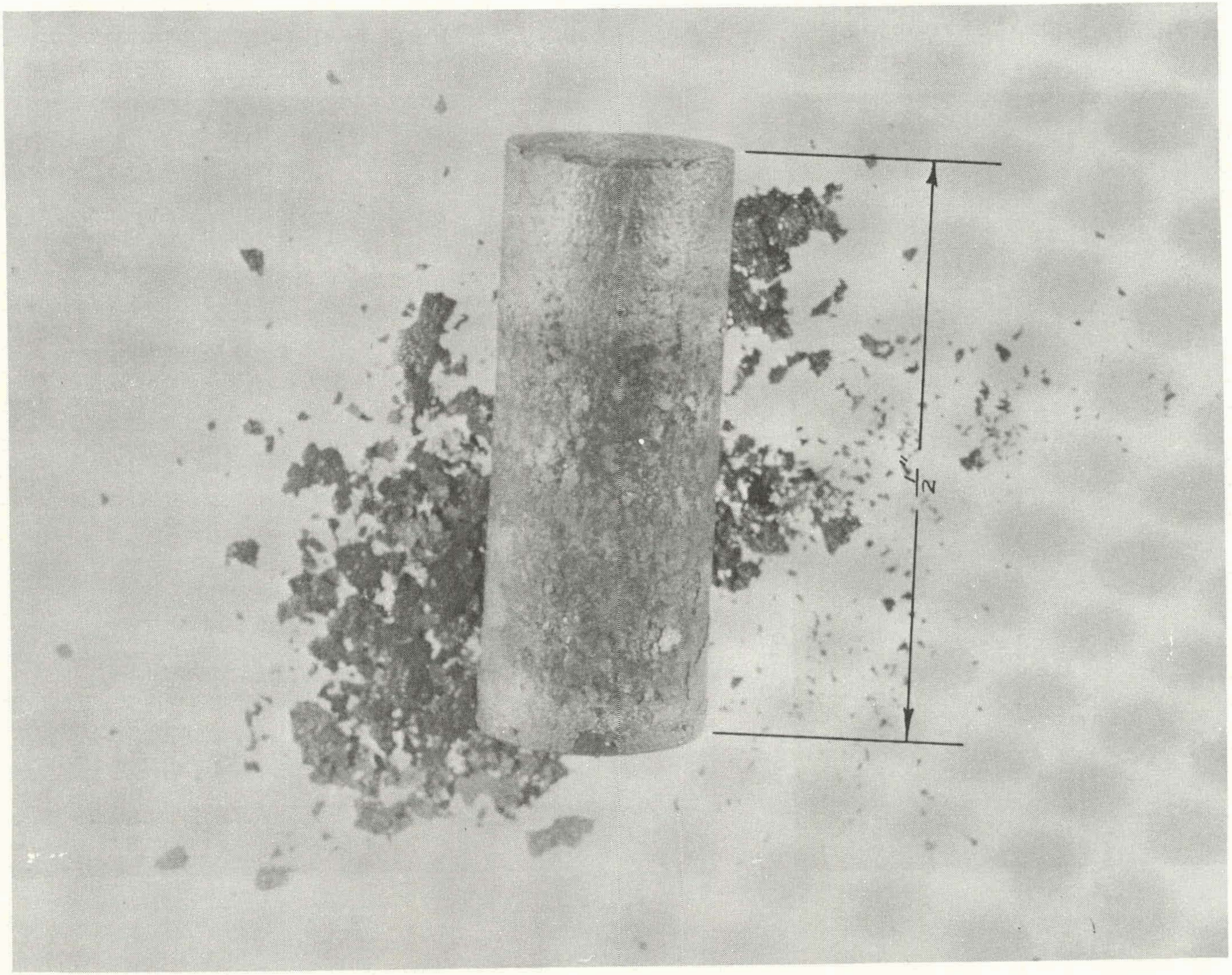

Figure 21. Experiment No. 36

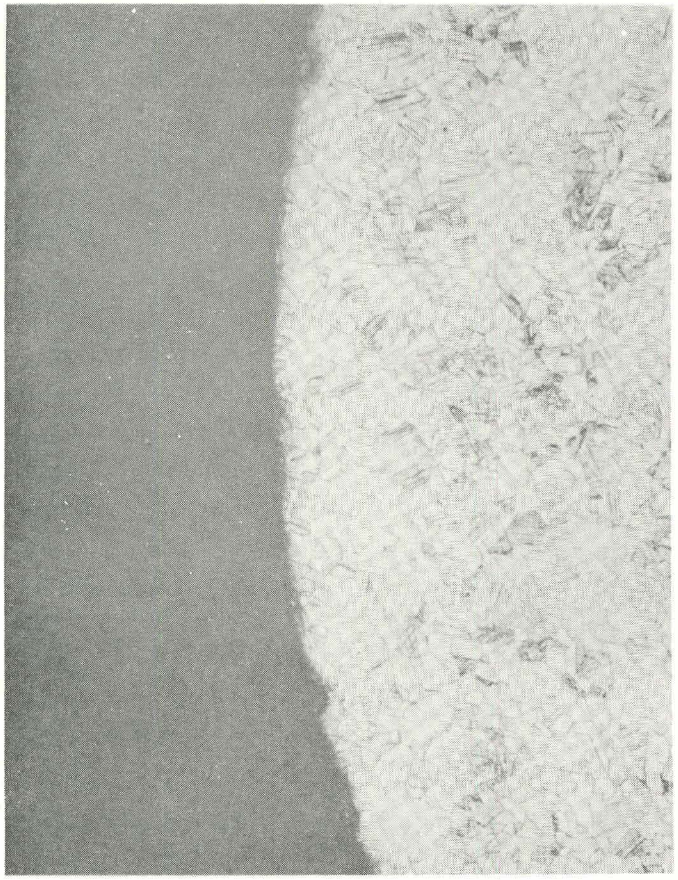

Figure 22
Unreacted 316 Stainless Steel
Sample 80 X

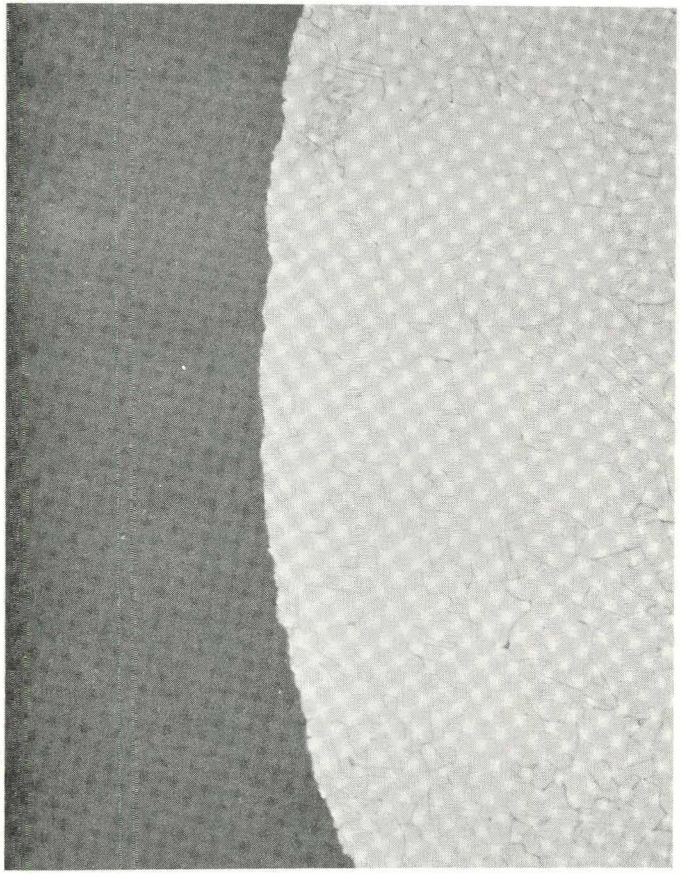

Figure 23
Photomicrographs of The Sectioned
316 Stainless Steel Sample from
Experiment 36

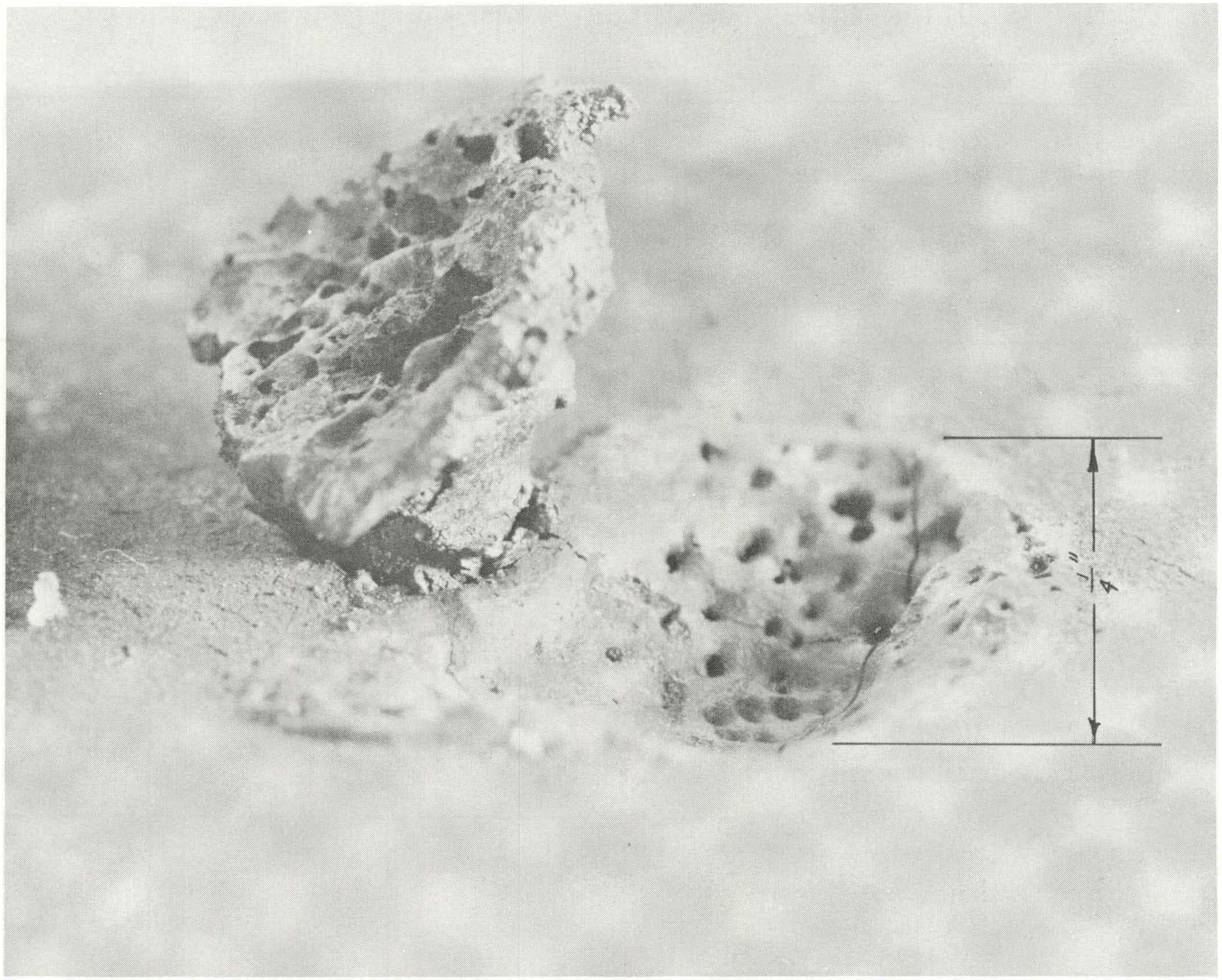

Figure 24. Experiment No. 21

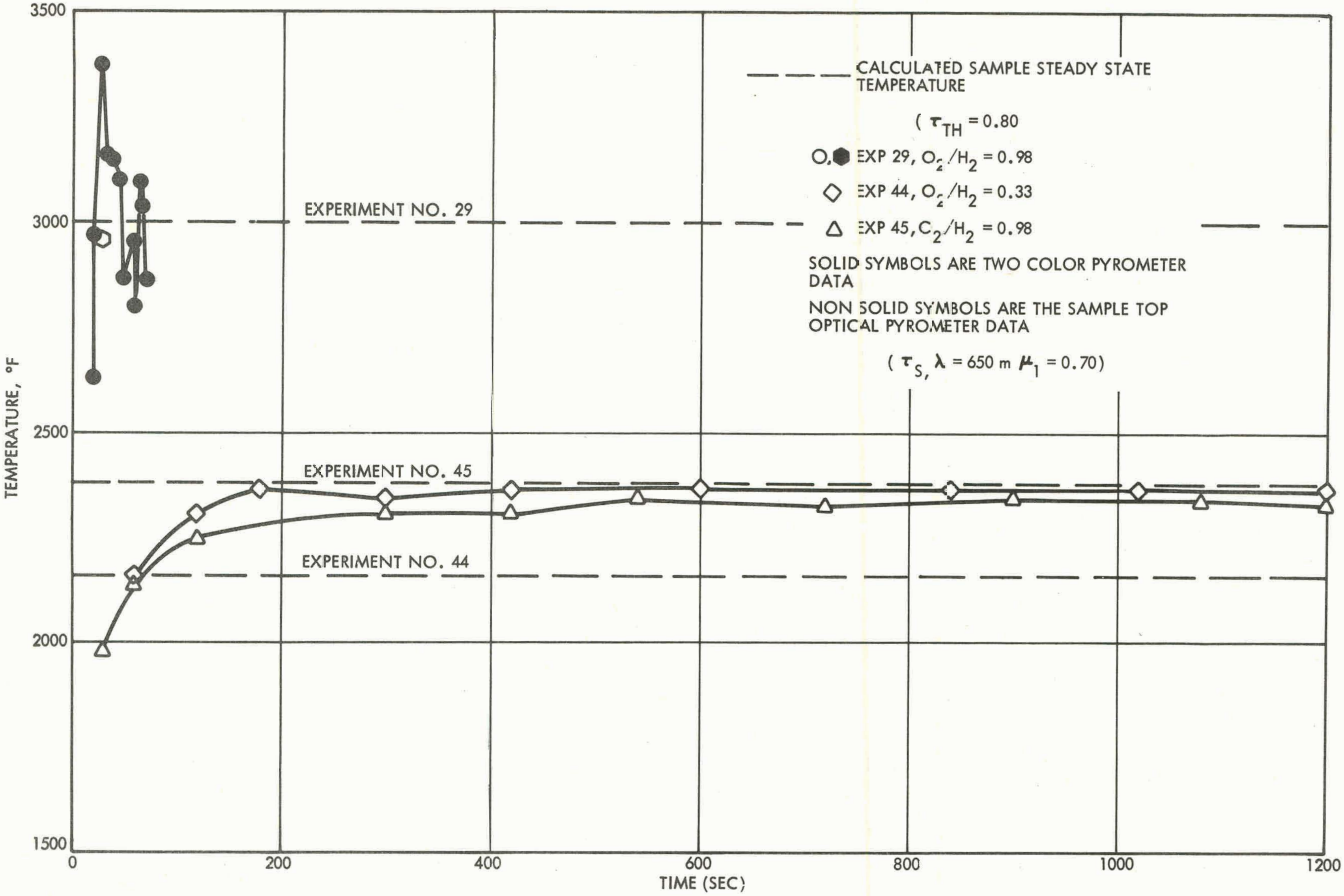

Figure 25. Temperature Time Data for Haynes Alloy 25 in a Hydrogen-Oxygen Flame Environment

Table 4. Experimental Conditions for Haynes Alloy "25"—Hydrogen-Oxygen Torch Experiments

Experiment Number	26	27	28	29	30	31	38	39	40	41	42	43	44	45
Adiabatic Flame Temperature, °F	4790	4790	4790	4790	4790	4790	4840	4840	4840	4840	4840	4840	4840	4790
Calculated Steady State Temperature, °F	2540	2670	2770	3000	2380	1810	2045	2135	2340	2495	2805	2920	2160	2380
O_2 Flow, liters/min	3.90	4.90	5.88	8.80	2.95	0.75	0.75	0.82	1.00	1.30	2.00	2.64	0.93	2.95
H_2 Flow, liters/min	4.00	5.00	6.00	9.00	3.00	0.76	2.27	2.46	3.00	4.00	6.00	8.00	2.80	3.00
O_2/H_2 Ratio	0.98	0.98	0.98	0.98	0.98	0.98	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.98
Initial Heat Flux, Btu/ft^2-sec	63.8	79.5	93.5	137.2	47.5	16.5	25.6	29.7	44.0	59.2	99.0	119.7	31.0	47.5
Total Run Time, sec	360	378	428	70.5	360	360	360	360	360	360	216	77	1200	1200
Surrounding Atmosphere	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air
Equilibrium Flame Composition														
X_{O_2}*	0.270	0.270	0.270	0.270	0.270	0.270	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.270
X_{H_2}	0.034	0.034	0.034	0.034	0.034	0.034	0.312	0.312	0.312	0.312	0.312	0.312	0.312	0.034
X_{H_2O}	0.516	0.516	0.516	0.516	0.516	0.516	0.533	0.533	0.533	0.533	0.533	0.533	0.533	0.516
X_{OH}	0.110	0.110	0.110	0.110	0.110	0.110	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.110
X_H	0.022	0.022	0.022	0.022	0.022	0.022	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.022
X_O	0.044	0.044	0.044	0.044	0.044	0.044	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.044

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*X = Mole Fraction

Haynes 25 in fuel-rich flames (H_2O vapor the only reactant) and the behavior of this alloy in oxygen-rich flames (where both water and oxygen were present in appreciable concentrations).

In experiments in which the Haynes 25 samples melted, there still appeared to be little evidence for rapid heating due to surface reaction, and there certainly was no evidence of a transition to a rapid vapor phase combustion in any of the experiments which were conducted. Experiment 29 (Figure 25) was typical of the experiments in which the sample melted. The measured temperatures were at most a few hundred degrees above the calculated temperatures and there was no sparking or bubbling as was observed in the stainless steel experiments.

Figure 26 shows a photograph of a Haynes 25 test specimen after exposure for 20 minutes to a fuel-rich hydrogen-oxygen flame at a specimen temperature of approximately 2350°F (experiment number 44). As can be seen from this photograph, there was considerably scaling of the sample and some erosion of the top of the sample. The test specimen from experiment 44 was sectioned, polished, etched and examined microscopically. Figure 27 shows a photomicrograph of an unreacted Haynes 25 sample and Figure 28 shows a photomicrograph of the sectioned test specimen from experiment 44. There does not appear to be any evidence of internal oxidation of the test specimen and it would appear that oxidation was limited to scaling and erosion of the external surface.

3.2.4 The Behavior of Haynes Alloy 25 in the CO-O_2 Flame System

Several experiments were completed in which Haynes 25 cylinders were exposed to carbon monoxide-oxygen flame environments which were thermochemically defined. Experiments were conducted in fuel-rich flames in which carbon monoxide and carbon dioxide were the principle combustion species and in oxygen-rich flames which contained significant concentrations of oxygen as well as carbon monoxide and carbon dioxide. Table 5 presents the experimental conditions for each of the carbon monoxide-oxygen flame tests. Tables A-46 to A-52 of the appendix summarize the measured temperature versus time data and estimated corrosion rates for each experiment.

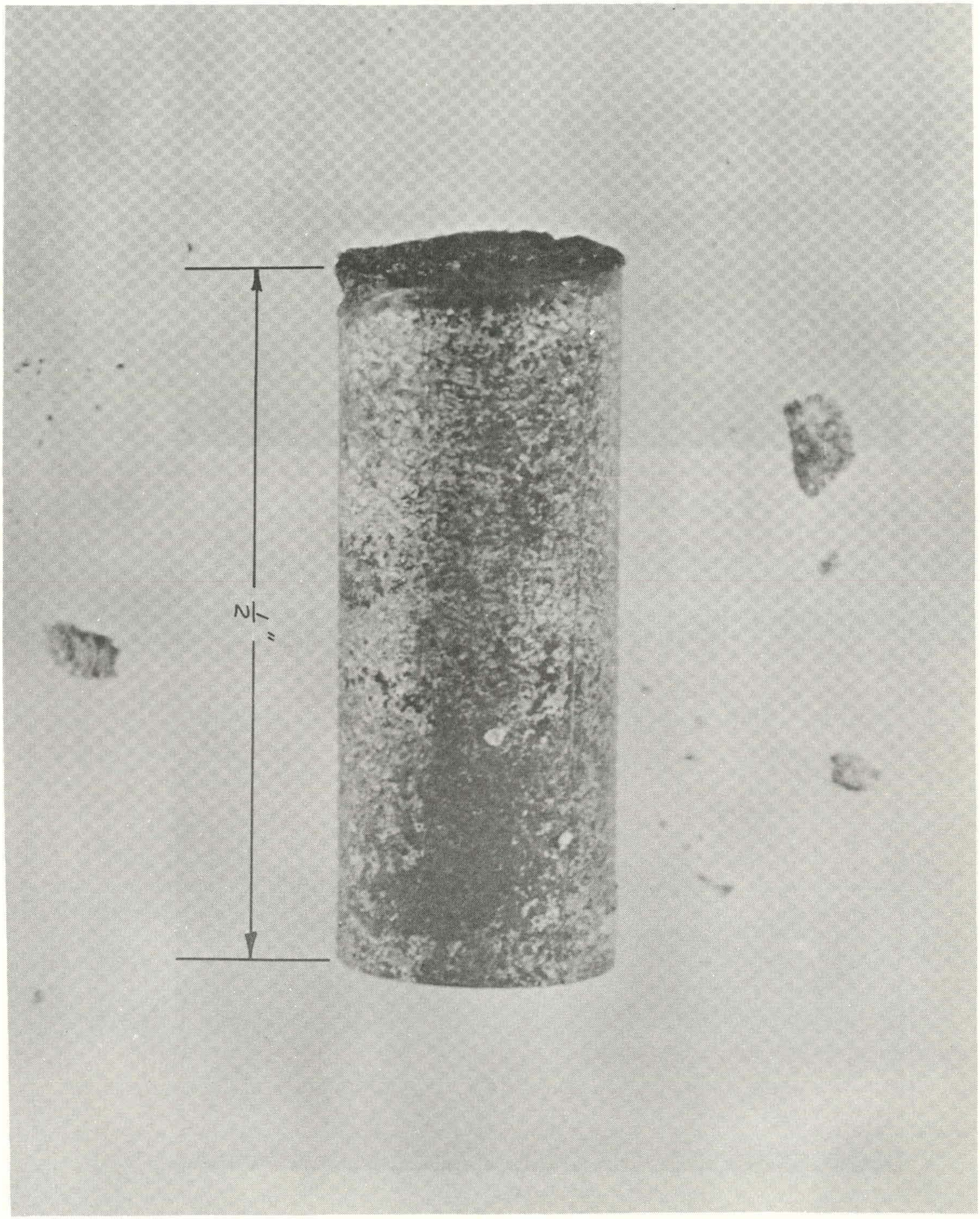

Figure 26. Experiment No. 44

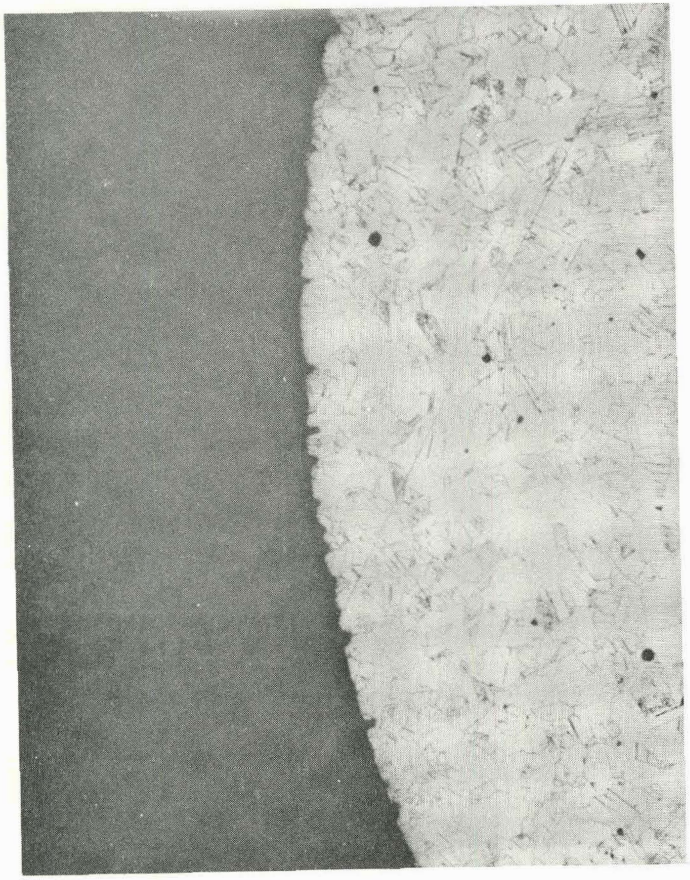

Figure 27. Unreacted Haynes 25 Sample 80 X

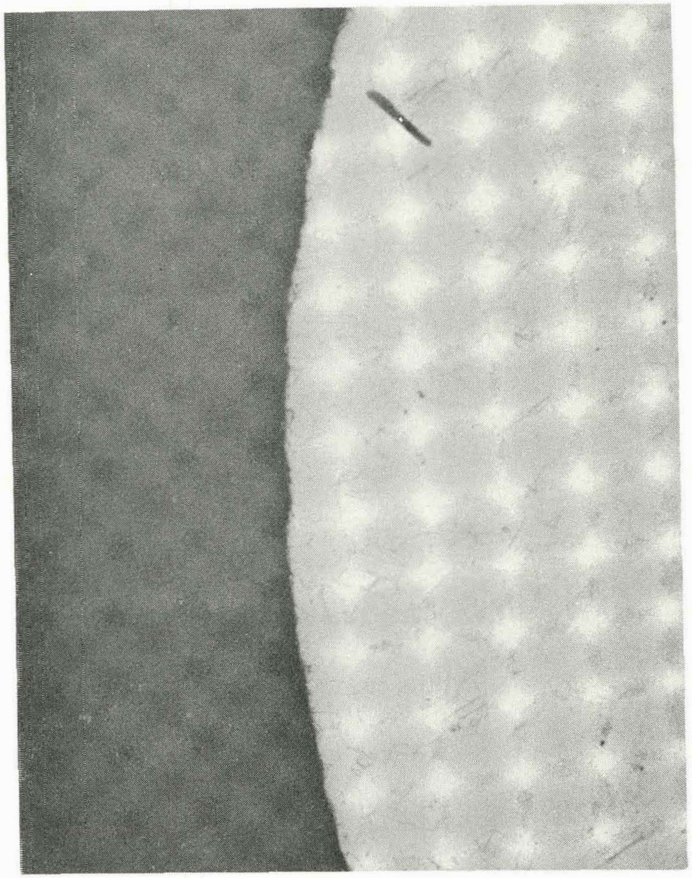

Figure 28. Sectional Haynes 25 Specimen After Experiment 44

Table 5. Experimental Conditions for Haynes Alloy "25" Carbon Monoxide-Oxygen Torch Experiments

Experiment Number	122	123	124	125	126	127	128
Adiabatic Flame Temperature, ^{o}F	4655	4655	4655	4655	4890	4890	4890
Calculated Steady State Temperature, ^{o}F	2085	2015	2085	2085	2000	2080	2165
O_2 Flow, liters/min	1.98	1.76	1.98	1.98	2.40	3.00	3.6
CO Flow, liters/min	9.00	8.00	9.00	9.00	4.00	5.00	6.00
O_2/CO Ratio	0.22	0.22	0.22	0.22	0.60	0.60	0.60
Initial Heat Flux, Btu/ft^2-sec	28.45	25.00	28.45	28.45	24.20	28.19	32.50
Total Run Time, sec	360	360	360	1200	360	360	360
Surrounding Atmosphere	Air	Air	Air	Air	Air	Air	Air
Equilibrium Flame Composition							
X_{CO}*	0.586	0.586	0.586	0.586	0.304	0.304	0.304
X_{CO_2}	0.392	0.392	0.392	0.392	0.458	0.458	0.458
X_O	0.008	0.008	0.008	0.008	0.045	0.045	0.045
X_{O_2}	0.015	0.015	0.015	0.015	0.193	0.193	0.193

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*X = Mole Fraction

Figure 29 compares the experimental and calculated temperature versus time data for a fuel-rich and an oxygen-rich experiment. The oxygen-rich experiment has a surface temperature somewhat higher than the fuel-rich experiment even though the calculated temperatures for the two experiments were nearly the same (80°F apart). This would indicate somewhat faster surface reaction (and hence higher surface heat generation) in the oxygen-rich experiment. Further evidence of a more rapid reaction in the oxygen-rich flames can be seen from Table 6 which lists the apparent corrosion rates and sample temperatures for all of the experiments. The corrosion rate data (calculated from initial and final sample weights) for these experiments should be meaningful, since all experiments were run at temperatures below the alloy melting point and there was no appreciable spalling of scales from the sample surfaces. As can be seen from Table 6, the apparent corrosion rates in the oxygen-rich flames ($O_2/CO = 0.6$) was much greater than in the fuel-rich flames.

Table 6. Apparent Corrosion Rates For Haynes Alloy 25 in Carbon Monoxide-Oxygen Flame Environments

Experiment Number	Peak Sample Temperature (°F)	O_2-CO Mole Ratio	Apparent Corrosion Rate Weight Gain (mg/cm^2-hr)
122	2143	0.22	5.2
123	2110	0.22	3.5
124	2152	0.22	1.0
125	2209	0.22	.07
126	2209	0.60	35.7
127	2295	0.60	27.9
128	2480	0.60	72.3

Figure 30 shows a photograph of the Haynes 25 sample after exposure to the oxygen-rich carbon monoxide-oxygen flame at 2295°F for 6 minutes. This sample had quite an extensive scale on the outside of the cylinder. A photomicrograph of the sectioned sample also showed some internal oxidation (Figure 31).

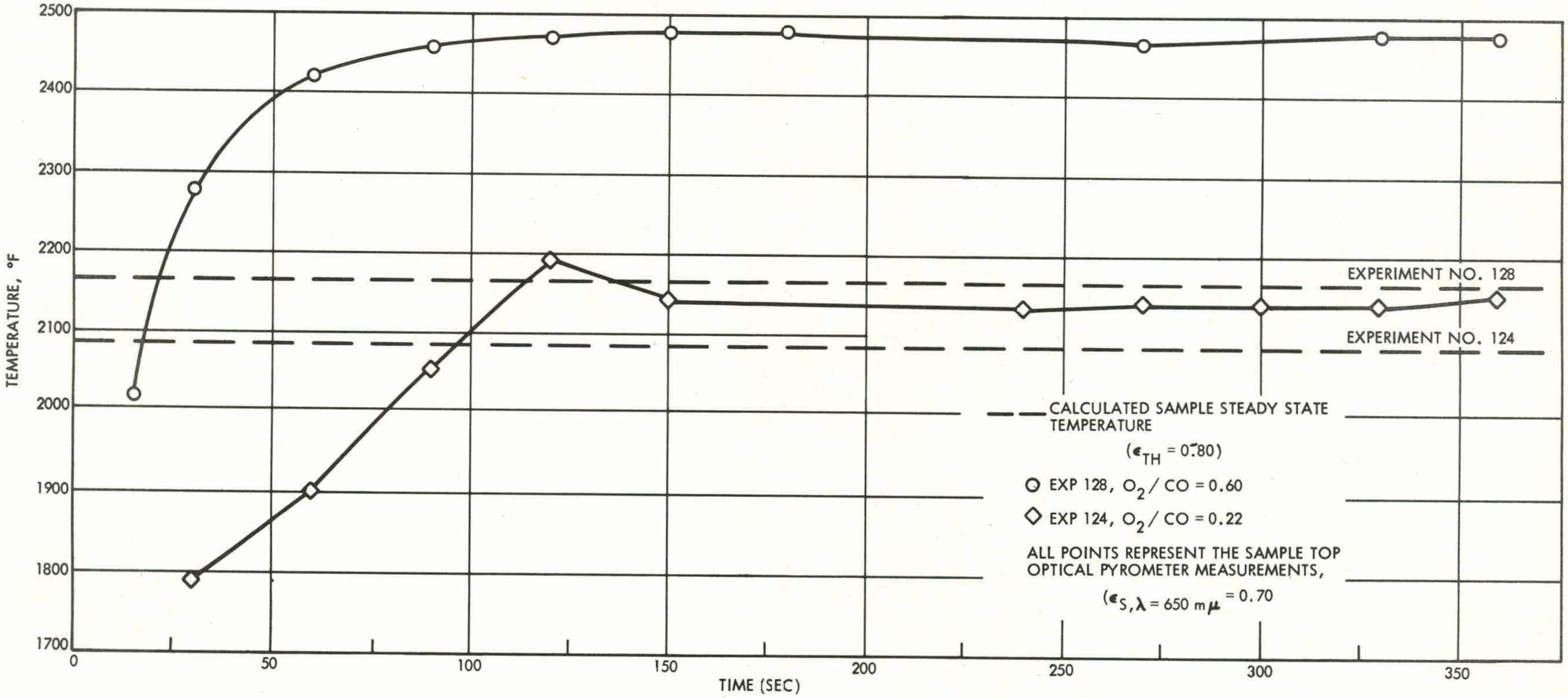

Figure 29. Temperature Time Data for Haynes Alloy 25 in a Carbon Monoxide-Oxygen Flame Environment

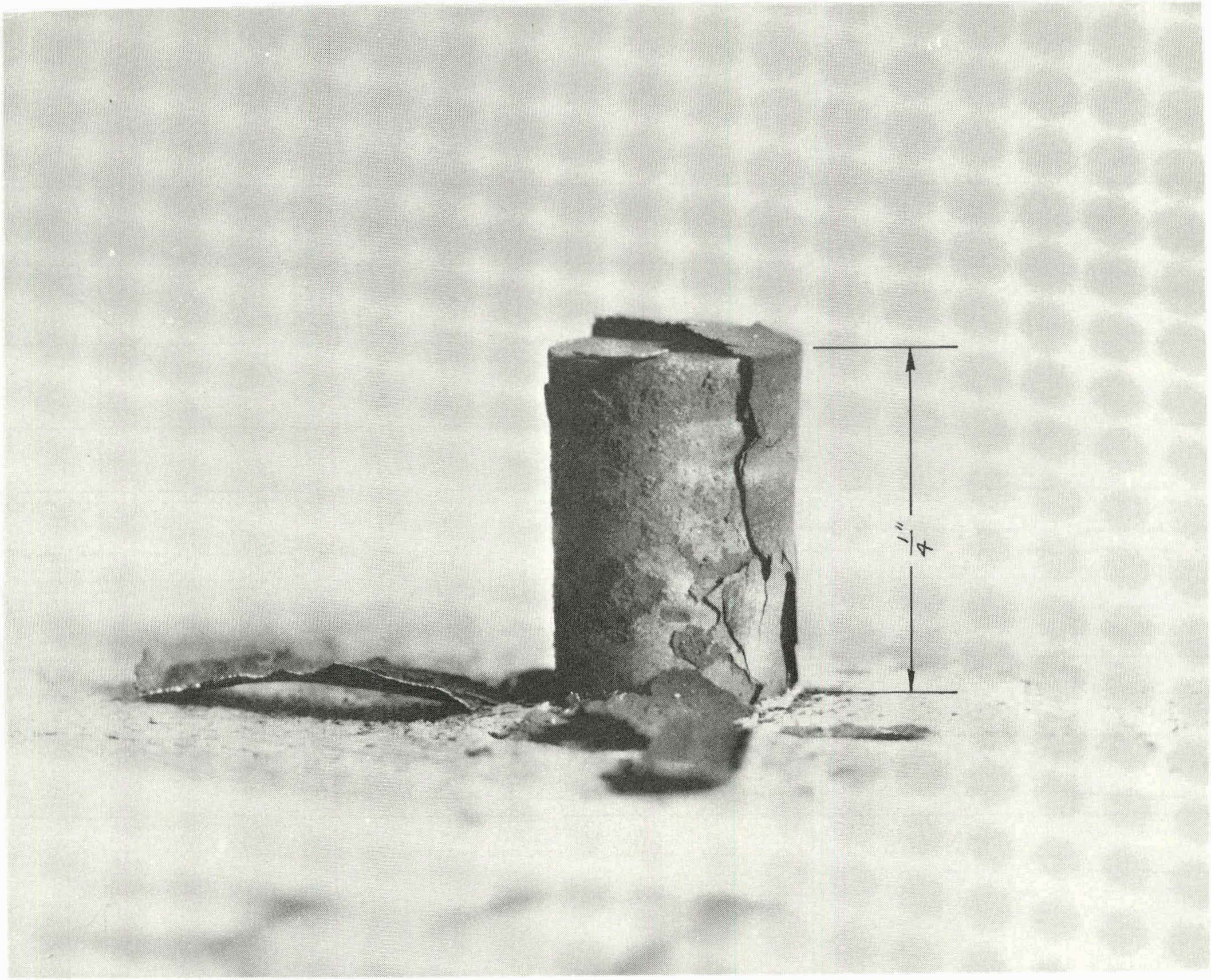

Figure 30. Experiment No. 127

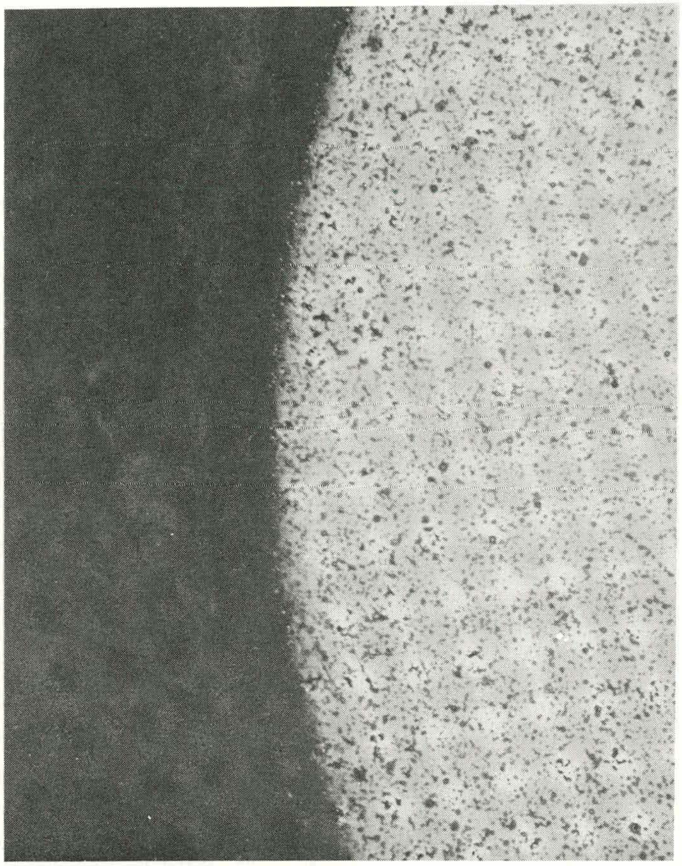

Figure 31. Sectioned Sample of Haynes 25
After Experiment No 127 80 X

Figure 32 shows a photograph of the test sample from fuel-rich experiment number 124. This sample was exposed to the fuel-rich flame for 6 minutes at 2143°F. Relatively little external oxidation was apparent, and the sectioned sample showed no indication of internal oxidation.

3.2.5 The Behavior of Hastelloy C and Hastelloy X in the H_2-O_2 Flame System

A number of experiments were conducted in which cylindrical samples of Hastelloy alloy C and Hastelloy alloy X were exposed to the H_2-O_2 flame under both fuel-rich and oxygen-rich conditions. The two alloys are being considered together, rather than separately, because the same test matrix was conducted with each alloy and the test results with thc two alloys were nearly identical. The experimental procedures were the same as previously described for the type 304 stainless steel experiments (section 3.2.1). Table 7 lists the detailed conditions for each experiment with Hastelloy C and Table 8 presents the same information for the experiments with Hastelloy X. Tables A-53 to A-66 of the appendix list the detailed temperature versus time data for the experiments with Hastelloy C while Tables A-67 to A-80 present the same information for the Hastelloy X tests.

Figure 33 compares the measured and calculated temperature versus time data for several experiments with Hastelloy C in both fuel-rich and oxygen-rich flames. In all cases, the measured sample temperatures agreed quite closely with the calculated temperatures (±150°F) indicating no significant surface heat input due to reaction. Even in experiments in which the sample melted (experiment 57) there was no indication of rapid surface heating or ignition of the sample. There was no real evidence of any difference between the interaction of Hastelloy C with the fuel-rich flame and the interaction with the oxygen-rich environment.

Figure 34 presents a plot of the calculated and measured temperature versus time data for several experiments with Hastelloy X. The results are very similar to those obtained in the Hastelloy C - H_2-O_2 flame experiments. The measured and calculated sample temperatures agreed rather well (±100°F) and there was no tendency for the samples to ignite or combust in the vapor phase even when heated above the melting range. The samples appeared to behave in approximately the same manner in both fuel-rich and oxygen-rich flames.

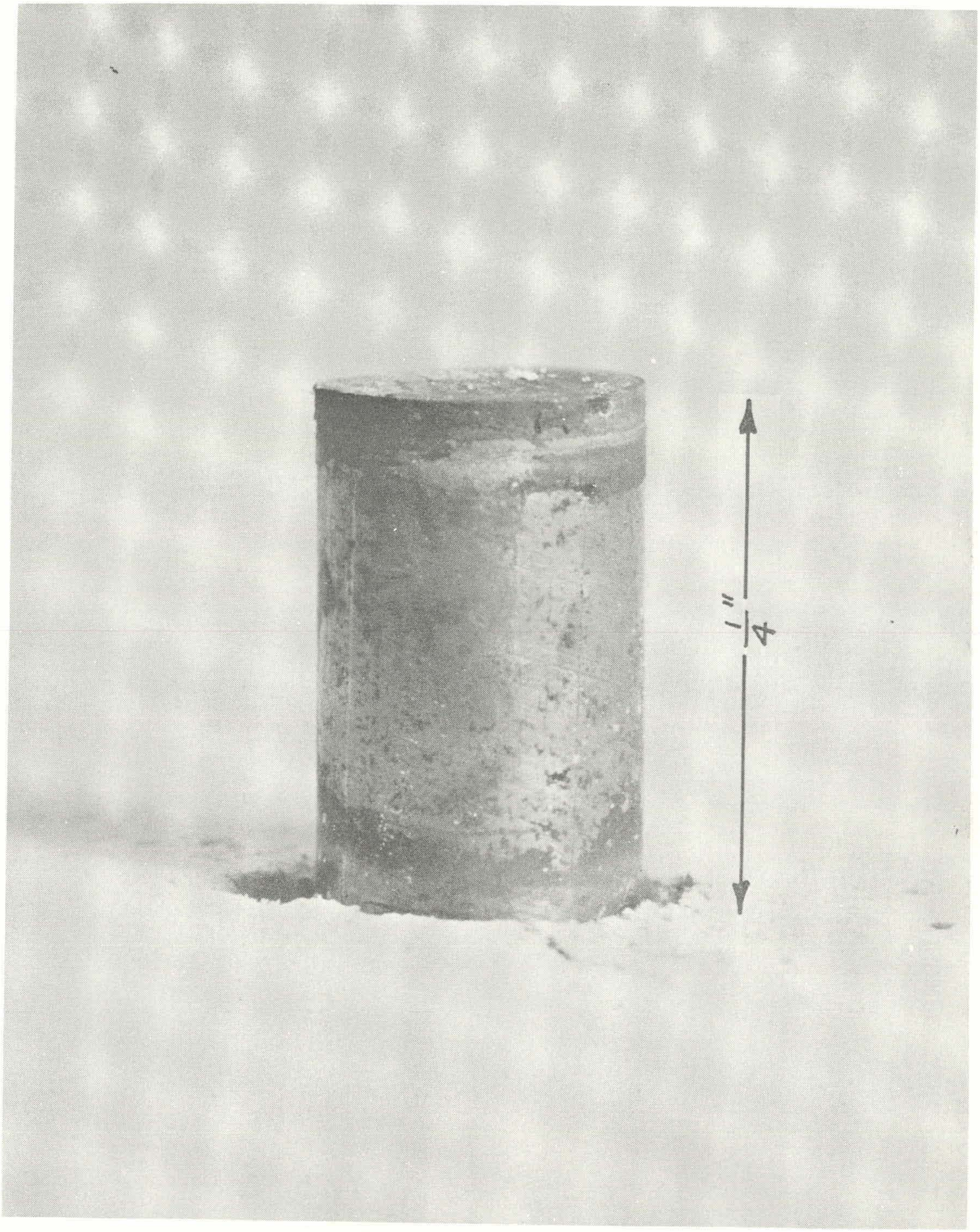

Figure 32. Experiment No. 124

Table 7. Conditions of Hastelloy Type C Torch Experiments — Hydrogen-Oxygen Flame

Experiment Number	46	47	48	49	50	51	52	53	54	55	56	57	58	59
Adiabatic Flame Temperature, °F	4790	4790	4790	4790	4790	4790	4840	4840	4840	4840	4840	4840	4790	4840
Calculated Steady State Temperature, °F	1810	2380	2540	2670	2770	3000	2045	2135	2340	2495	2805	2920	2540	2340
O_2 Flow, liters/min	0.75	2.95	3.90	4.90	5.88	9.80	0.75	0.82	1.00	1.30	2.00	2.64	3.90	1.0
H_2 Flow, liters/min	0.76	3.00	4.00	5.00	6.00	9.00	2.27	2.46	3.00	4.00	6.00	8.00	4.00	3.0
O_2/H_2 Ratio	0.98	0.98	0.98	0.98	0.98	0.98	0.33	0.33	0.33	0.33	0.33	0.33	0.98	0.33
Initial Heat Flux, Btu/ft^2-sec	16.5	45.9	63.8	79.5	93.5	137.2	25.6	29.7	44.0	59.2	99.0	119.7	63.8	44
Total Run Time, sec	360	360	360	360	360	36	360	360	360	360	63	42	1200.	1200
Surrounding Atmosphere	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air
Equilibrium Flame Compositions														
X_{O_2}*	0.270	0.270	0.270	0.270	0.270	0.270	0.006	0.006	0.006	0.006	0.006	0.006	0.270	0.006
X_{H_2}	0.034	0.034	0.034	0.034	0.034	0.034	0.312	0.312	0.312	0.312	0.312	0.312	0.034	0.312
X_{H_2O}	0.516	0.516	0.516	0.516	0.516	0.516	0.533	0.533	0.533	0.533	0.533	0.533	0.516	0.533
X_{OH}	0.110	0.110	0.110	0.110	0.110	0.110	0.052	0.052	0.052	0.052	0.052	0.052	0.110	0.052
X_H	0.022	0.022	0.022	0.022	0.022	0.022	0.088	0.088	0.088	0.088	0.088	0.088	0.022	0.088
X_O	0.044	0.044	0.044	0.044	0.044	0.044	0.009	0.009	0.009	0.009	0.009	0.009	0.044	0.009

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*X = Mole Fraction

Table 8. Conditions of Hastelloy Type X Torch Experiments—Hydrogen-Oxygen Flame

Experiment Number	60	61	62	63	64	65	66	67	68	69	70	71	72	73
Adiabatic Flame Temperature, °F	4790	4790	4790	4790	4790	4790	4840	4840	4840	4840	4840	4840	4790	4840
Calculated Steady State Temperature, °F	1810	2380	2540	2670	2770	3000	2045	2135	2340	2495	2805	2920	2380	2340
O_2 Flow, liters/min	0.75	2.95	3.90	4.90	5.88	8.80	0.75	0.82	1.00	1.30	2.00	2.64	2.95	1.00
H_2 Flow, liters/min	0.76	3.00	4.00	5.00	6.00	9.00	2.27	2.46	3.00	4.00	6.00	8.00	3.00	3.00
O_2/H_2 Ratio	0.98	0.98	0.98	0.98	0.98	0.98	0.33	0.33	0.33	0.33	0.33	0.33	0.98	0.33
Initial Heat Flux, Btu/ft^2-sec	16.5	45.9	63.8	79.5	93.5	137.2	25.6	29.7	44.0	59.2	99.0	119.7	45.9	44.00
Total Run Time, sec	300	360	360	360	360	360	360	360	360	360	57	34.5	1200	1200
Surrounding Atmosphere	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air
Equilibrium Flame Compositions														
X_{O_2}*	0.270	0.270	0.270	0.270	0.270	0.270	0.006	0.006	0.006	0.006	0.006	0.006	0.270	0.006
X_{H_2}	0.034	0.034	0.034	0.034	0.034	0.034	0.312	0.312	0.312	0.312	0.312	0.312	0.034	0.312
X_{H_2O}	0.516	0.516	0.516	0.516	0.516	0.516	0.533	0.533	0.533	0.533	0.533	0.533	0.516	0.533
X_{OH}	0.110	0.110	0.110	0.110	0.110	0.110	0.052	0.052	0.052	0.052	0.052	0.052	0.110	0.052
X_H	0.022	0.022	0.022	0.022	0.022	0.022	0.088	0.088	0.088	0.088	0.088	0.088	0.022	0.088
X_O	0.044	0.044	0.044	0.044	0.044	0.044	0.009	0.009	0.009	0.009	0.009	0.009	0.044	0.009

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*X = Mole Fraction

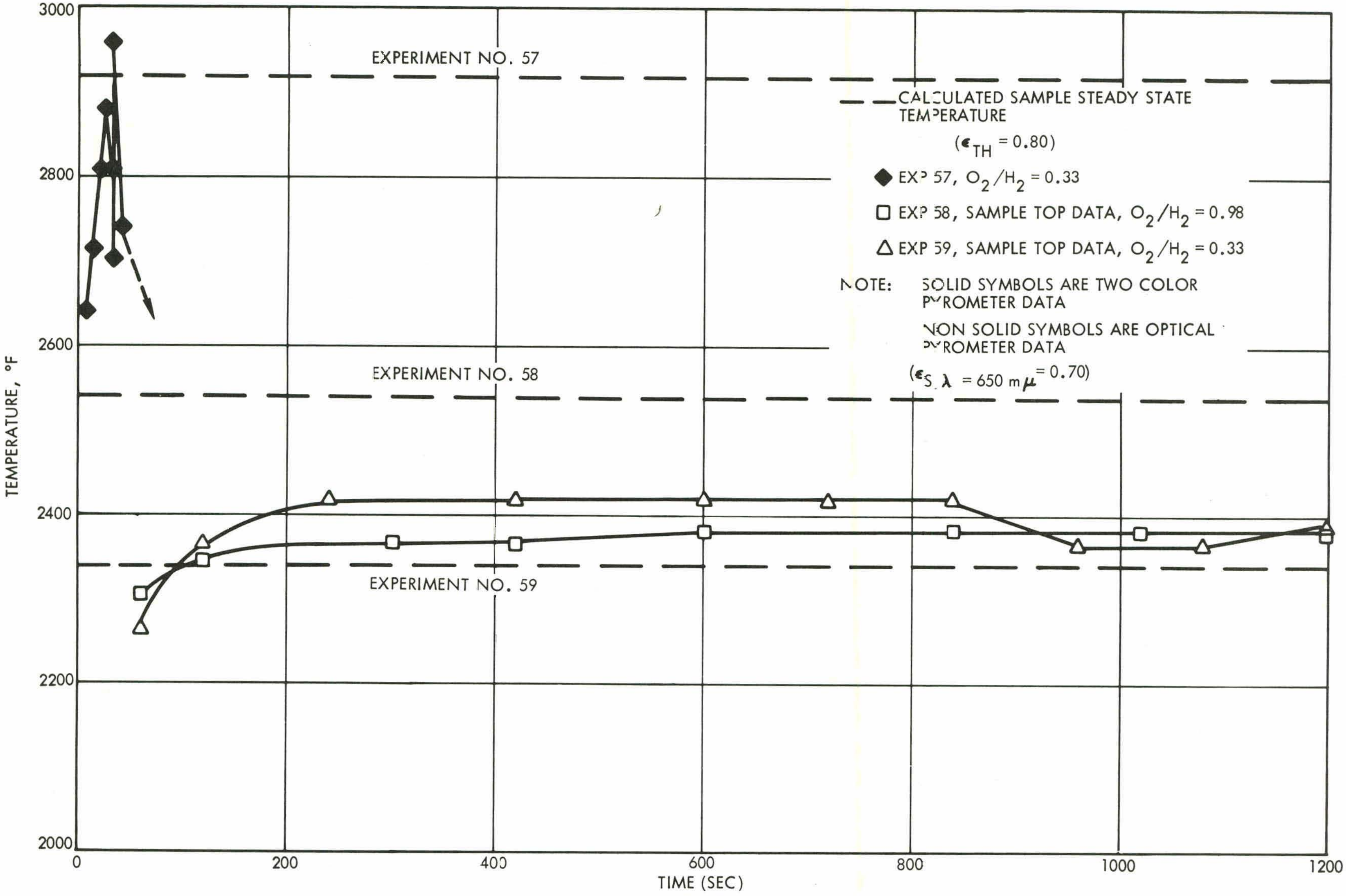

Figure 33. Temperature Time Data for Hastelloy C in a Hydrogen-Oxygen Flame Environment

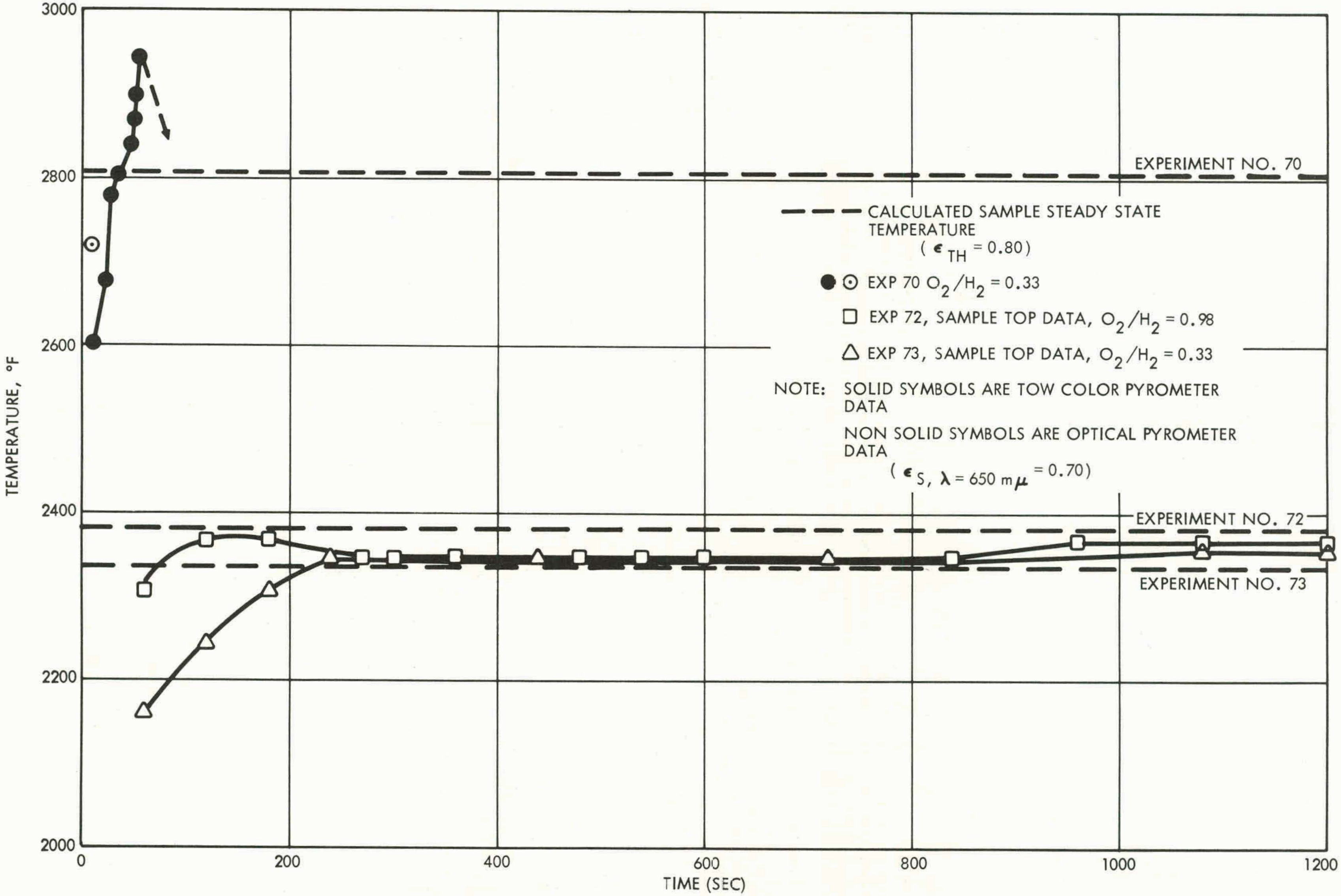

Figure 34. Temperature Time Data for Hastelloy X in a Hydrogen-Oxygen Flame Environment

Figure 35 shows a photograph of a Hastelloy C sample after exposure to the fuel-rich flame for 20 minutes at a peak temperature of 2418°F (experiment 59). As can be seen, there was an external oxide coating formed on the sample and some melting on the top. When this sample was sectioned, however, and observed microscopically, there was no evidence of internal oxidation. Figure 36 shows a photomicrograph of the test specimen from experiment 59.

Figure 38 shows a photograph of a Hastelloy X test sample after exposure for 20 minutes to the fuel-rich flame at peak temperatures of 2356°F. This sample showed very little external scaling and when sectioned showed no evidence of internal oxidation.

3.2.6 Behavior of Tungsten in the H_2-O_2 Flame System

Tungsten coupons (1 x 1/4 x 0.030 inch) were exposed to hydrogen-oxygen flame environments under both fuel-rich and oxygen-rich conditions. Table 9 details the conditions for each experiment. Tables A-81 to A-93 of the appendix presents the detailed temperature versus time measurements and the average reaction rate for each experiment. In the experiments with tungsten, the samples did not melt, and the oxide which formed (WO_3) was volatile and, hence, evaporated from the tungsten sample surface. Thus, the average reaction rates as calculated from initial and final sample weights gave meaningful indications of the rates at which oxidation was taking place.

Table 10 presents the average sample oxidation rates, peak sample temperatures, and flame conditions for the experiments conducted with tungsten coupons. As is apparent from this table, there was exceedingly rapid reaction of the tungsten with the H_2-O_2 flames, particularly in the cases in which both oxygen and water vapor were present in the flame environment in high concentrations ($O_2/H_2 = 0.98$). Indeed, in some of the experiments the tungsten coupons completely disappeared in a matter of a few seconds.

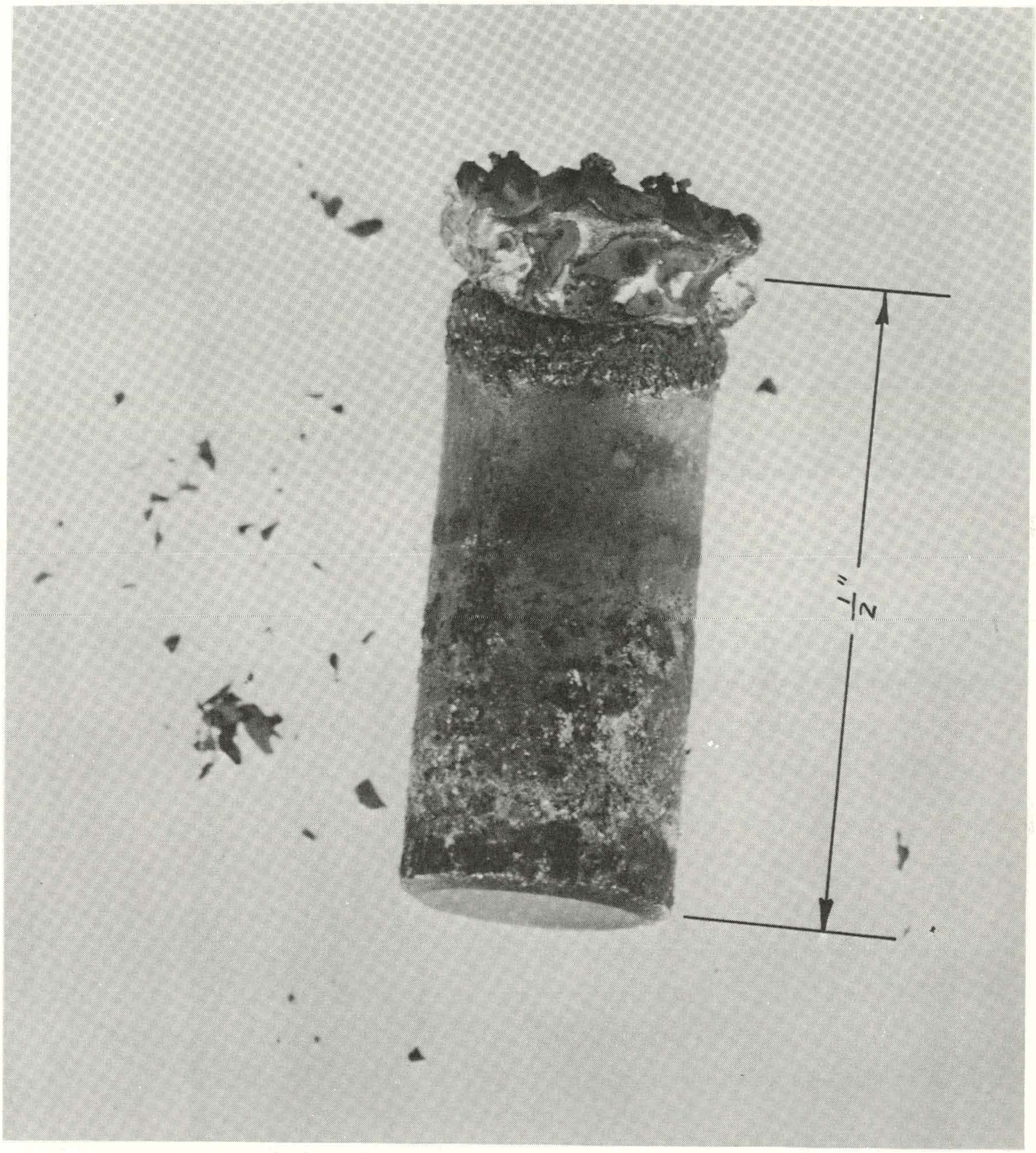

Figure 35. Experiment No. 59

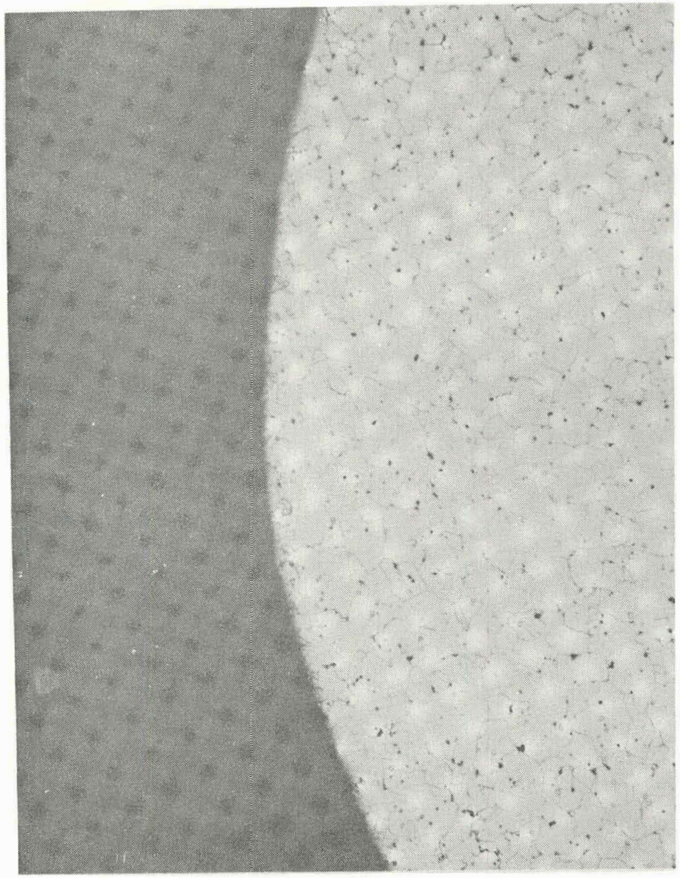

Figure 36. Unreacted Hastelloy C
Sample 80 X

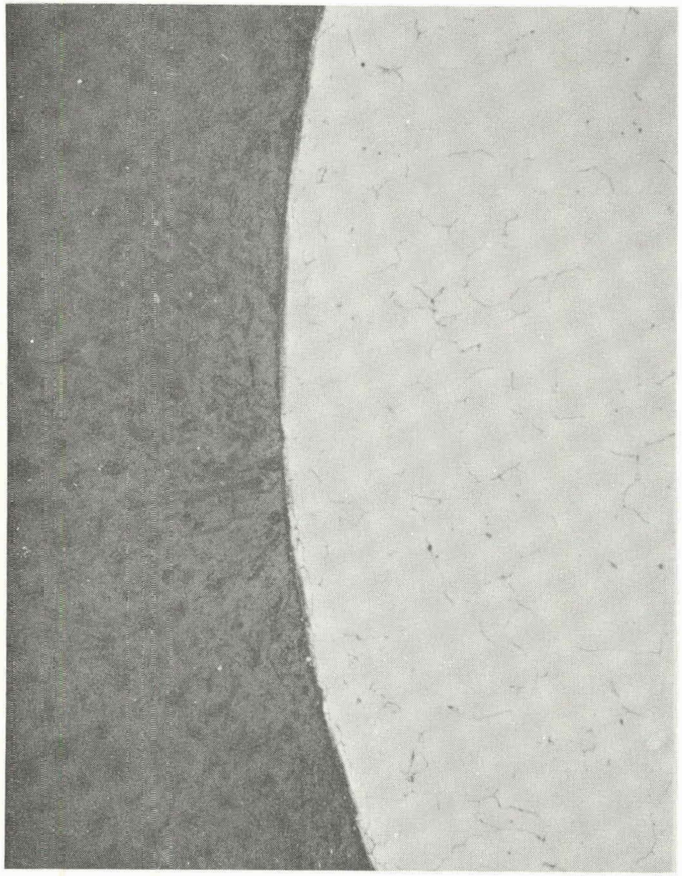

Figure 37. Photomicrograph of Test
Specimen from Experiment
No. 59 80 X

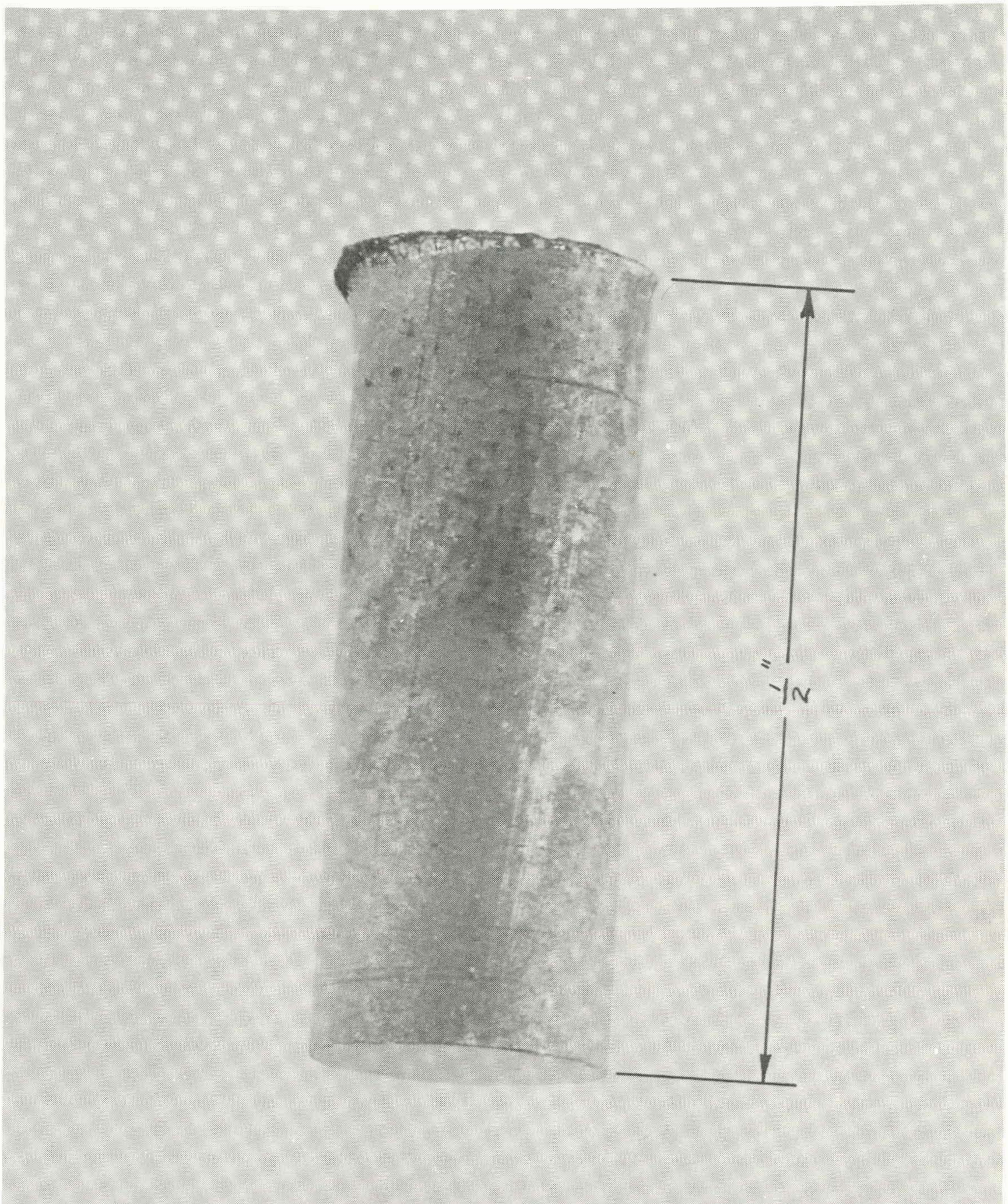

Figure 38. Experiment No. 73

Table 9. Conditions of Uncoated Tungsten Torch Experiments—Hydrogen-Oxygen Flame

Experiment Number	74	75	76	77	78	79	80	81	82	83	84	86	88
Adiabatic Flame Temperature, °F	4790	4790	4840	4840	4840	4790	4840	4840	4790	4790	4840	4790	4840
Calculated Steady State Temperature, °F	1970	2530	2110	2180	2385	2695	2555	2555	2830	2920	2980	2695	2695
O_2 Flow, liters/min	0.75	2.95	0.75	0.82	1.00	3.90	1.30	1.30	4.90	5.88	2.64	3.9	1.57
H_2 Flow, liters/min	0.76	3.00	2.27	2.46	3.00	4.00	4.00	4.00	5.00	6.00	8.0	4.0	4.72
O_2/H_2 Ratio	0.98	0.98	0.33	0.33	0.33	0.98	0.33	0.33	0.98	0.98	0.33	0.98	0.33
Initial Heat Flux, Btu/ft^2-sec	10.20	29.35	13.74	15.90	23.40	39.40	31.70	31.70	49.15	57.70	64.00	39.40	39.4
Total Run Time, sec	300	27	300	300	180	25	60	60	4.1	3.75	42	21.75	58
Surrounding Atmosphere	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air
Equilibrium Flame Composition													
X_{O_2}*	0.270	0.270	0.006	0.006	0.006	0.270	0.006	0.006	0.270	0.270	0.006	0.270	0.006
X_{H_2}	0.034	0.034	0.312	0.312	0.312	0.034	0.312	0.312	0.034	0.034	0.312	0.034	0.312
X_{H_2O}	0.516	0.516	0.533	0.533	0.533	0.516	0.533	0.533	0.516	0.516	0.533	0.516	0.533
X_{OH}	0.110	0.110	0.052	0.052	0.052	0.110	0.052	0.052	0.110	0.110	0.052	0.110	0.052
X_H	0.022	0.022	0.088	0.088	0.088	0.022	0.088	0.088	0.022	0.022	0.088	0.022	0.088
X_O	0.044	0.044	0.009	0.009	0.009	0.044	0.044	0.009	0.044	0.044	0.009	0.044	0.009

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*X = Mole Fraction

Table 10. Average Oxidation Rates for Tungsten Samples in the H_2-O_2 Flame System

Experiment Number	Peak Sample Temperature (°F)	O_2/H_2 Mole Ratio	Average Oxidation Rate Over the Duration of the Experiment (mg/cm^2-hr)
74	2180	0.98	-193
75	> 3600	0.98	-133,000
76	2660	0.33	-600
77	2700	0.33	-961
78	3200	0.33	-8,900
79	> 3600	0.98	-1,550,000
80	3038	0.33	-39,900
81	3400	0.33	-25,900
82	> 3600	0.98	---
83	> 3600	0.98	-115,000
84	> 3600	0.98	-700,000
86	> 3600	0.98	-1,728,000
88	> 3600	0.33	-35,800

Figure 39 shows the calculated and measured temperature versus time data for two experiments at the same heat flux (and, hence, the same calculated steady state temperature). Experiment 86 was conducted in the oxygen-rich flame environment ($O_2/H_2 = 0.98$) and experiment 88 in the fuel-rich flame ($O_2/H_2 = 0.33$). Both experiments showed peak sample temperatures which were at least 1000°F above the calculated sample temperature which assumes no heat due to reaction. In both experiments the high sample temperatures which were obtained were due to the extremely rapid exothermic oxidation of the tungsten samples in the flame environments. That is, the samples ignited in both the fuel-rich and oxygen-rich flames. In the oxygen-rich flame (experiment 86) sample temperatures were off-scale at several points (> 3600°F). Moreover, there was such a tremendous evolution of WO_3 smoke during this experiment that it was likely that the pyrometer was not actually seeing the surface of the sample itself but rather the somewhat cooler oxide smoke at some distance from the tungsten surface.

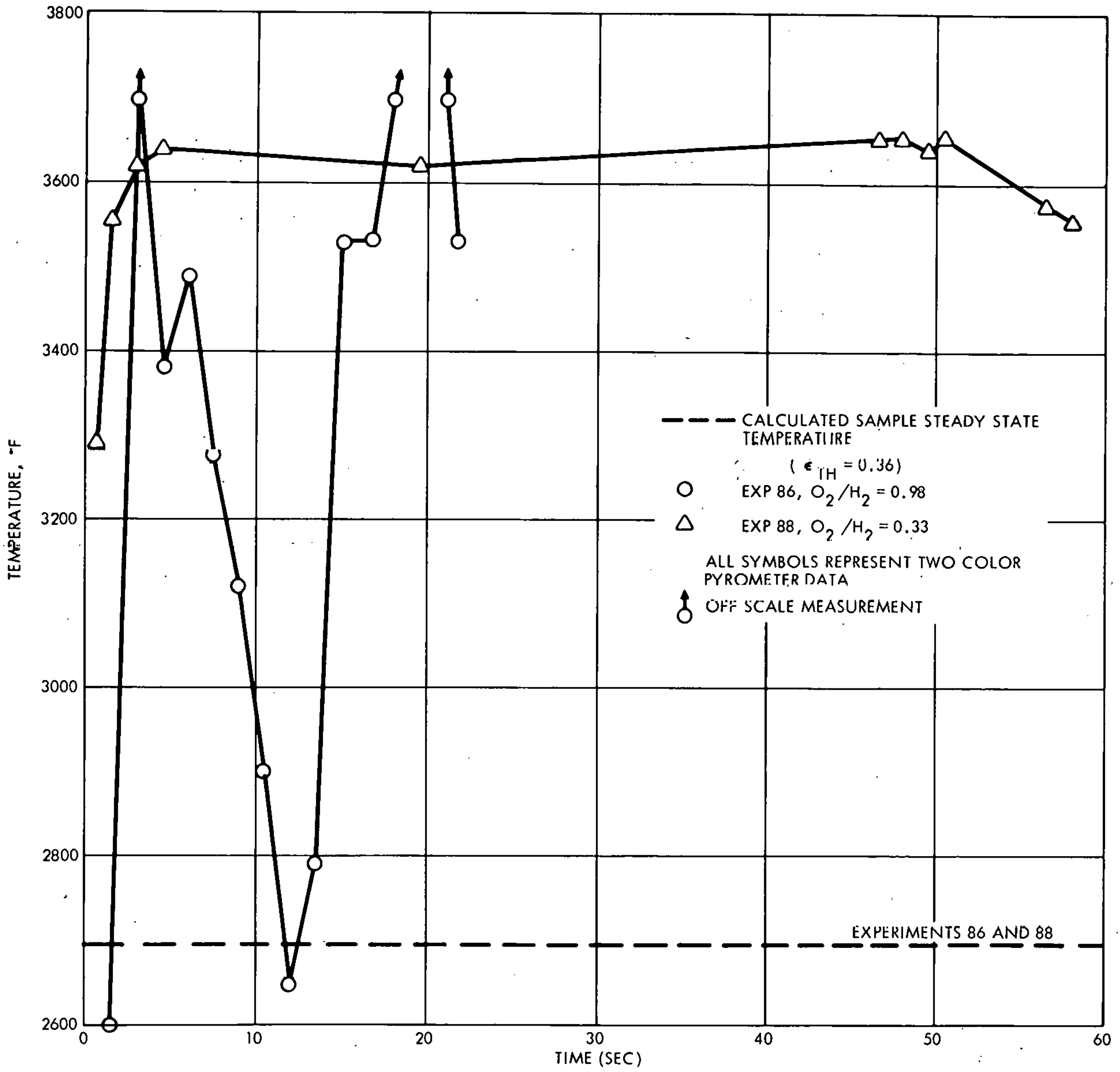

Figure 39. Temperature Time Data for Uncoated Tungsten in a Hydrogen-Oxygen Flame Environment

Hence, the actual surface temperature of the burning sample during experiment 86 may be considerably greater than was indicated in Figure 39. The combustion rate of the fuel-rich flame experiment (experiment 88) was much lower than the oxygen-rich flame experiment and the amount of oxide smoke formed was much smaller. Hence, for fuel-rich experiment number 88 it was likely that the measured temperatures actually were representative of surface temperatures.

Figure 40 shows a plot of the peak measured sample temperatures versus the calculated sample temperatures (which assume no heat generation due to surface reaction) for experiments in both the fuel-rich and oxygen-rich flames. It would appear that the tungsten samples had ignition temperatures in the hydrogen-oxygen flame environments of about 2200 to 2400°F.

Figure 41 shows a graph of the logarithm of the apparent corrosion rate versus the calculated sample temperature for experiments in the fuel-rich and oxygen-rich H_2-O_2 flames. At calculated temperature above the ignition temperature range (2200 to 2400°F) the samples exposed to the oxygen-rich flame oxidized at rates which varied from 0.5 to 1.5 orders of magnitude greater than the corresponding experiments in fuel-rich flames.

Figure 42 shows a photograph of an unreacted test specimen. Figure 43 shows a photograph of the test specimen after exposure to the fuel-rich flame for 180 seconds. The combustion rate was much slower in this experiment than in the oxygen-rich flame experiment (experiment 79). It is interesting to note how the tungsten oxide condensed around the sample in the fuel rich flame experiment (Figure 44). This type of condensation was not noted in the oxygen rich flame experiments.

Color motion pictures (64 frames per second) were taken in several of the experiments with tungsten samples. Figure 45 shows four selected frames from the motion picture taken of experiment number 86 (oxygen-rich flame; $O_2/H_2 = 0.98$). The frames were taken 1/4 second apart during the steady state combustion of the tungsten sample. It is apparent from these selected frames that a significant amount of sample oxidation took place within a time span of 1 second.

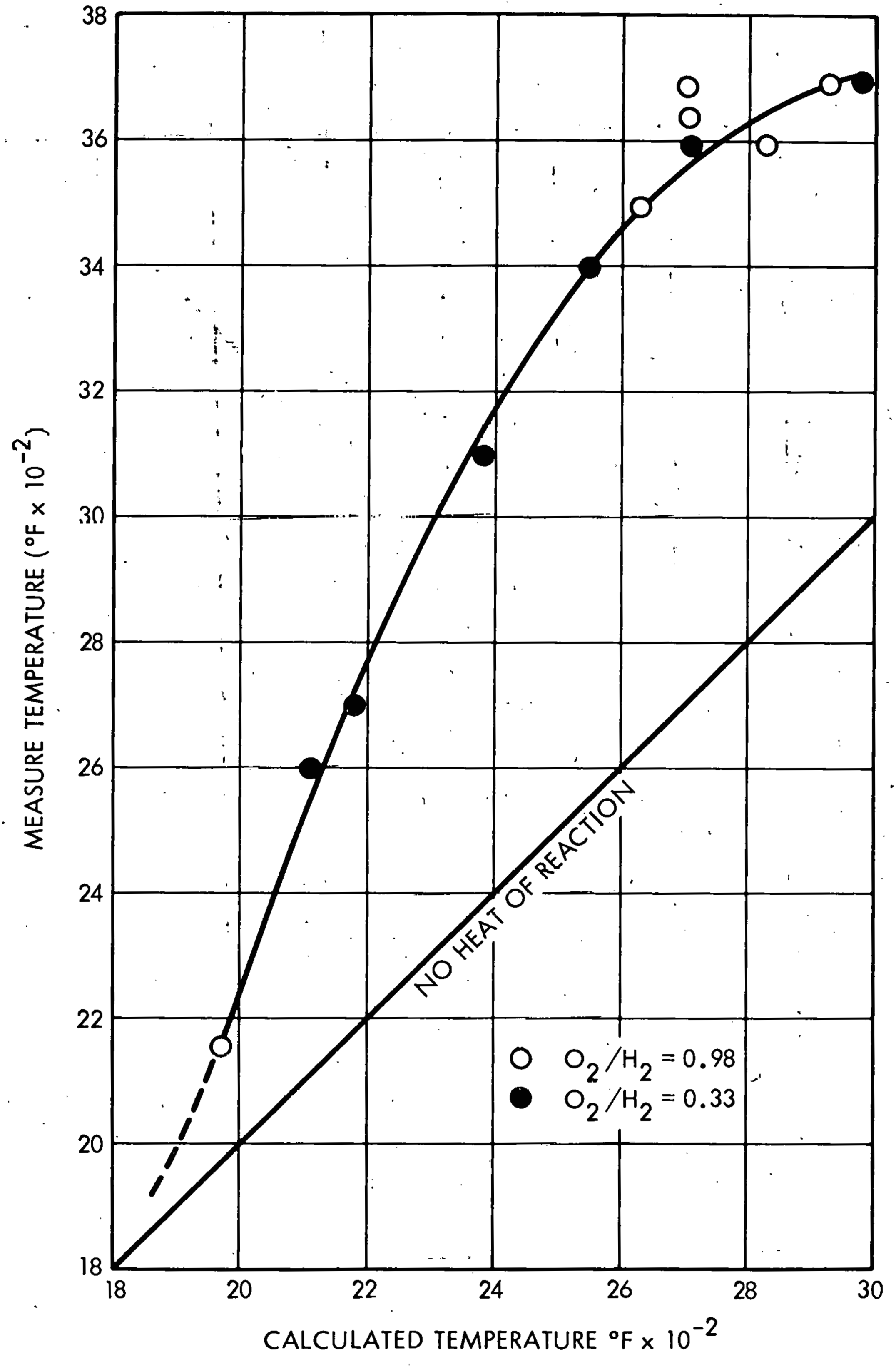

Figure 40. Measured Temperature versus Calculated Temperature for Tungsten Samples in a H_2-O_2 Flame

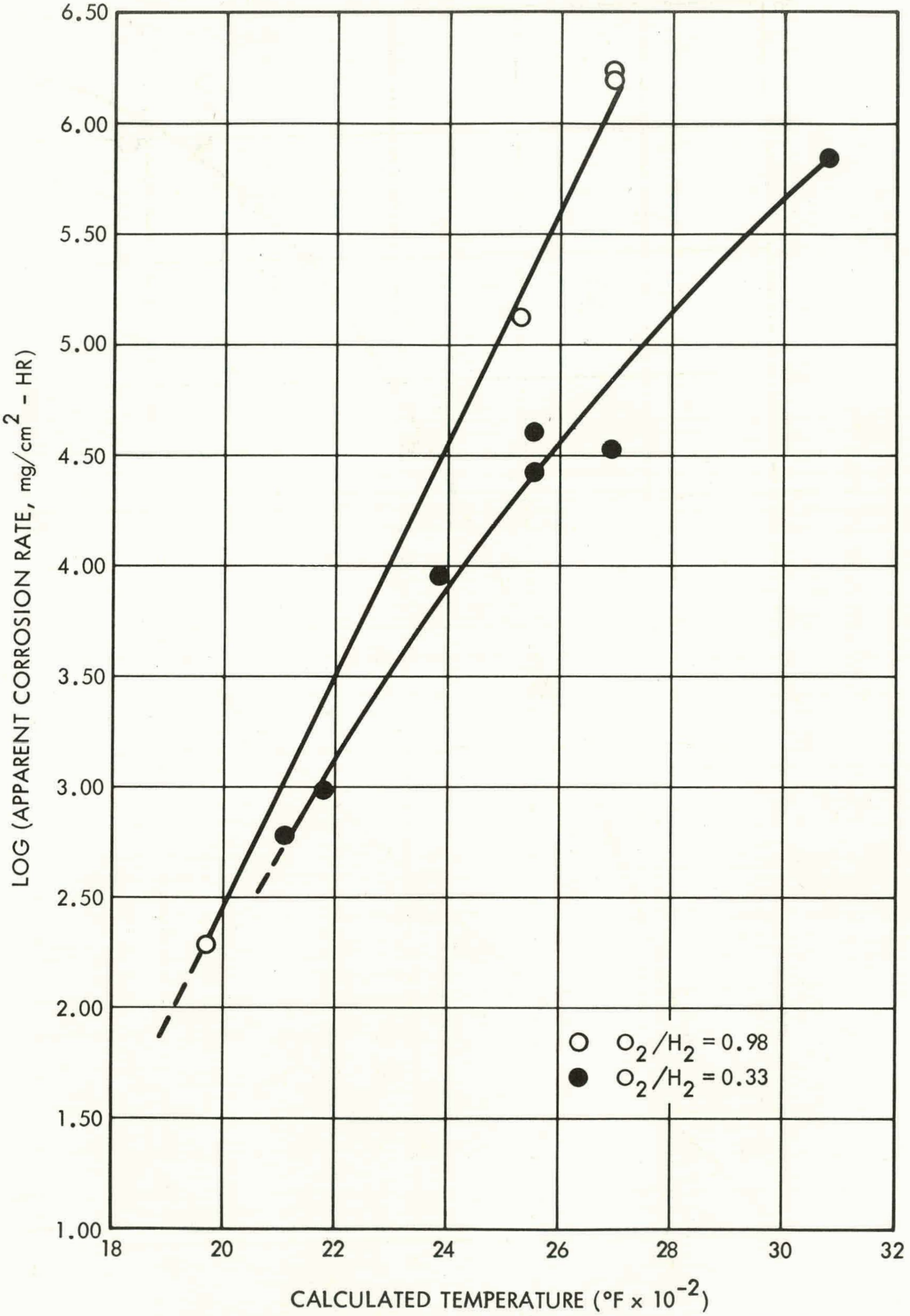

Figure 41. Apparent Tungsten Corrosion Rate as a Function of the Calculated Sample Temperature

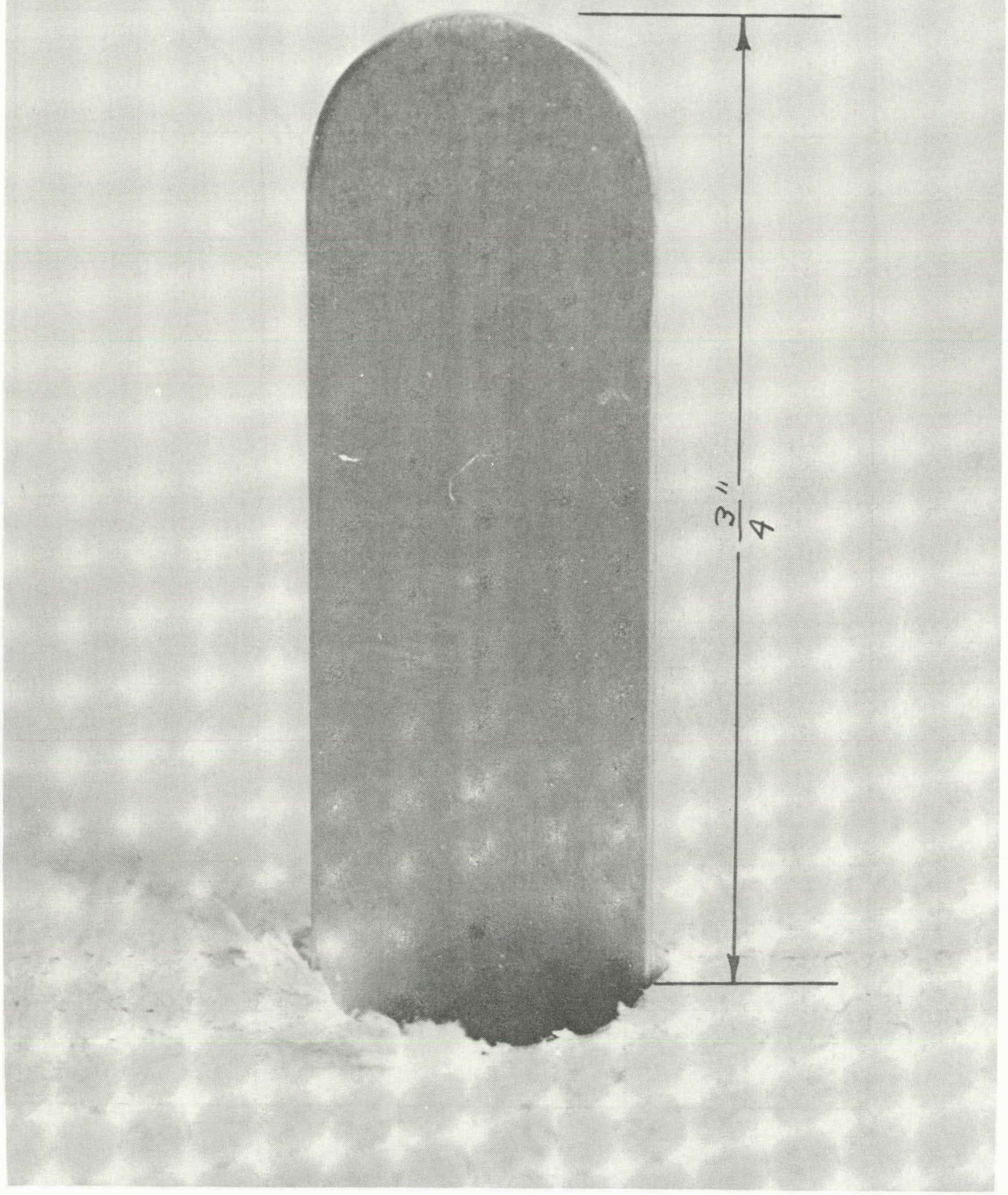

Figure 42. Unreacted Coupon Sample

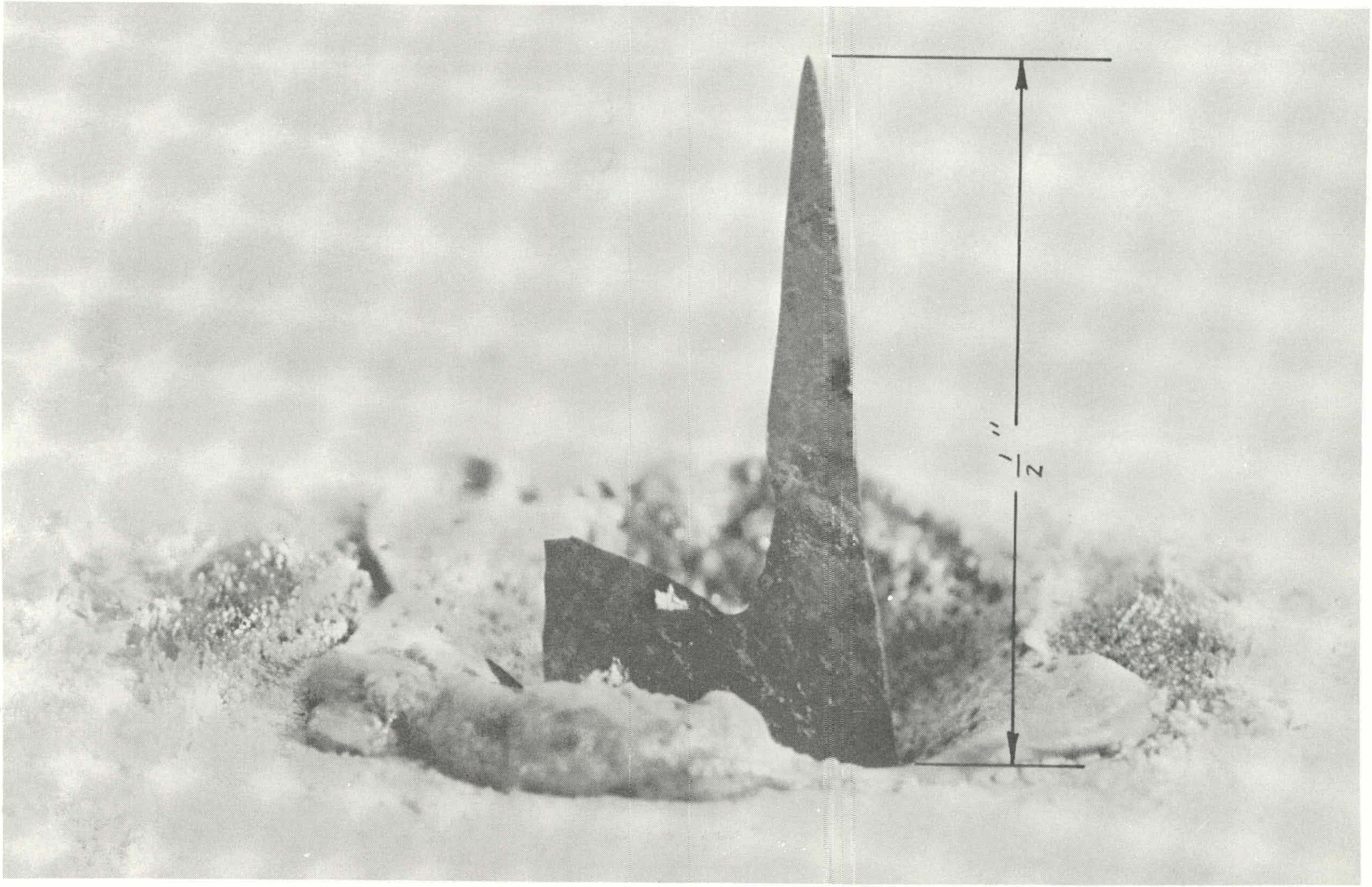

Figure 43. Experiment Nc 79

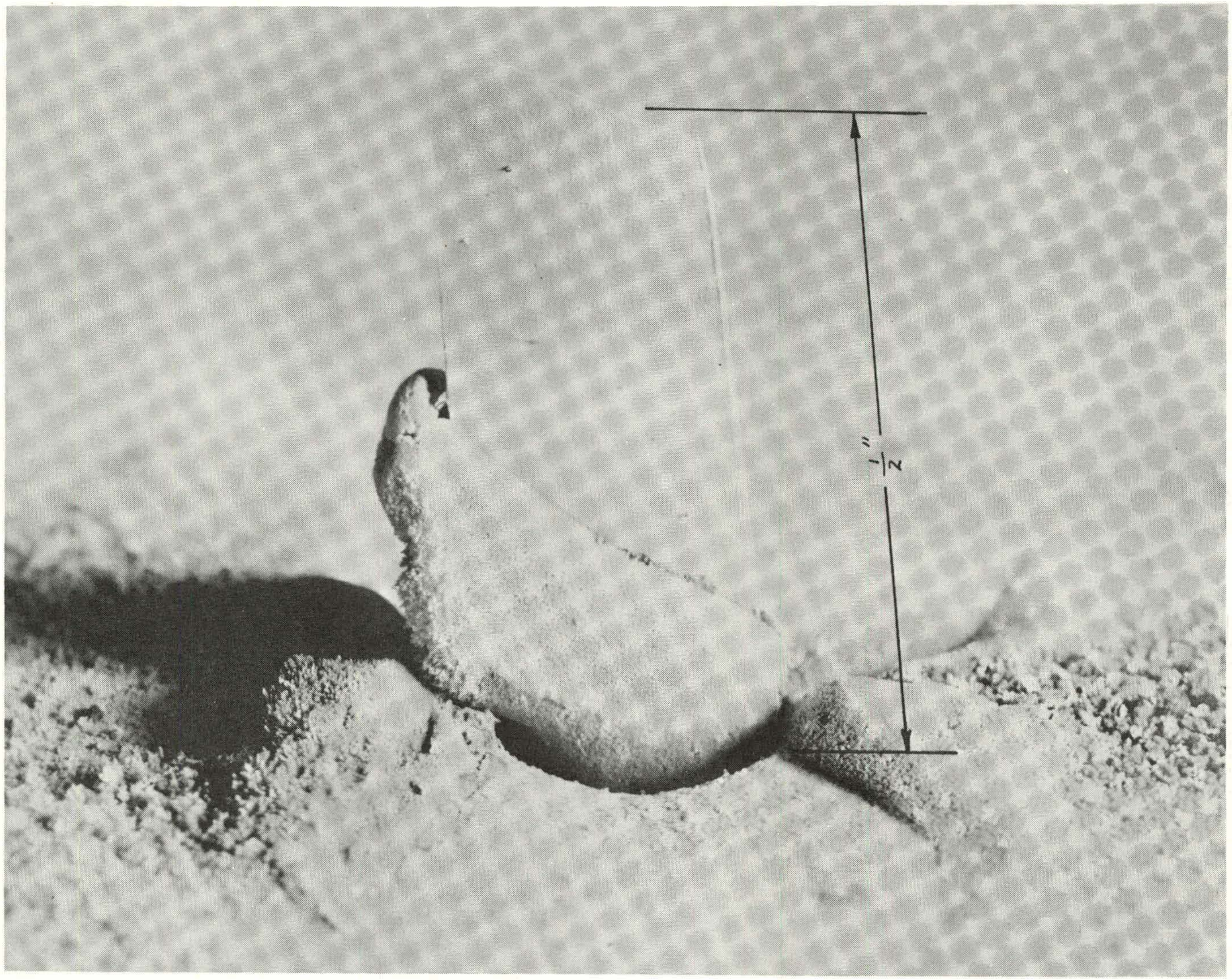

Figure 44. Experiment No. 78

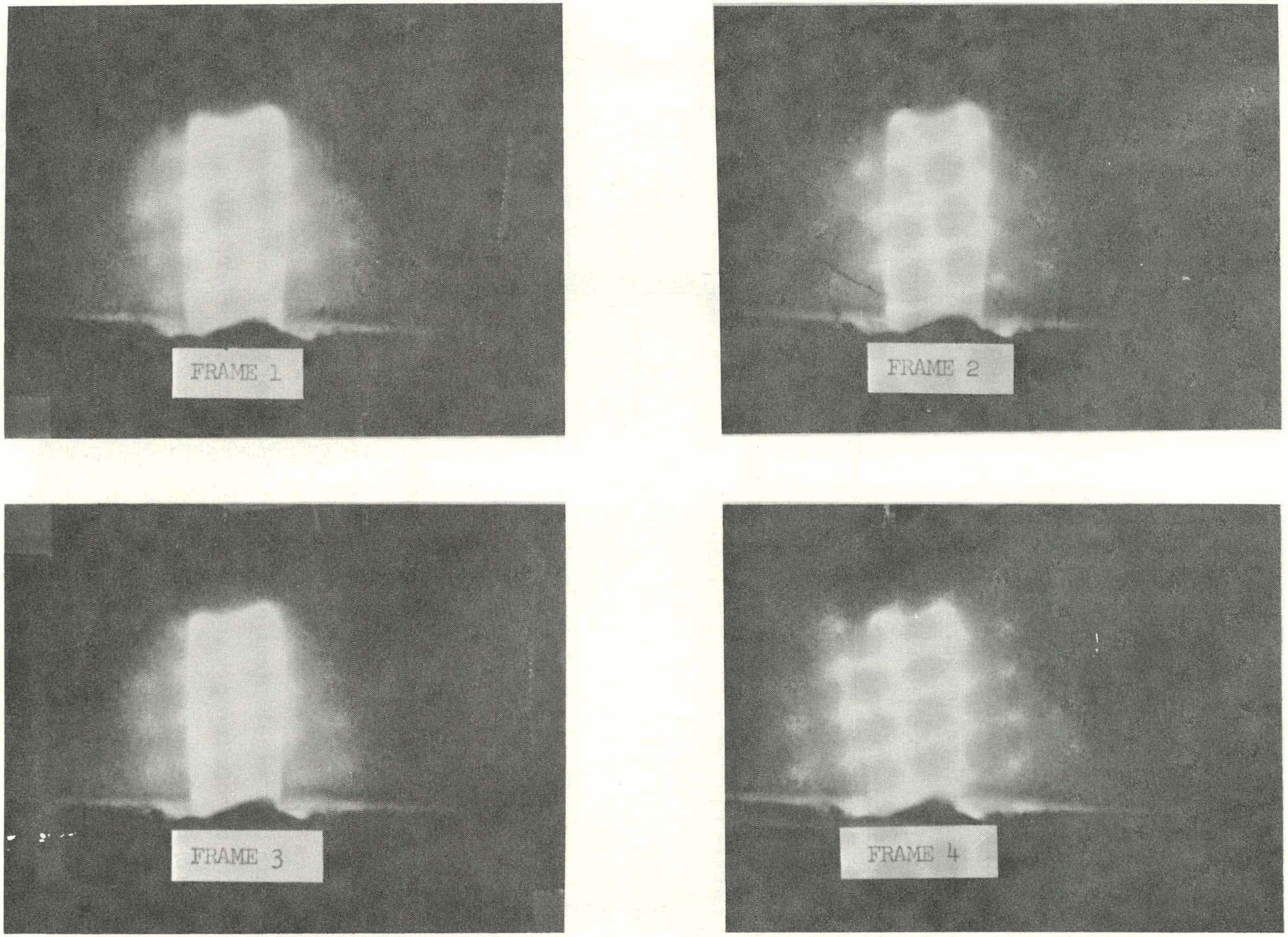

Figure 45. Selected Frames From 720 Motion Picture of the Combustion of Tungsten

3.2.7 The Behavior of Tantalum-10% tungsten in the H_2-O_2 Flame System

Test specimens (1 x 1/4 x 0.030 inch) of tantalum-10% Tungsten alloy (Fansteel Corporation) were exposed to hydrogen-oxygen flame environments in a manner analogous to the previously described experiments with pure tungsten. Table 11 presents the detailed experimental conditions for each test and Tables A-94 to A-110 present the measured temperature versus time data for each experiment.

Figure 46 shows the measured and calculated temperature versus time curves for three experiments which were all conducted at the same initial heat flux. In one of the experiments (experiment 104) the tantalum-10% tungsten sample was exposed to a fuel-rich flame (O_2/H_2 = 0.33) in which water vapor was the only reactive specie present. In the other two experiments (93 and 103) the samples were exposed to oxygen-rich flames (H_2/O_2 = 0.98) in which both water vapor and oxygen were present in high concentrations. All three experiments showed surface temperatures well in excess of the calculated surface temperature (which assumes no heat generation due to reaction) indicating that the samples had ignited.

The samples exposed to the oxygen-rich flames obtained much higher steady state temperatures (and, hence, much faster combustion rates) than samples exposed to the fuel-rich flame. Indeed, with the exception of experiments at the lowest heat fluxes, those samples which were exposed to the oxygen rich flames obtained sample temperatures which were off-scale on the low scale (2600 to 3700°F) of the two-color pyrometer. In experiment 92 the high scale (4000 to 6000°F) of the two-color pyrometer was used to measure the sample temperature. The peak two-color temperature reading for this experiment was 6000°F. There was some uncertainty in the validity of this temperature measurement, however, since it was not possible to check the calibration of the two-color pyrometer at temperatures as high as 6000°F. However, from observations of the reacted samples it would seem very likely that sample temperatures in excess of 4000°F were reached.

Table 11. Conditions of Tantalum-10 Percent Tungsten Torch Experiments—Hydrogen-Oxygen Flame

Experiment Number	89	90	91	92	93	94	95	96	97	98	99	100	101	102	104	103	105
Adiabatic Flame Temperature, °F	4790	4790	4790	4790	4840	4840	4840	4790	4790	4790	4840	4790	4840	4840	4840	4790	4790
Calculated Steady State Temperature, °F	1925	2465	2630	2630	2055	2125	2335	2200	2125	2155	2505	2630	2810	2925	2630	2630	2630
O_2 Flow, liters/min	0.75	2.95	3.90	3.90	0.75	0.82	1.0	1.812	1.47	1.57	1.3	3.9	2.0	2.64	1.57	3.9	3.9
H_2 Flow, liters/min	0.76	3.00	4.00	4.00	2.26	2.46	3.0	1.85	1.50	1.60	4.0	4.0	6.0	8.0	4.72	4.0	4.0
O_2/H_2 Ratio	0.98	0.98	0.98	0.98	0.33	0.33	0.33	0.98	0.98	0.98	0.33	0.98	0.33	0.33	0.33	0.98	0.98
Initial Heat Flux, Btu/ft^2-sec	10.20	29.35	39.40	39.40	13.74	15.90	23.40	18.3	15.93	16.86	31.70	39.40	53.10	64.00	39.40	39.40	39.40
Total Run Time, sec	360	13	6.38	1.86	360	360	360	15.38	360	12	180	3.75	62.25	4.25	49	12	11
Surrounding Atmosphere	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air
Equilibrium Flame Composition																	
X_{O_2}*	0.270	0.270	0.270	0.270	0.006	0.005	0.006	0.270	0.270	0.270	0.006	0.270	0.006	0.006	0.006	0.270	0.270
X_{H_2}	0.034	0.034	0.034	0.034	0.312	0.312	0.312	0.034	0.034	0.034	0.312	0.034	0.312	0.312	0.312	0.034	0.034
X_{H_2O}	0.516	0.516	0.516	0.516	0.533	0.533	0.533	0.516	0.516	0.516	0.533	0.516	0.533	0.533	0.533	0.516	0.516
X_{OH}	0.110	0.110	0.110	0.110	0.052	0.052	0.052	0.110	0.110	0.110	0.052	0.110	0.052	0.052	0.052	0.110	0.110
X_H	0.022	0.022	0.022	0.022	0.088	0.088	0.088	0.022	0.022	0.022	0.088	0.022	0.088	0.088	0.088	0.022	0.022
X_O	0.044	0.044	0.044	0.044	0.009	0.009	0.009	0.044	0.044	0.044	0.009	0.044	0.009	0.009	0.009	0.044	0.044

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*X = Mole Fraction

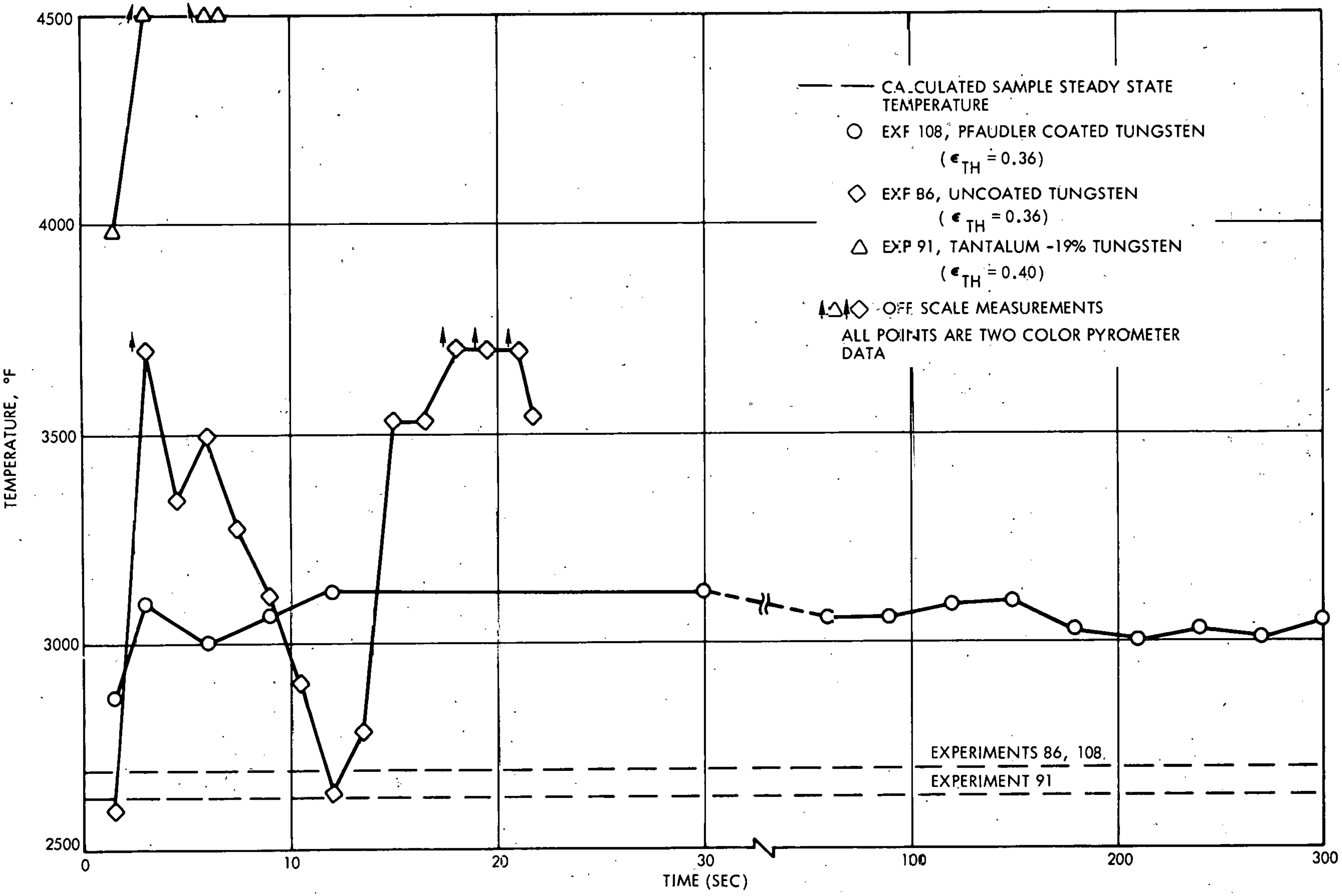

Figure 46. Comparison of the Temperature Time Data for Pfaudler Coated Tungsten UnCoated Tungsten, and Tantalum -10% Tungsten in a Hydrogen-Oxygen Flame Environment (O_2/H_2 = 0.98)

Figure 47 shows a plot of the calculated sample temperature versus the peak observed temperatures for experiments in both oxygen-rich and fuel-rich flames. It would appear that the ignition temperature for tantalum-10% tungsten samples in the hydrogen-oxygen flames were in the range from 2100° to 2300°F.

Figures 48 and 49 show photographs of samples exposed to the oxygen-rich flames for periods of 6 seconds and 13 seconds, respectively. It is apparent from these photographs that extremely rapid surface reaction took place. Moreover, it appears that molten phases were formed which would indicate sample temperatures in excess of 4000°F. Figure 50 shows a photograph of a tantalum-10% tungsten sample after exposure to the fuel-rich flame (water vapor the only reactant) for 360 seconds. A comparison of Figures 48, 49, and 50 shows that the fuel-rich flame reacted much slower with the tantalum-10% tungsten samples than did the oxygen-rich flames.

3.2.8 The Behavior of Tantalum-10% Tungsten in the CO-O_2 Flame System

Several experiments were conducted in which the tantalum-10% tungsten specimens were exposed to carbon monoxide-oxygen flame environments under both fuel-rich and oxygen-rich conditions. The tests were conducted in the same manner as the previously described (section 3.2.7) experiments in H_2-O_2 flames. Table 12 lists the experimental conditions for each test and Tables A-111 to A-116 of the Appendix present the temperature-time data for each experiment.

Figure 51 compares the measured temperature versus time data for two experiments in which the samples were exposed to the flame environments at the same heat flux and, hence, at the same calculated steady state sample temperature. In the first experiment (experiment 131) the specimen was exposed to a fuel-rich flame (CO and CO_2 the only reactants) while in the second experiment (experiment 132) the sample "saw" the oxygen-rich flame (CO, CO_2 and O_2 reactants). The measured sample temperature in the oxygen-rich flame experiment was considerably higher than the sample temperature in the fuel-rich experiment indicating a more rapid surface reaction in the oxygen-rich flame.

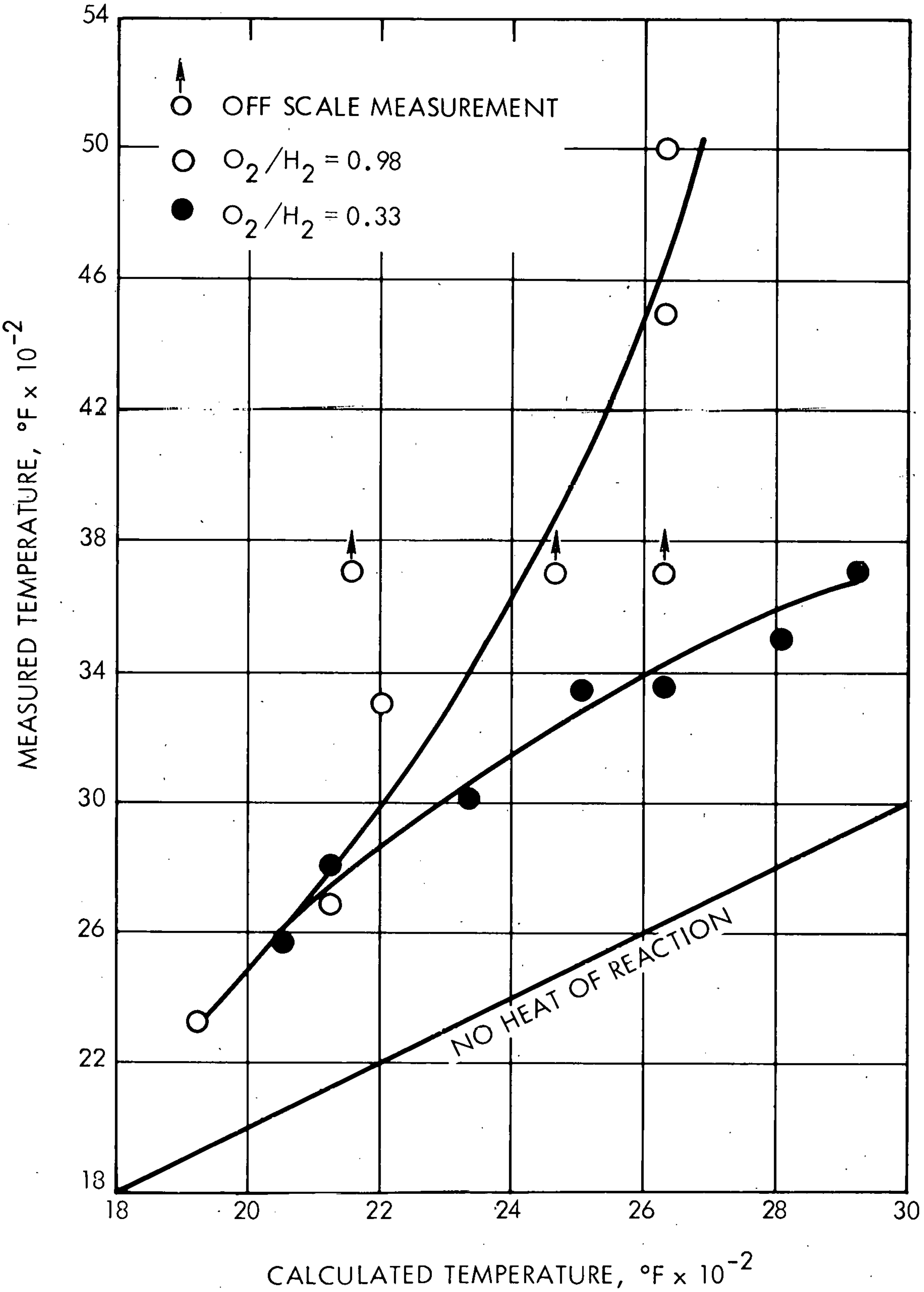

Figure 47. Tantalum - 10% Tungsten

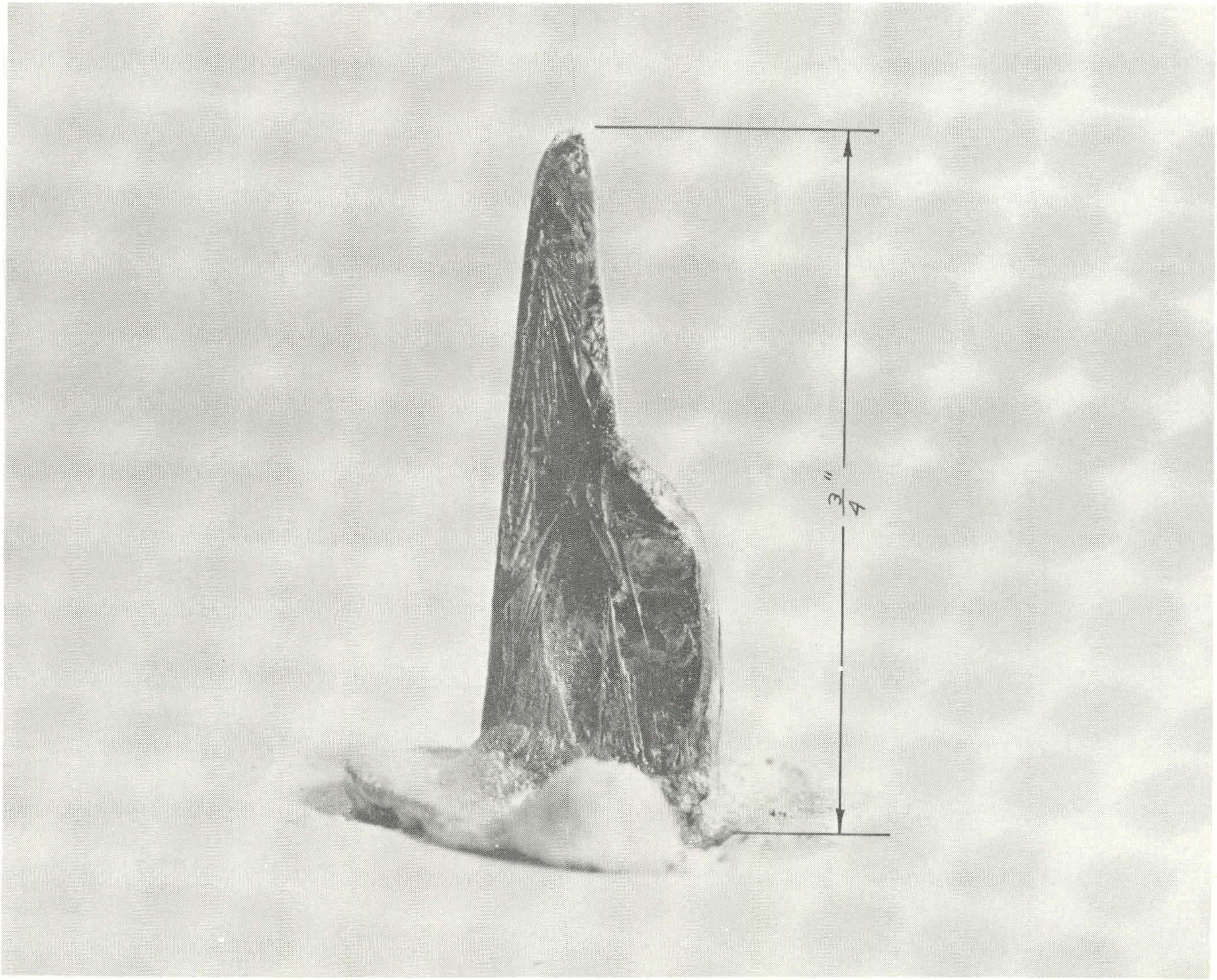

Figure 48. Experiment No. 91

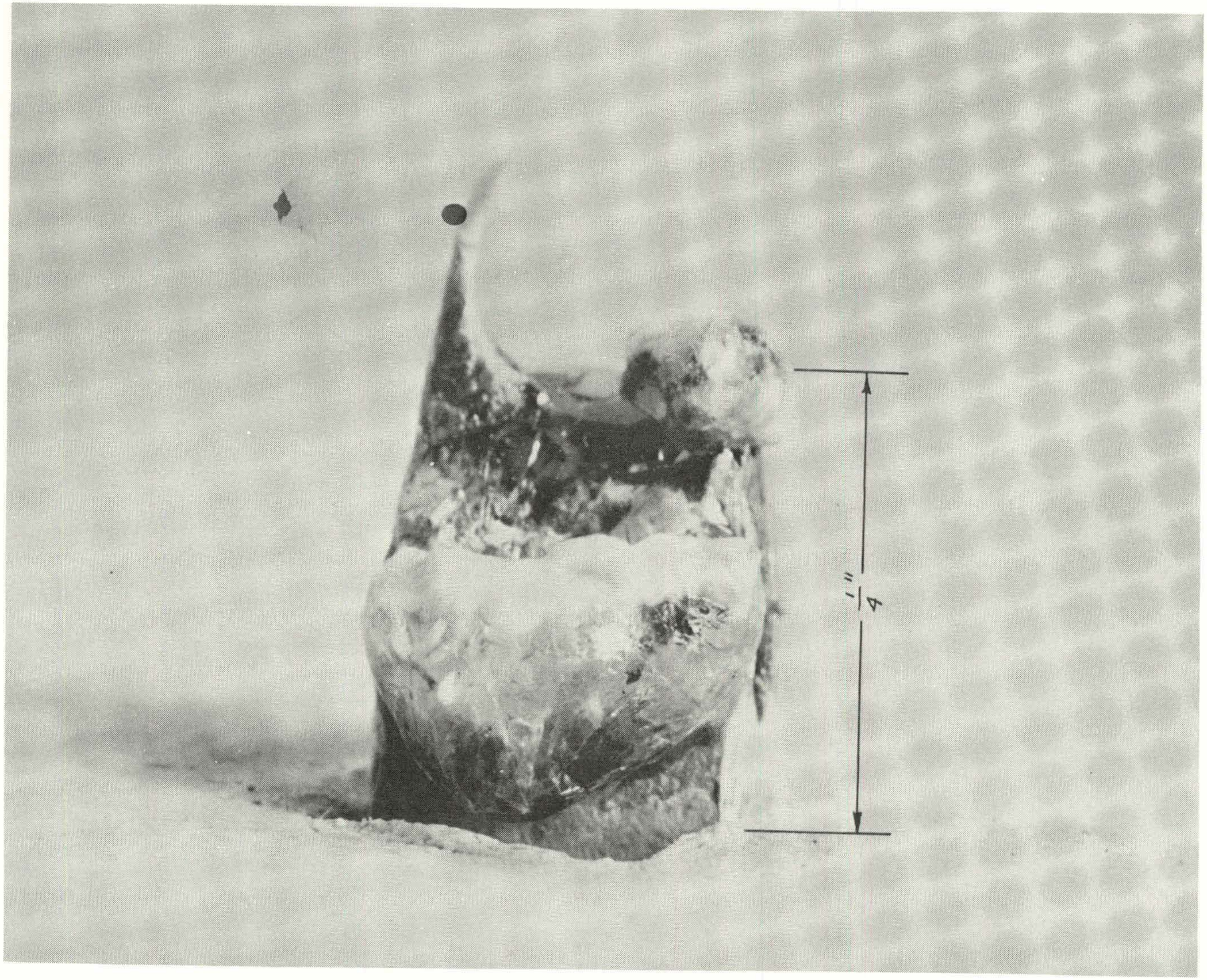

Figure 49. Experiment No. 90

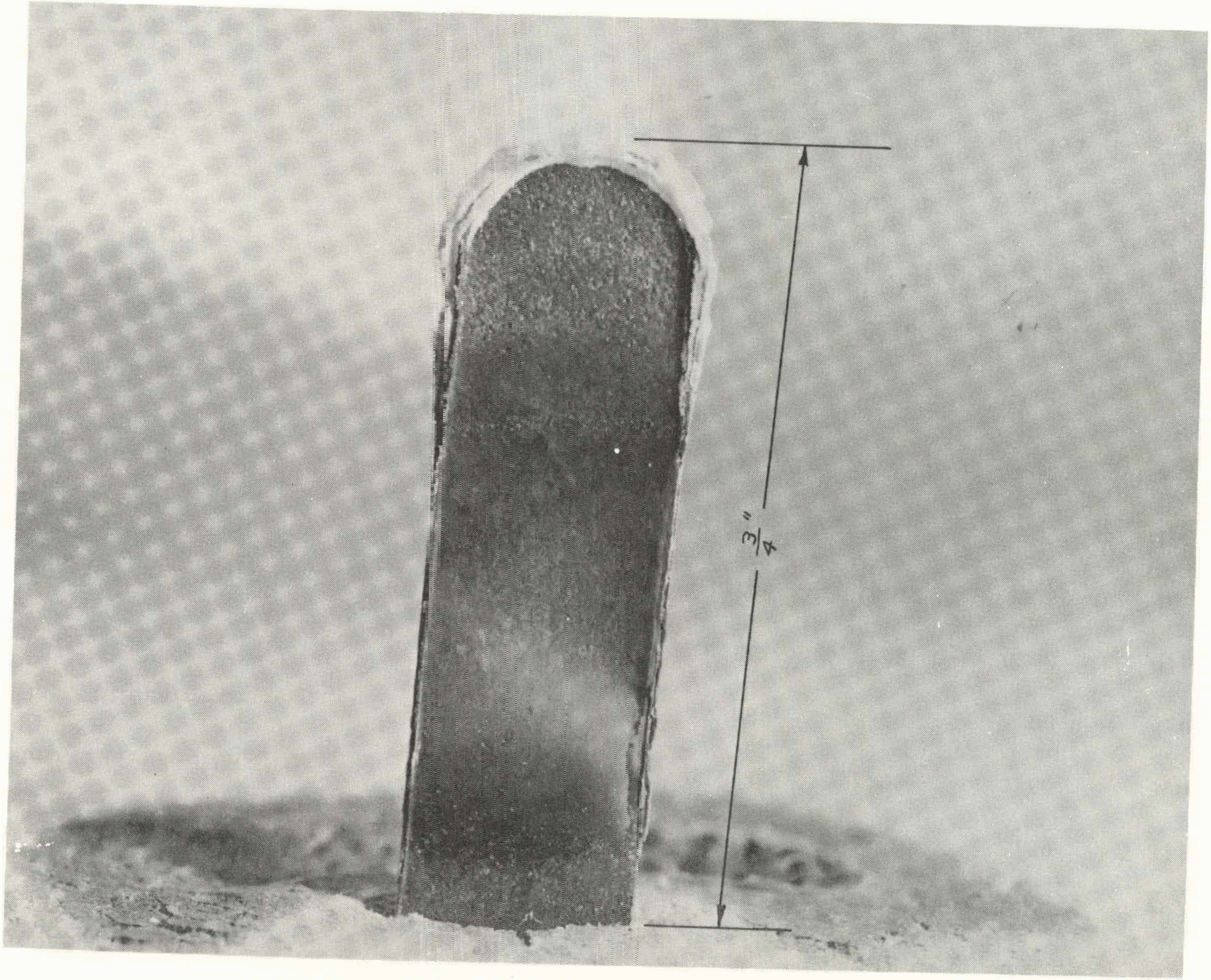

Figure 50. Experiment No. 95

Table 12. Conditions of Tantalum-10 Percent Tungsten Torch Experiments—Carbon Monoxide Oxygen Flame

Experiment Number	129	130	131	132	133	134
Adiabatic Flame Temperature, °F	4655	4655	4655	4890	4890	4890
Calculated Steady State Temperature, °F	1905	2022	2118	2189	2114	2031
O_2 Flow, liters/min	1.36	1.54	1.98	3.60	3.00	2.40
CO Flow, litters/min	6.00	7.00	9.00	6.00	5.00	4.00
O_2/CO Ratio	0.22	0.22	0.22	0.60	0.60	0.60
Initial Heat Flux, Btu/ft^2-sec	10.25	13.34	16.22	18.55	16.06	13.8
Total Run Time, sec	360	300	360	360	180	180
Surrounding Atmosphere	Air	Air	Air	Air	Air	Air
Equilibrium Flame Composition						
X_{CO}*	0.586	0.586	0.586	0.304	0.304	0.304
X_{CO_2}	0.392	0.392	0.392	0.458	0.458	0.458
X_O	0.008	0.008	0.008	0.045	0.045	0.045
X_{O_2}	0.015	0.015	0.015	0.193	0.193	0.193

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*X = Mole Fraction

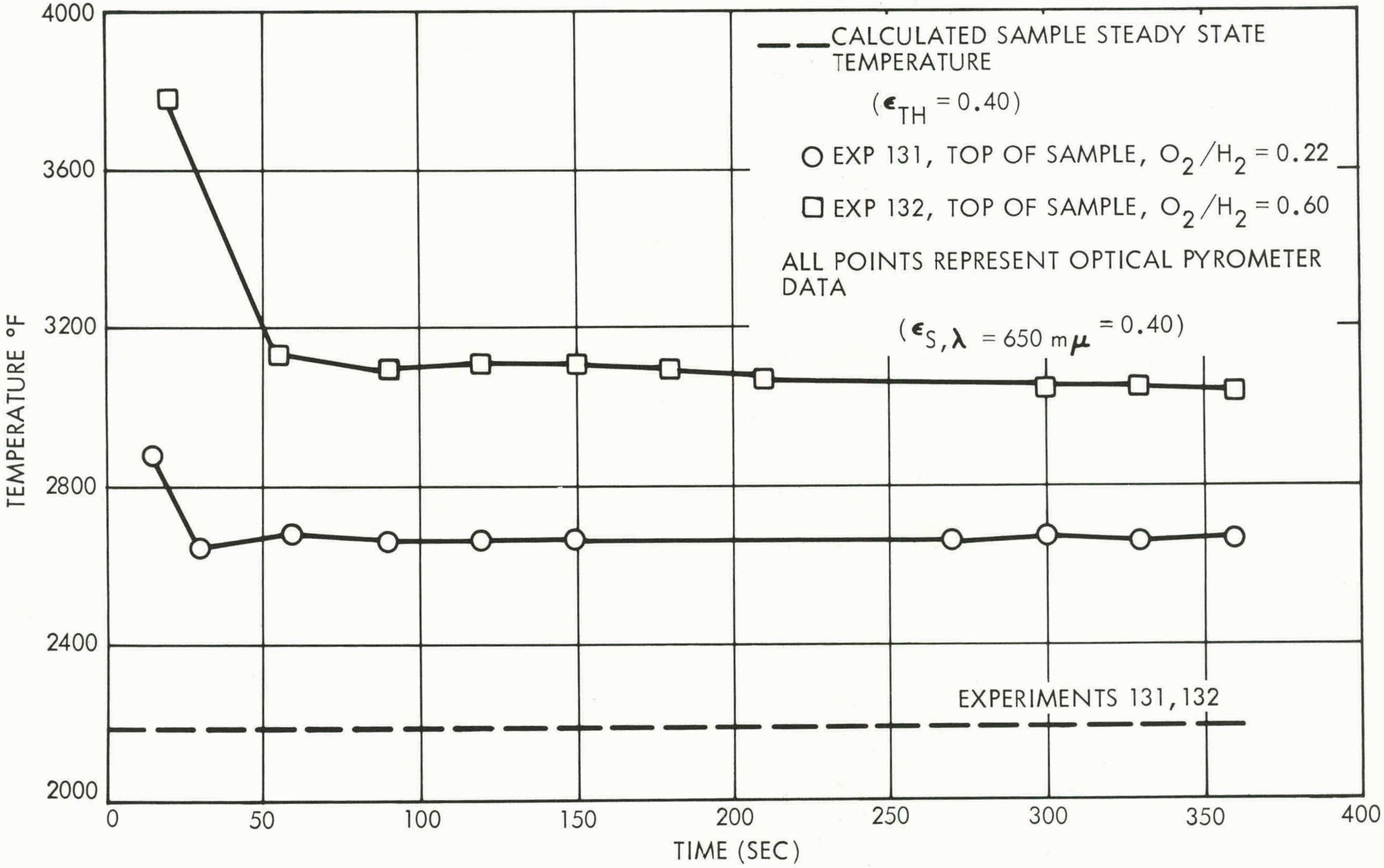

Figure 51. Temperature Time Data for Tantalum -10% Tungsten in a Carbon Monoxide-Oxygen Flame Environment

Figures 52 and 53 show photographs of test specimens after exposure for 6 minutes to the oxygen rich and fuel-rich flames respectively. It is apparent that considerably more oxidation took place in the oxygen-rich flame than in the fuel-rich flame which is in agreement with the temperature-time data for the two experiments.

Although rapid reaction was observed for tantalum-10% tungsten samples exposed to oxygen-rich $CO-O_2$ flames, the rate of reaction was still much slower than the extremely rapid combustion observed in oxygen-rich H_2-O_2 flames.

3.2.9 The Behavior of Pfaudler Silicide Coated Tungsten in the H_2-O_2 Flame System

A number of experiments were conducted in which tungsten samples which had been coated with a two to three mil silicide coating[*] were exposed to the hydrogen-oxygen flame system under both fuel-rich and oxygen-rich conditions. Table 13 presents the experimental conditions for each test and Tables A-117 to A-132 of the appendix presents the measured and calculated temperature versus time data.

The silicide coating was quite effective in eliminating the catastrophic oxidation of tungsten (for time periods of a few minutes) in both the fuel-rich and oxygen-rich flames as long as the sample temperature did not exceed about 3000°F. At sample temperatures above 3000°F, however, rapid coating failure was observed in both fuel-rich and oxygen-rich flames with a subsequent catastrophic oxidation of the tungsten metal substrate. Figure 54 shows a photograph of a coated specimen after exposure for 100 seconds at peak temperatures of about 3200°F. It is apparent from this photograph that the coating failed at the top. Figure 55 shows a photograph of a specimen exposed to the fuel-rich flame for 160 seconds at peak temperature as high as 4000°F (the calculated steady state temperature for this specimen excluding heat generation due to reaction was 2980°F). As can be seen from the photograph, the coating completely failed and much of the sample was oxidized.

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[*] Proprietary coating prepared by the Pfaudler Corporation.

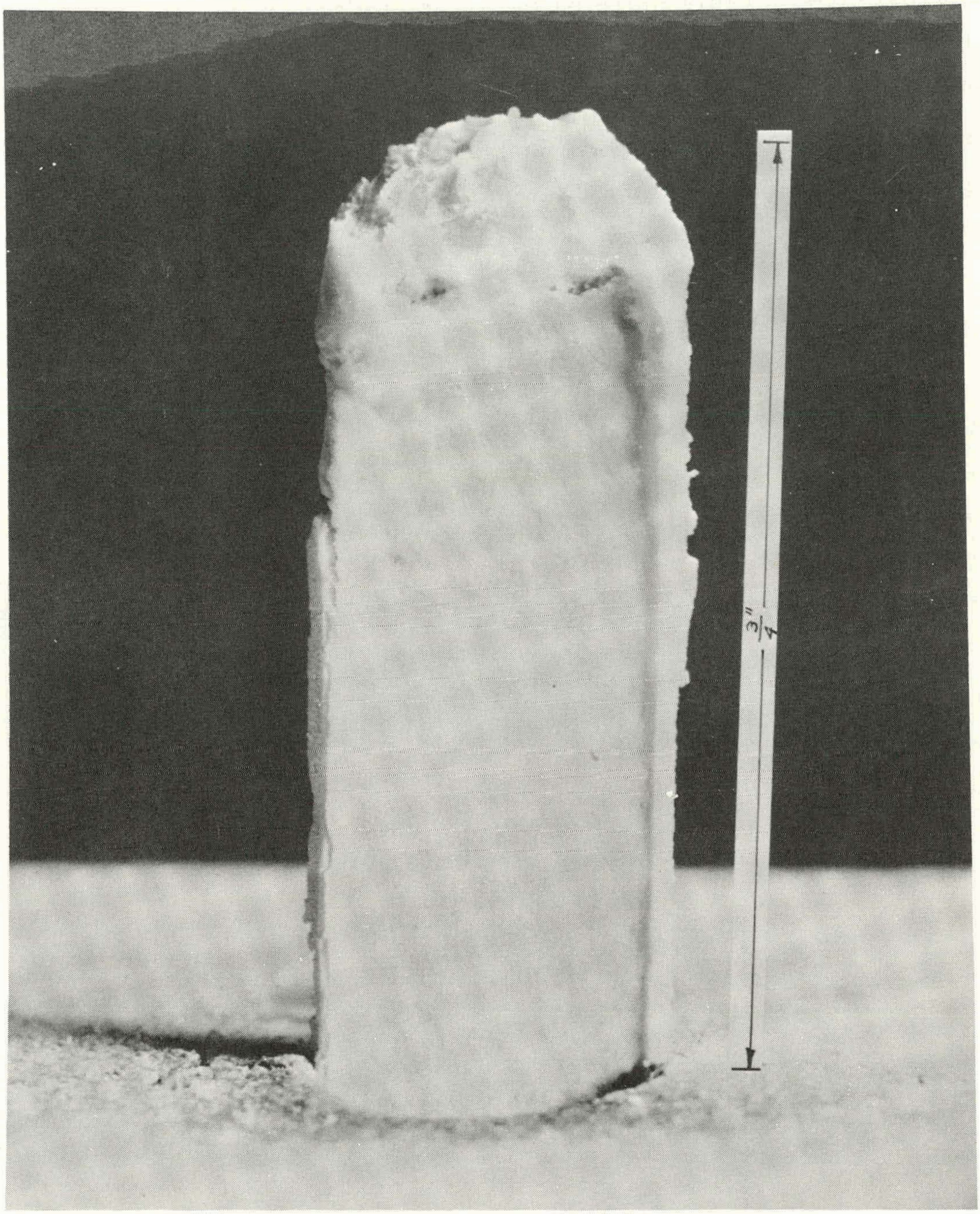

Figure 52. Experiment No. 132

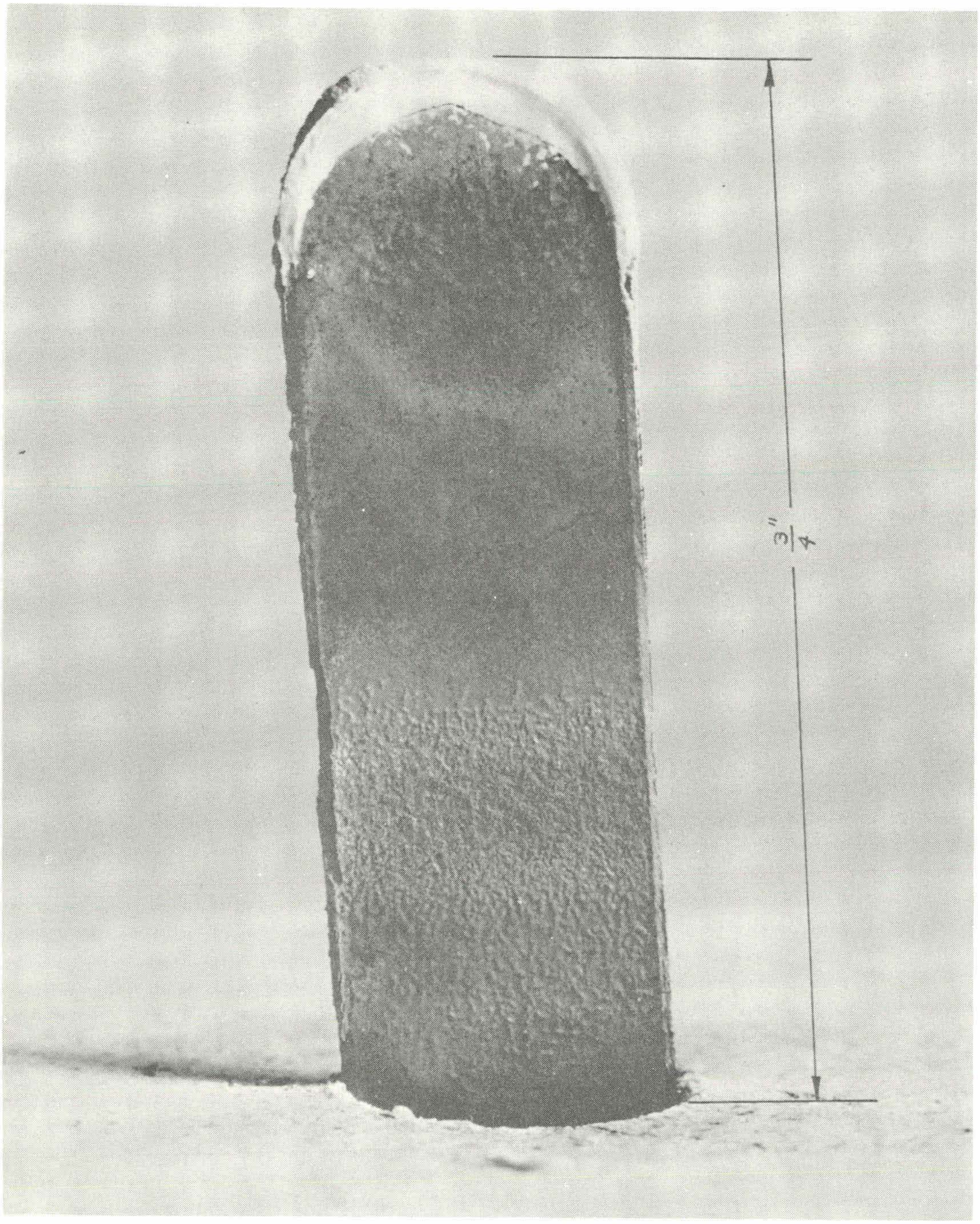

Figure 53. Experiment No. 131

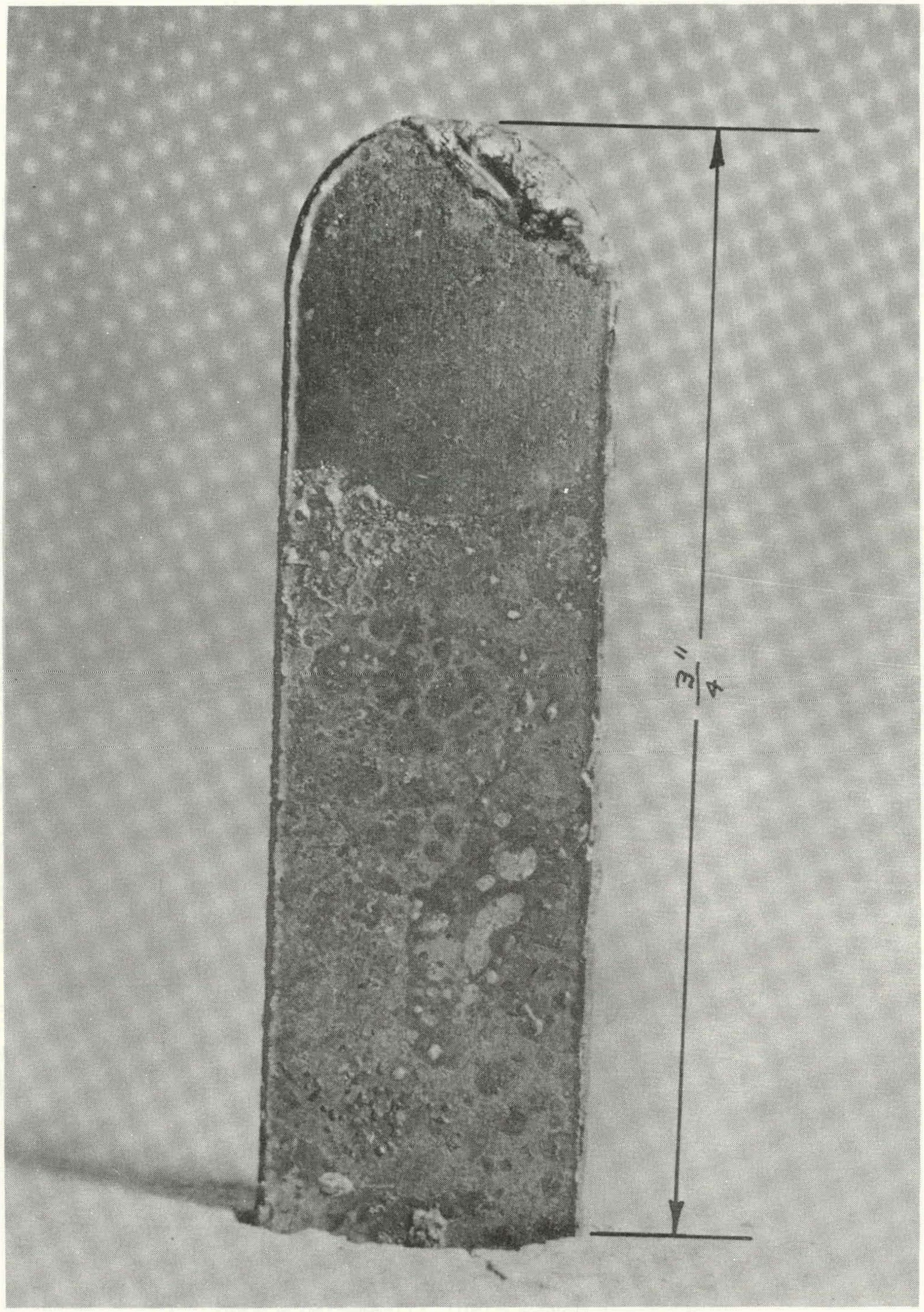

Figure 54. Experiment No. 111

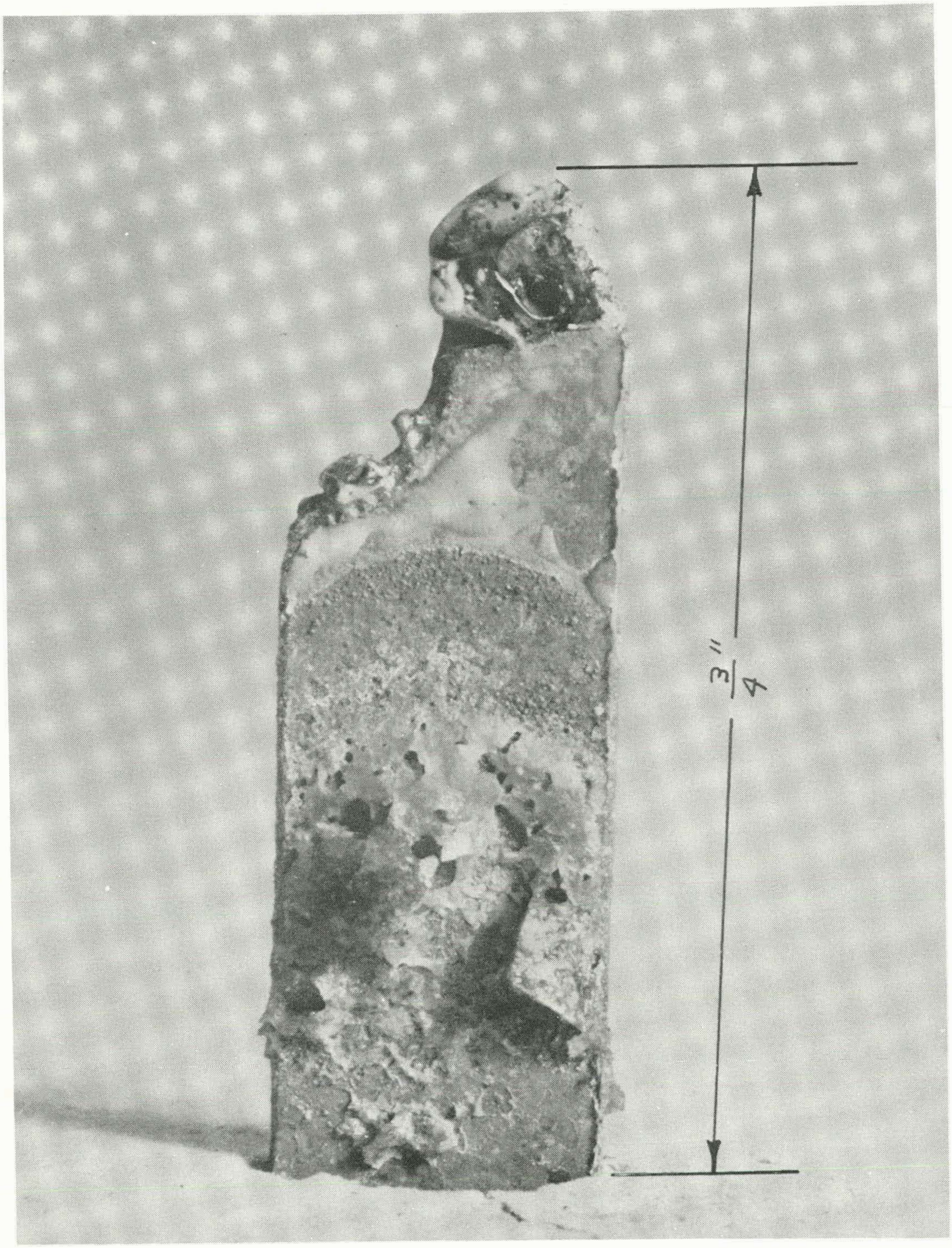

Figure 55. Experiment No. 117

Table 13. Conditions of Pfaudler Coated Tungsten Torch Experiments — Hydrogen-Oxygen Flame

Experiment Number	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121
Adiabatic Flame Temperature, °F	4790	4790	4790	4790	4790	4790	4840	4840	4840	4840	4840	4840	4840	4840	4840	4840
Calculated Steady State Temperature, °F	1970	2530	2695	2830	2920	3130	2110	2180	2385	2555	2865	2980	2695	2695	2695	2695
O_2 Flow, liters/min	0.75	2.95	3.90	4.90	5.88	8.80	0.75	0.82	1.00	1.30	2.00	2.64	1.57	1.57	1.57	1.57
H_2 Flow, liters/min	0.76	3.00	4.00	5.00	6.00	9.00	2.27	2.46	3.00	4.00	6.00	8.00	4.72	4.72	4.72	4.72
O_2/H_2 Ratio	0.98	0.98	0.98	0.98	0.98	0.98	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Initial Heat Flux, Btu/ft^2-sec	10.20	29.35	39.40	49.15	57.70	84.7	13.74	15.90	23.40	31.70	53.10	64.00	39.40	39.40	39.40	39.40
Total Run Time, sec	360	360	300	15	260	96	360	360	327	357	63	161	27	300.75	300.87	600.85
Surrounding Atmosphere	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air
Equilibrium Flame Composition																
X_{O_2}*	0.270	0.270	0.270	0.270	0.270	0.270	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
X_{H_2}	0.034	0.034	0.034	0.034	0.034	0.034	0.312	0.312	0.312	0.312	0.312	0.312	0.312	0.312	0.312	0.312
X_{H_2O}	0.516	0.516	0.516	0.516	0.516	0.516	0.533	0.533	0.533	0.533	0.533	0.533	0.533	0.533	0.533	0.533
X_{OH}	0.110	0.110	0.110	0.110	0.110	0.110	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052
X_H	0.022	0.022	0.022	0.022	0.022	0.022	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088
X_O	0.044	0.044	0.044	0.044	0.044	0.044	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009

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*X = Mole Fraction

3.2.10 The Behavior of Pfaudler Silicide Coated Tungsten in the CO-O_2 Flame System

Several tests were conducted in which the silicide coated tungsten samples were exposed to the CO-O_2 flame environment under both carbon monoxide-rich and oxygen-rich conditions. Table 14 details the experimental conditions for each test and Tables A-133 to A-138 present the measured and calculated temperature versus time data.

The peak sample temperatures which could be obtained in the carbon monoxide-oxygen flame experiments were of the order of 2700°F. Under these temperature conditions in both fuel-rich and oxygen-rich flames the samples appeared to maintain their integrity at least for time periods of up to 20 minutes. Figure 56 shows a photograph of a sample which was exposed to the fuel-rich flame for 20 minutes at temperatures in the 2700°F range. Although there was some indication of coating breakdown around the edges of the sample, no catastrophic oxidation occurred in 20 minutes. Figure 57 shows a photograph of a sample exposed for 20 minutes to the oxygen-rich flame under similar temperature conditions to the sample shown in Figure 55. As can be seen from a comparison of Figures 55 and 56 the results in the two experiments were very similar.

Table 14. Conditions of Pfaudler Coated Tungsten Torch Experiment — Carbon Monoxide-Oxygen Flame

Experiment Number	135	136	137	138	139	140
Adiabatic Flame Temperature, °F	4655	4655	4890	4890	4655	4890
Calculated Steady State Temperature, °F	2181	2087	2250	2094	2181	2250
O_2 Flow, liters/min	1.98	1.54	3.60	2.40	1.98	3.60
CO Flow, liters/min	9.00	7.00	6.00	4.00	9.00	6.00
O_2/CO Ratio	0.22	0.22	0.60	0.60	0.22	0.60
Initial Heat Flux, Btu/ft^2-sec	16.22	13.34	18.55	13.80	16.22	18.55
Total Run Time, sec	240	240	360	360	1200	1200
Surrounding Atmosphere	Air	Air	Air	Air	Air	Air
Equilibrium Flame Composition						
X_{CO}*	0.586	0.586	0.304	0.304	0.586	0.304
X_{CO_2}	0.392	0.392	0.458	0.458	0.392	0.458
X_O	0.008	0.008	0.045	0.045	0.008	0.045
X_{O_2}	0.015	0.015	0.193	0.193	0.015	0.193

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*X = Mole Fraction

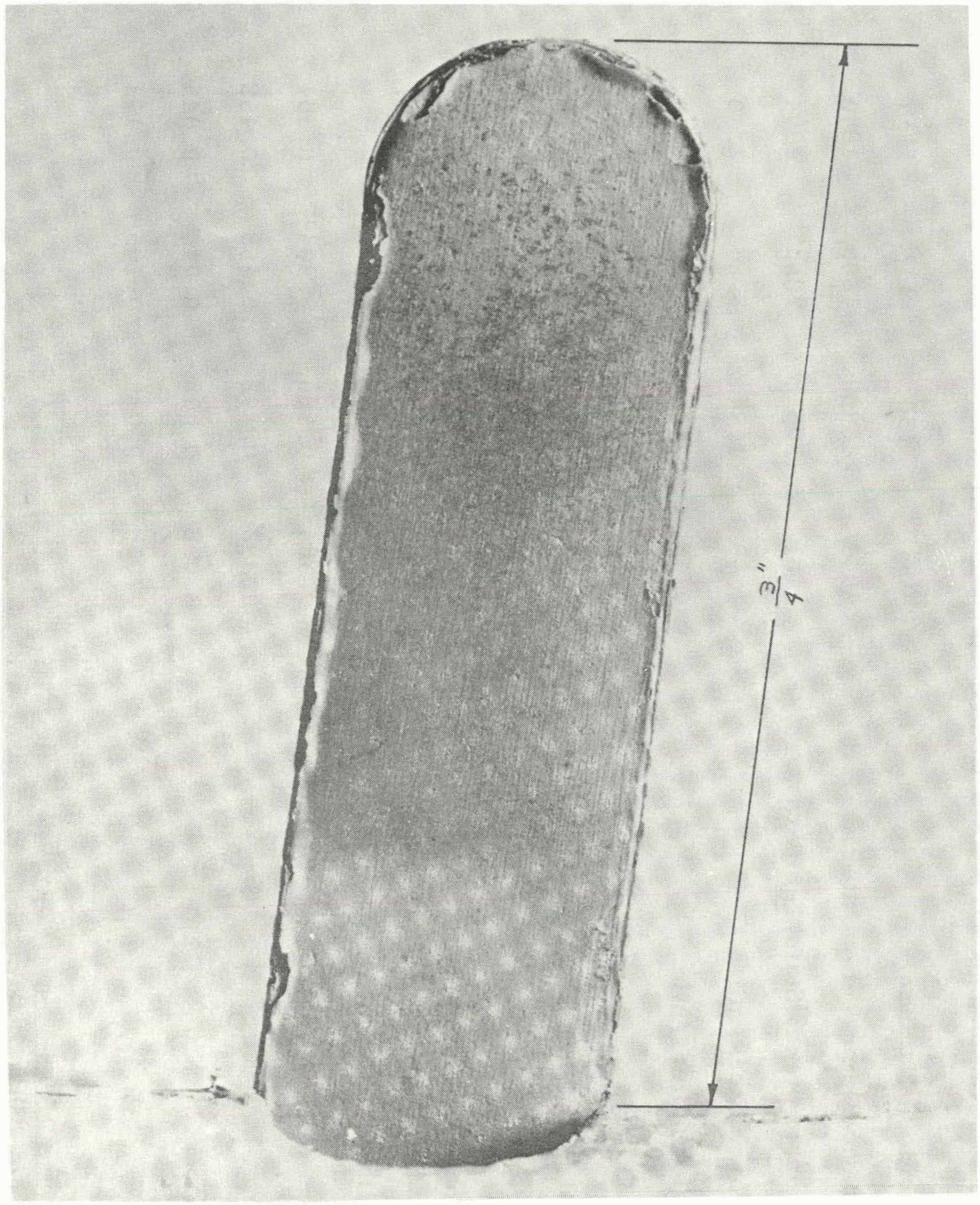

Figure 56. Experiment No. 140

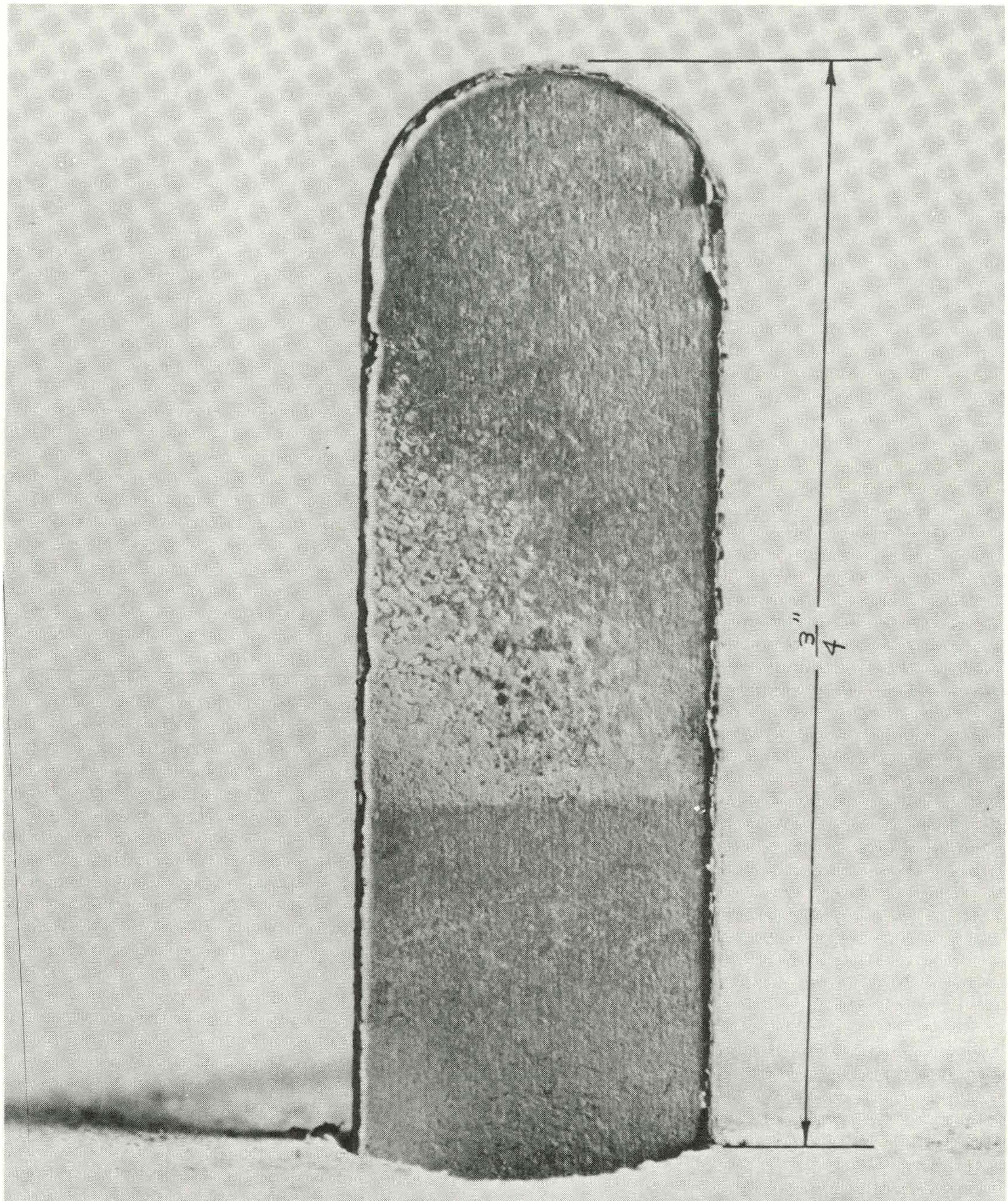

Figure 57. Experiment No. 139

4. CONCLUSIONS

In order to rationally assess the probability of a release of radioisotope due to chemical failure of the containment material in a launch abort incident, two types of information are required: first, the behavior of the containment material in a wide range of well defined launch abort environments must be determined; and second, the probability of occurrence of particular launch abort environments must be established. This program has been aimed at obtaining the first type of information, whereas a continuing program of experimental and analytical work at the Sandia Corporation is directed towards assessing the probability of occurrence of particular launch abort environments. All of the conclusions presented in this section refer to the first type of information. That is to say, the conclusions presented refer to to what would be expected to happen <u>if</u> a particular launch abort environment occurs.

Based on the experimental results of this program, the following conclusions regarding the behavior of containment materials in launch abort environments are presented:

a) In pure oxygen at temperatures up to 2200°F, 316 Stainless Steel, Haynes 25, Hastelloy C, and Hastelloy X, all oxidize at a rate which is too slow to be of concern from a safety point of view.* At temperatures from 2200°F up to the melting range of the alloys (2400° to 2600°F), however, the oxidation rate was sufficiently rapid that a significant fraction of a sample of any of the above alloys was oxidized in a period of 1 or 2 hours.

b) The reaction of Haynes 25 with pure nitric oxide was somewhat slower than the reaction of this alloy with pure oxygen under identical conditions of temperature and pressure. Hence, it would seem likely that flame environments containing high concentrations of nitric oxide would be no more reactive with Haynes 25 than flame environments which contain high concentrations of oxygen.

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* A reaction was considered to be "of concern from a safety point of view" if a significant fraction of a sample was oxidized in a period of minutes.

c) Well designed radioisotope capsules fabricated from 304 Stainless Steel, 316 Stainless Steel, Haynes 25, Hastelloy C, or Hastelloy X should be able to withstand (chemically) short term (period of minutes) exposure to abort flame environments containing oxygen, nitrogen, hydrogen, water, carbon monoxide, and carbon dioxide at capsule temperatures up to about 2300°F.

d) In flame environments containing high concentrations of water vapor and/or oxygen, capsules fabricated from 304 or 316 Stainless Steel are likely to ignite and react rapidly and exothermically with the flame environment if the surface temperature of the capsules reaches the melting range of the alloys (∼2400° to 2600°F).

e) In flame environments containing high concentrations of both water vapor and oxygen, the uncoated refractory metals tungsten and tantalum-10% tungsten react exceedingly rapidly. Ignition temperatures for these two refractory metals in oxygen-rich hydrogen-oxygen flames was of the order of 2200°F. Indeed, reaction rates in this type of flame environment were much faster than would be expected from the literature data for the static reactions of these metals with oxygen and water. Based on the experimental flame tests, it would seem unlikely that uncoated tantalum or tungsten-based refractory capsules (at temperatures in excess of 2200°F) could withstand an abort flame environment containing high concentrations of both water and oxygen for periods of time in excess of a few seconds.

f) In flame environments containing high concentrations of water, carbon dioxide, and carbon monoxide, but no appreciable oxygen; the oxidation of uncoated tantalum and tungsten-based alloys was considerably slower than in the oxygen-rich flames. However, the reaction between the uncoated refractory alloys and this flame environment was still sufficiently rapid to indicate that extensive oxidation of refractory capsules would take place when they were exposed to this type of abort flame for periods of minutes at temperatures in excess of 2000°F.

g) The Pfaudler silicide coating can provide short term (period of minutes) oxidation protection to tungsten capsules exposed to flame environments containing water, oxygen, hydrogen, carbon monoxide and carbon dioxide provided the capsule surface temperature does not exceed 2900°F. It must be kept in mind, however, that if even a small portion of the thin silicide coating is abraded or scraped off of the capsule during an abort, then the coating system will no longer be effective in protecting the tungsten substrate.

REFERENCES

1. J. L. Blumenthal, "Study of the Chemical Integrity of Radioisotope Containment Materials in Launch Abort Environments," Summary Technical Report Phase I SC-DC-65-1918, Sandia Corporation, December 1965.

2. J. L. Blumenthal and M. J. Santy, "An Experimental Investigation of the Behavior of Beryllium in Simulated Launch-Abort Environments," SC-DC-65-1637, Sandia Corporation, December 1965.

APPENDIX A

TEMPERATURE-TIME DATA FOR THE EXPERIMENTAL FLAME TESTS

Table A-1

Experiment No. 1

Material—Type 304 Stainless Steel

Flame Environment—H_2-O_2

Initial Weight—1.8445 g

Final Weight—Not Obtainable

Apparent Corrosion Rate—Not Obtainable

Calculated Steady State Temperature—2770°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
30	2160 B*	153	2600
60	2160 B	162	2650
90	2160 B	171	2710
120	2226 B	180	2770
150	2217 B	186	3020
180	2326 T*	195	3090
210	2487 T	204	3040
240	2543 T	213	3000
240	2346 B	228	3050
360	2777 T	243	3010
		261	2989
		282	2980
		300	2970
		315	2950
		333	2950
		364	2950

B* = Bottom Sample; T* = Top of Sample

REMARKS:

A hot zone was observed on the sample top. There was little sample deterioration except for some erosion on top.

Table A-2

Experiment No. 2

Material — Type 304 Stainless Steel

Flame Environment — H_2-O_2

Initial Weight — 1.7649 g

Final Weight — Not Obtainable

Apparent Corrosion Rate — Not Obtainable

Calculated Steady State Temperature — 2670°F

Temperature-Time Data:

Time (sec)	Optical Pyrometer Temperature (°F)
30	2143 T*
45	1845 B*
70	2209 T
90	1979 B
120	2285 T
140	2018 B
165	2264 T
180	2346 T
210	2428 T
240	2450 T
270	2143 B
300	2450 T

B* = Bottom of Sample

T* = Top of Sample

REMARKS:

Sample has visible oxide coating. No signs of melting with little, if any, deterioration.

Table A-3

Experiment No. 3

Material—Type 304 Stainless Steel

Flame Environment—H_2-O_2

Initial Weight—1.8012 g

Final Weight—Not Obtainable

Apparent Corrosion Rate—Not Obtainable

Calculated Steady State Temperature—3000°F

Temperature-Time Data:

Two Color Pyrometer	
Time (sec)	Temperature (°F)
0+	2600
0.5	2820
1.5	2650
3	2810
4.5	3380
6	3470
9	3530
12	3470
15	3460
18	3470
21	3450

REMARKS:

Sample appeared to melt instantaneously. An apparent ignition took place. A considerable amount of sample erosion was evident.

Table A-4

Experiment No. 4

Material — Type 304 Stainless Steel

Flame Environment — H_2-O_2

Initial Weight — 1.8097 g

Final Weight — Not Obtainable

Apparent Corrosion Rate — Not Obtainable

Calculated Steady State Temperature — 3000°F

Temperature-Time Data:

Two Color Pyrometer

Time (sec)	Temperature (°F)
1.5	2600
3	2690
3.8	2720
4.5	3380
5.2	3525
6	3370
9	3420
12	3525

REMARKS:

See Remarks Experiment No. 3.

Table A-5

Experiment No. 5
Material—Type 304 Stainless Steel
Flame Environment—H_2-O_2
Initial Weight—1.8488 g
Final Weight—1.8874 g
Apparent Corrosion Rate—+1304 mg/cm^2-hr
Calculated Steady State Temperature—2805°F
Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
60	2143 B*
40	2797 THZ*

Two Color Pyrometer

Time (sec)	Temperature (°F)
5	2600
7.5	3170
12	3370
18	3395
24	3435
30	3345
36	3380
42	3380
48	3380
54	3370
60	3350
73	3300
85	3300
91	3290
44.5	3250

B* = Bottom of Sample; THZ* = Top hot zone

REMARKS:

Sample appeared to ignite on upper top edges. Little deterioration except on top of sample.

Table A-6

Experiment No. 6
Material — Type 304 Stainless Steel
Flame Environment — H_2-O_2
Initial Weight — 1.7952 g
Final Weight — 1.8142 g
Apparent Corrosion Rate — +281 mg/cm^2-hr
Calculated Steady State Temperature — 2495°F
Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
15	2077 B*
60	2837 THZ*
90	2418 B
120	3012 THZ
135	2418 B
150	2872 THZ
180	2797 THZ
210	2438 B
210	2757 T*

Two Color Pyrometer

Time (sec)	Temperature (°F)
34	2600
40.5	2655
48	2785
57	2860
66	2870
75	2890
90	2990
105	3090
120	3090
135	3090
147	3080
159	3070
171	3070
183	3060
198	3060
213	3000

B* = Bottom of Sample; THZ* = Top hot zone;
T* = Top of Sample

REMARKS:

Upper edge portion of sample appeared to be boiling. No real sparking effect observed. Some sample erosion on top.

Table A-7

Experiment No. 7

Material—Type 304 Stainless Steel

Flame Environment—H_2-O_2

Initial Weight—1.8601 g

Final Weight—1.8765 g

Apparent Corrosion Rate— +145.5 mg/cm^2-hr

Calculated Steady State Temperature—2340°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
25	1863 B*	192	2600
35	1979 B	204	2625
55	2346 T*	216	2650
75	2428 T	228	2630
90	2176 B	240	2670
120	2487 T	252	2675
150	2525 T	267	2680
165	2264 B	282	2650
180	2553 T	285	2650
210	2505 T	294	2690
225	2505 T	303	2715
255	2244 B	315	2604
285	2525 T	324	2640
330	2487 T	336	2635
345	2487 T	345	2620
360	2160 B	354	2675

B* = Bottom of Sample; T* = Top of Sample

REMARKS:

Sample shows a heavy, visible oxide coating. Boiling effect observed on sample top; however, little erosion evident.

Table A-8

Experiment No. 8

Material—Type 304 Stainless Steel

Flame Environment—H_2-O_2

Initial Weight—1.8159 g

Final Weight—1.8968 g

Apparent Corrosion Rate—6050 mg/cm^2-hr

Calculated Steady State Temperature—2920°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
30	3314 THZ*

Two Color Pyrometer

Time (sec)	Temperature (°F)
5	2600
6	2910
7	3260
9	3235
12	3310
15	3340
18	3380
21	3430
24	3430
27	3410
30	3440
33	3470
36	3450
39	3430
41	3430

THZ* = Top hot zone

REMARKS:

Sample top appeared to ignite. A visible oxide coating formed on the remainder of the sample.

Table A-9

Experiment No. 9

Material — Type 304 Stainless Steel

Flame Environment — H_2-O_2

Initial Weight — 1.7719 g

Final Weight — 1.7725 g

Apparent Corrosion Rate — +3.93 mg/cm^2-hr

Calculated Steady State Temperature — 2045°F

Temperature-Time Data:

Time (sec)	Optical Pyrometer Temperature (°F)
30	1845 B*
60	1863 T*
90	1959 T
100	1752 B
140	2137 T
165	2077 T
200	2087 T
225	2094 T
240	2102 T
280	1940 B
330	2116 T
360	2127 T
390	2127 T
420	2127 T
440	1979 B
480	2127 T

B* = Bottom of Sample

T* = Top of Sample

REMARKS:

Sample showed no signs of melting or igniting. A thin oxide coating visible over entire sample.

Table A-10

Experiment No. 10

Material—Type 304 Stainless Steel

Flame Environment—H_2-O_2

Initial Weight—1.6695 g

Final Weight—1.6495 g

Apparent Corrosion Rate— -176.5 mg/cm^2-hr

Calculated Steady State Temperature—2340°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
30	1979 B*
45	2285 T*
60	1959 B
90	2397 T
120	2438 T
135	2438 T
180	2637 T
210	2193 B
240	2525 T
270	2525 T
300	2209 B
330	2515 T
375	2525 T

B* = Bottom of Sample

T* = Top of Sample

REMARKS:

The sample top showed signs of bubbling. Very little top erosion however. A visible oxide coating formed over entire sample.

Table A-11

Experiment No. 11

Material — Type 304 Stainless Steel

Flame Environment — H_2-O_2

Initial Weight — 1.7375 g

Final Weight — 1.7377 g

Apparent Corrosion Rate — +1.75 mg/cm^2-hr

Calculated Steady State Temperature — 1810°F

Temperature-Time Data:

Optical Pyrometer	
Time (sec)	Temperature (°F)
30	1566 T*
45	1676 T
60	1771 T
65	1530 B*
90	1808 T
120	1826 T
135	1584 B
180	1863 T
210	1863 T
240	1870 T
270	1863 T
360	1870 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

No signs of ignition or any form of rapid reaction.
A very thin oxide coating formed on the sample.

Table A-12

Experiment No. 12

Material — Type 304 Stainless Steel

Flame Environment — H_2-O_2

Initial Weight — 1.6044 g

Final Weight — 1.6050 g

Apparent Corrosion Rate — +4.49 mg/cm^2-hr

Calculated Steady State Temperature — 2135°F

Temperature-Time Data:

Time (sec)	Optical Pyrometer Temperature (°F)
30	1901 T*
60	1998 T
90	2110 T
105	1940 B*
120	2135 T
150	2151 T
180	2100 T
190	1979 B
210	2176 T
240	2183 T
270	2193 T
330	2185 T
360	2185 T
420	2185 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

No signs of melting or igniting. A moderate coating observed on sample surface.

Table A-13

Experiment No. 13

Material — Type 304 Stainless Steel

Flame Environment — H_2-O_2

Initial Weight — 1.7596 g

Final Weight — 1.7568 g

Apparent Corrosion Rate — -779 mg/cm^2-hr

Calculated Steady State Temperature — 3000°F

Temperature-Time Data:

Two Color Pyrometer

Time (sec)	Temperature (°F)
3	2600
4	2880
5	3310
6	3130
7	2930
8	2700
9	2705
11	2695

REMARKS:

An apparent ignition took place.
Considerable top melting and deterioration observed.

Table A-14

Experiment No. 14
Material — Type 304 Stainless Steel
Flame Environment — H_2-O_2
Initial Weight — 1.6432 g
Final Weight — 1.6863 g
Apparent Corrosion Rate — +1910 mg/cm^2-hr
Calculated Steady State Temperature — 2495°F
Temperature-Time Data:

Two Color Pyrometer

Time (sec)	Temperature (°F)
42	2600
43	2670
45	2685
48	2715
51	2680
54	2710
57	2710
60	2750
63	2745
66	2795
69	2805
71	2790

REMARKS:

See Remarks Experiment No. 6.

Table A-15

Experiment No. 15

Material — Type 304 Stainless Steel

Flame Environment — H_2-O_2

Initial Weight — 1.6616 g

Final Weight — 1.6788 g

Apparent Corrosion Rate — +3485 mg/cm^2-hr

Calculated Steady State Temperature — 2920°F

Temperature-Time Data:

Two Color Pyrometer	
Time (sec)	Temperature (°F)
4	2600
5	3000
6	3020
7.5	3130
9	3200
12	3220
15	3230
15.5	3250

REMARKS:

See Remarks Experiment No. 8.

Table A-16

Experiment No. 32

Material — Type 304 Stainless Steel

Flame Environment — H_2-O_2

Initial Weight — 1.6491 g

Final Weight — 1.7221 g

Apparent Corrosion Rate — +7660 mg/cm^2-hr

Calculated Steady State Temperature — 2670°F

Temperature - Time Data:

None Obtained.

REMARKS:

Sample appeared to ignite completely. Entire exposed portion of sample eroded. Remainder of sample shows a heavy, flakey oxide coating.

Table A-17

Experiment No. 33

Material — Type 304 Stainless Steel

Flame Environment — H_2-O_2

Initial Weight — 1.7007 g

Final Weight — 1.6987 g

Apparent Corrosion Rate — -5.24 mg/cm^2-hr

Calculated Steady State Temperature — 2215°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
60	1901 T*
180	1959 T
360	1998 T
600	1998T
720	1998 T
900	2018 T
960	7018 T
1200	2018 T

T* = Top of Sample

REMARKS:

No ignition or hot zones observed. The sample top shows slight pitting. The formation of a thin oxide coating over the entire sample was observed.

Table A-18

Experiment No. 34

Material—Type 304 Stainless Steel

Flame Environment—H_2-O_2

Initial Weight—1.7325 g

Final Weight—1.7278 g

Apparent Corrosion Rate—-12.3 mg/cm^2-hr

Calculated Steady State Temperature—2320°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
60	2127 T*
180	2209 T
300	2226 T
420	2244 T
480	2085 B*
600	2428 THZ*
720	2244 T
900	2274 T
960	2418 THZ
1020	2418 THZ
1140	2160 B
1200	2418 THZ

T* = Top of Sample; B* = Bottom of Sample;
THZ* = Top Hot Zone.

REMARKS:

No ignition, melting, or bubbling. A small hot spot was observed on top. A flakey oxide coating formed on the entire sample surface.

Table A-19

Experiment No. 35
Material — Type 304 Stainless Steel
Flame Environment — H_2-O_2
Initial Weight — 1.8532 g
Final Weight — 1.8759 g
Apparent Corrosion Rate — +59.4 mg/cm^2-hr
Calculated Steady State Temperature — 2135°F
Temperature-Time Data:

	Optical Pyrometer
Time (sec)	Temperature (°F)
60	1901 T*
180	1881 B*
240	0244 T
300	2110 B
420	2264 T
540	2110 B
660	2285 T
780	2127 B
900	2285 T
1020	2114 B
1080	2295 T
1200	2110 B

T* = Topof Sample; B* = Bottom of Sample

REMARKS:

No ignition, melting, or bubbling. Slight sample surface oxidation.

Table A-20

Experiment No. 16

Material—Type 316 Stainless Steel

Flame Environment—H_2-O_2

Initial Weight—1.5811 g

Final Weight—Not obtainable

Apparent Corrosion Rate—Not obtainable

Calculated Steady State Temperature—2770°F

Temperature-Time Data:

	Two Color Pyrometer
Time (sec)	Temperature (°F)
12	2600
12.37	2675
12.78	3120
13.1	3340
13.5	3145
15	3410
15.75	3540
16.5	3275
18	3315
19.5	3340
21	3328
24	3350
27.8	3182

REMARKS:

Sample appeared to ignite completely. Complete sample deterioration.

Table A-21

Experiment No. 17

Material — Type 316 Stainless Steel

Flame Environment — H_2-O_2

Initial Weight — 1.5901 g

Final Weight — 1.6329 g

Apparent Corrosion Rate — +4350 mg/cm^2-hr

Calculated Steady State Temperature — 2770°F

Temperature-Time Data:

Two Color Pyrometer

Time (sec)	Temperature (°F)	
23	2648	
24.5	2685	
26	2822	
27.5	3536	
29	3190	
30.5	3260	Fuel Cut
32	2848	
33.5	2600	

REMARKS:

See Remarks Experiment No. 16.

Table A-22

Experiment No. 18

Material — Type 316 Stainless Steel

Flame Environment — H_2-O_2

Initial Weight — 1.7309 g

Final Weight — 1.7585 g

Apparent Corrosion Rate — +411 mg/cm^2-hr

Calculated Steady State Temperature — 2670°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
30	2599 B*	38	2600
180	3012 THZ*	47	2690
		59	2740
		71	2710
		83	2710
		95	2675
		107	2845
		119	2870
		131	3120
		140	2895
		152	2860
		164	2850
		176	2860
		188	2770
		200	2825
		211	2760

B* = Bottom of Sample; THZ* = Top Hot Zone

REMARKS:

Sample appeared to ignite on the top. A heavy oxide coating observable on the remainder of sample.

Table A-23

Experiment No. 19

Material — Type 316 Stainless Steel

Flame Environment — H_2-O_2

Initial Weight — 1.6261 g

Final Weight — 1.6073 g

Apparent Corrosion Rate — -164 mg/cm^2-hr

Calculated Steady State Temperature — 2540°F

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
30	1845 B*	114	2600
45	2418 T*	117	2600
60	2450 T	123	2600
75	2193 B	135	2710
105	2562 T	150	2740
150	2580 T	174	2640
165	2580 T	204	2670
180	2264 B	234	2850
210	2543 T	252	2765
270	2924 THZ*	264	2830
300	2562 T	282	2820
330	2264 B	300	2870
360	2562 T	318	2870
		331	3240
		345	3020
		360	3040

B* = Bottom of Sample; T* = Top of Sample; THZ* = Top Hot Zone

REMARKS:

Sample appeared to ignite slightly on upper top edge only. Little sample erosion except on top. A heavy oxide coating observed on the rest of the sample.

Table A-24

Experiment No. 20

Material — Type 316 Stainless Steel

Flame Environment — H_2-O_2

Initial Weight — 1.6674 g

Final Weight — 1.6496 g

Apparent Corrosion Rate — -155.4 mg/cm^2-hr

Calculated Steady State Temperature — 2380°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
15	2018 T*
60	2487 T
90	2127 B*
120	2580 T
120	2226 B
180	2580 T
180	2226 B
240	2618 T
240	2226 B
360	2637 T
360	2244 B

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

Very little, if any, sample deterioration. Visible oxide coating over entire sample. No melting or ignition seen.

Table A-25

Experiment No. 21
Material — Type 316 Stainless Steel
Flame Environment — H_2-O_2
Initial Weight — 1.6139 g
Final Weight — 1.7652 g
Apparent Corrosion Rate — +2610 mg/cm^2-hr
Calculated Steady State Temperature — 2805°F
Temperature-Time Data:

Time (sec)	Two Color Pyrometer Temperature (°F)
7	2600
13	3170
22	3270
34	3350
46	3350
58	3230
70	3350
88	3370
100	3310
112	3300
124	3230
136	3200
146	3180
158	3140
170	3170
182	3190

REMARKS:

Sample ignited almost instaneously. Exposed portion of sample totally eroded.

Table A-26

Experiment No. 22

Material — Type 316 Stainless Steel

Flame Environment — H_2-O_2

Initial Weight — 1.4328 g

Final Weight — 1.4461 g

Apparent Corrosion Rate — +124.3 mg/cm^2-hr

Calculated Steady State Temperature — 2495°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
30	2305 T*
45	2505 T
60	2599 T
70	2264 B*
120	2737 T
130	2717 T
150	2305 B
180	2757 T
210	2797 T
240	2326 B
270	2737 T
300	2717 T
310	2326 B

Two Color Pyrometer

Time (sec)	Temperature (°F)
96	2600
105	2605
120	2660
138	2650
150	2640
168	2685
180	2710
198	2695
216	2760
234	2770
252	2755
276	2735
294	2770
306	2695
324	2760
336	2770

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

Sample appeared to show a top ignition. A heavy oxide coating observed on the sample.

Table A-27

Experiment No. 23

Material — Type 316 Stainless Steel

Flame Environment — H_2-O_2

Initial Weight — 1.4918 g

Final Weight — Not Obtainable

Apparent Corrosion Rate — Not Obtainable

Calculated Steady State Temperature — 2920°F

Temperature-Time Date:

	Two Color Pyrometer
Time (sec)	Temperature (°F)
0 +	2600
3	2600
4	2710
5	2660
7	2740
8	2890
9	3030
12	3030
14	3280
14.5	3410
15	3420
21	3340
28.5	3430
29	3030
30	3150
31	2970

REMARKS:

Sample ignited almost instantly. The sample tob blew off in an explosive fashion. An optical pyrometer reading showed a temperature of 1450°C just prior to the explosion.

Table A-28

Experiment No. 24

Material — Type 316 Stainless Steel

Flame Environment — H_2-O_2

Initial Weight — 1.5739 g

Final Weight — 1.5390 g

Apparent Corrosion Rate — -344 mg/cm^2-hr

Calculated Steady State Temperature — 2340°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
30	2157 B*	210	2600
45	2244 T*	213	2620
60	2305 T	216	2612
90	2367 T	217	2600
95	2209 B		
120	2505 T		
150	2468 T		
160	2244 B		
180	2487 T		
240	2487 T		
270	2487 T		
300	2244 B		
330	2505 T		
360	2487 T		

B* = Bottom of Sample; T* = Top of Sample

REMARKS:

Sample appeared to bubble on upper most edges. A visible oxide coating formed on the sample.

Table A-29

Experiment No. 25

Material — Type 316 Stainless Steel

Flame Environment — H_2-O_2

Initial Weight — 1.5174 g

Final Weight — 1.4145 g

Apparent Corrosion Rate — -898 mg/cm^2-hr

Calculated Steady State Temperature — 2045°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
60	1657 T*
80	1584 B*
90	1789 T
120	1901 T
150	1959 T
180	1959 T
210	2137 T
240	2137 T
270	1881 B
300	2157 T
360	2137 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

No signs of melting or ignition. Very little, if any, sample deterioration. Slight oxide formation on sample surface.

Table A-30

Experiment No. 36

Material — Type 316 Stainless Steel

Flame Environment — H_2-O_2

Initial Weight — 1.7317 g

Final Weight — 1.7434 g

Apparent Corrosion Rate — +30.7 mg/cm^2-hr

Calculated Steady State Temperature — 2135°F

Temperature-Time Data:

Time (sec)	Optical Pyrometer Temperature (°F)
120	2110 T*
240	2037 B*
360	2244 T
480	2085 B
600	2264 T
720	2110 B
840	2285 T
960	2143 B
1080	2285 T
1200	2143 B

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

No ignition, melting, or bubbling. No visible sample erosion. A visible oxide coating was observed on the sample surface.

Table A-31

Experiment No. 37

Material — Type 316 Stainless Steel

Flame Environment — H_2-O_2

Initial Weight — 1.7474 g

Final Weight — 1.7492 g

Apparent Corrosion Rate — +4.72 mg/cm^2-hr

Calculated Steady State Temperature — 2320°F

Temperature-Time Data:

Time (sec)	Optical Pyrometer Temperature (°F)
60	2094 T*
120	2176 T
240	2226 T
270	2110 B*
360	2285 T
420	2326 T
480	2346 T
600	2127 B
660	2346 T
880	2143 B
900	2356 T
1020	2367 T
1140	2160 B
1200	2367 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

No ignition, melting, or bubbling. A thin oxide coating was observed on the sample surface.

Table A-32

Experiment No. 26

Material—Haynes Alloy 25

Flame Environment—H_2-O_2

Initial Weight—2.0643 g

Final Weight—2.0383 g

Apparent Corrosion Rate— -227 mg/cm^2-hr

Calculated Steady State Temperature—2540 °F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
30	2094 B*
60	2438 T*
90	2543 T
120	2543 T
150	2562 T
180	2264 B
210	2562 T
240	2543 T
270	2264 B
300	2562 T
360	2580 T

B* = Bottom of Sample; T* = Top of Sample

REMARKS:

No hot zones or bubbling observed. A dark brown flakey oxide coating resulted.

Table A-33

Experiment No. 27

Material—Haynes Alloy 25

Flame Environment—H_2-O_2

Initial Weight—2.0378 g

Final Weight—2.0354 g

Apparent Corrosion Rate—-19.72 mg/cm^2-hr

Calculated Steady State Temperature—2670°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
30	2244 T*	243	2618
60	2580 T	255	2675
90	2209 B*	261	2638
135	2618 T	267	2635
150	2002 B	279	2695
180	2697 T	288	2675
210	2717 T	294	2745
240	2677 T	303	2762
270	2346 B	309	2779
300	2737 T	330	2788
330	2837 T	342	2864
345	2757 T	369	2854
360	2367 B	378	2795

T* = Top of Sample, B* = Bottom of Sample

REMARKS:

Sample showed a top hot spot with considerable top erosion or melting. No visible bubbling or spalling.

Table A-34

Experiment No. 28

Material—Haynes Alloy 25

Flame Environment—H_2-O_2

Initial Weight—2.0847 g

Final Weight—2.0244 g

Apparent Corrosion Rate—-442 mg/cm^2-hr

Calculated Steady State Temperature—2770°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
30	2407 T*	123	2600
45	2562 T	138	2640
60	2737 T	147	2675
90	2305 B*	153	2718
120	2797 T	161	2730
135	2872 T	185	2718
150	2977 T	197	2743
180	2418 B	233	2760
240	3093 T	256	2843
270	3133 T	280	2830
300	3154 T	340	2770
315	2367 B	395	2760
330	3214 T	419	2688
420	3234 T	428	2665

T* = Top of Sample, B* = Bottom of Sample

REMARKS:

A top hot zone formed with mushrooming effect. Formation of black oxide coating observed.

Table A-35

Experiment No. 29

Material—Haynes Alloy 25

Flame Environment—H_2-O_2

Initial Weight—2.0692 g

Final Weight—0.3848 g

Apparent Corrosion Rate—Unavailable (Sample melted)

Calculated Steady State Temperature—3000°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
30	2959*	21	2630
		25.5	2970
		28.13	3377
		33	3160
		39	3144
		45	3100
		51	2862
		54	2942
		57	2955
		60	2880
		63	3097
		66	3038
		70.5	2862

T* = Top of Sample

REMARKS:

Sample appeared to melt. A great deal of sample corrosion was observed.

Table A-36

Experiment No. 30

Material—Haynes Alloy 25

Flame Environment—H_2-O_2

Initial Weight—2.0031 g

Final Weight—2.0436 g

Apparent Corrosion Rate—+353 mg/cm^2-hr

Calculated Steady State Temperature—2380°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
30	1920 T*
60	2094 T
90	1845 B*
120	2176 T
150	2244 T
180	2285 T
210	2285 T
240	2285 T
300	2275 T
315	2077 B
330	2305 T
360	2305 T

T* = Top of Sample, B* = Bottom of Sample

REMARKS:

Sample showed no signs of melting or ignition. Thin coating formed on the surface.

Table A-37

Experiment No. 31
Material—Haynes Alloy 25
Flame Environment—H_2-O_2
Initial Weight—2.0987 g
Final Weight—2.0801 g
Apparent Corrosion Rate—-162.3 mg/cm^2-hr
Calculated Steady State Temperature—1810°F
Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
60	1566 T*
120	1676 T
180	1734 T
240	1734 T
300	1771 T
360	1771 T

T* = Top of Sample

REMARKS:

No melting or ignition. Very little, if any, observable corrosion.

Table A-38

Experiment No. 38

Material—Haynes Alloy 25

Flame Environment—H_2-O_2

Initial Weight—2.0703 g

Final Weight—2.0733 g

Apparent Corrosion Rate—+2.62 mg/cm^2-hr

Calculated Steady State Temperature—2045°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
30	1584 T*
60	1734 T
90	1881 T
120	1771 B*
130	1920 T
180	1979 T
210	1998 T
240	1998 T
270	1998 T
280	1845 B
300	1998 T
360	1998 T

T* = Top of Sample, B* = Bottom of Sample

REMARKS:

No bubbling or spalling observed. Very slight sample discoloration. No flakey oxide coating observed.

Table A-39

Experiment No. 39

Material—Haynes Alloy 25

Flame Environment—H_2-O_2

Initial Weight—2.0743 g

Final Weight—2.0652 g

Apparent Corrosion Rate—+0.786 mg/cm^2-hr

Calculated Steady State Temperature—2135°F

Temperature -Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
30	1789 T*
60	1979 T
90	2094 T
120	1940 B*
150	2127 T
180	2143 T
240	2160 T
270	2160 T
300	2160 T
315	1998 B
330	2160 T
360	2160 T

T* = Top of Sample, B* = Bottom of Sample

REMARKS:

Very slight oxide coating observed on sample top. No melting or bubbling.

Table A-40

Experiment No. 40
Material—Haynes Alloy 25
Flame Environment—H_2-O_2
Initial Weight—2.0666 g
Final Weight—2.0537 g
Apparent Corrosion Rate— -112.5 mg/cm^2-hr
Calculated Steady State Temperature—2340°F
Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
30	1979 T*
60	2260 T
90	2127 B*
120	2346 T
150	2397 T
180	2418 T
240	2244 B
270	2397 T
300	2397 T
360	2397 T

T* = Top of Sample, B* = Bottom of Sample

REMARKS:

No melting or bubbling. Visible white intermittent oxide coating on upper half and top of sample.

Table A-41

Experiment No. 41
Material—Haynes Alloy 25
Flame Environment—H_2-O_2
Initial Weight—2.0701 g
Final Weight—2.0606 g
Apparent Corrosion Rate— -82.8 mg/cm^2-hr
Calculated Steady State Temperature—2495°F
Temperature - Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
15	2244 T*
45	2505 T
60	2599 T
90	2285 B*
120	2609 T
150	2609 T
180	2609 T
210	2326 B
240	2628 T
300	2628 T
360	2628 T

T* = Top of Sample, B* = Bottom of Sample

REMARKS:

No general melting apparent. Sample top shows pitting and slight mushrooming. Oxide coating visible over entire sample.

Table A-42

Experiment No. 42
Material—Haynes Alloy 25
Flame Environment—H_2-O_2
Initial Weight—2.0519 g
Final Weight—2.0929 g
Apparent Corrosion Rate—+596 mg/cm^2-hr
Calculated Steady State Temperature—2805°F
Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
15	2580 T*	18	2600
45	2924 T	24	2670
60	2599 T	30	2730
90	2959 T	36	2800
135	2977 T	45	2825
180	2977 T	54	2860
210	2817 B*	66	2875
		81	2880
		108	2898
		135	2898
		171	2885
		192	2905
		198	2998
		207	3122
		211.5	3182
		216	2897

T* = Top of Sample, B* = Bottom of Sample

REMARKS:

Complete sample melting. Heavy oxide coating over entire melt.

Table A-43

Experiment No. 43

Material—Haynes Alloy 25

Flame Environment—H_2-O_2

Initial Weight—2.0679 g

Final Weight—1.9980 g

Apparent Corrosion Rate— -2850 mg/cm^2-hr

Calculated Steady State Temperature—2920°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
15	2959 T*	0+	2600
30	3113 T	3	2810
60	3194 T	6	2836
70	3214 T	9	2924
		12	2960
		18	3019
		24	3046
		33	3076
		63	3097
		69	3120
		71	3215
		74	3235
		75.5	3314
		77	3130

T* = Top of Sample

REMARKS:

Complete sample melting. Sample collapsed during melting and experiment stopped at 77 seconds elapsed time. Sample shows heavy oxide coating.

Table A-44

Experiment No. 44
Material—Haynes Alloy 25
Flame Environment—H_2-O_2
Initial Weight—2.0613 g
Final Weight—-2.0796 g
Apparent Corrosion Rate—+47.9 mg/cm^2-hr
Calculated Steady State Temperature—2160°F
Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
60	2160 T*
120	2305 T
150	2209 B*
180	2367 T
240	2244 B
300	2346 T
420	2367 T
480	2244 B
600	2367 T
606	2254 B
840	2367 T
900	2244 B
1020	2367 T
1200	2367 T

T* = Top of Sample, B* = Bottom of Sample

REMARKS

Sample shows white spotty coating over entire length. Sample top shows considerable pitting. No observable melting.

Table A-45

Experiment No. 45

Material — Haynes Alloy 25

Flame Environment — H_2-O_2

Initial Weight — 2.0551g

Final Weight — 2.0508g

Apparent Corrosion Rate — -11.28 mg/cm^2-hr

Calculated Steady State Temperature — 2380°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
30	1979 T*
60	2143 T
120	2254 T
180	2077 B*
300	2305 T
420	2305 T
540	2326 T
600	2094 B
720	2326 T
900	2346 T
1080	2346 T
1200	2336 T

T* = Top of Sample, B* = Bottom of Sample

REMARKS:

Flakey dark oxide coating over entire length of sample. Sample shows negligible pitting. No apparent sample melting.

Table A-46

Experiment No. 122

Material — Haynes Alloy 25

Flame Environment — $CO-O_2$

Initial Weight — 2.0813 g

Final Weight — 2.0819 g

Apparent Corrosion Rate — 5.23 mg/cm^2-hr

Calculated Steady State Temperature — 2085°F

Temperature-Time Data:

Optical Pyrometer	
Time (sec)	Temperature (°F)
15	1603 T*
60	1920 T
90	2077 T
100	1920 B*
120	2085 T
160	1940 B
210	2094 T
250	1959 B
270	2143 T
300	2135 T
305	1959 B
320	2135 T
340	1959 B
360	2143 T

T* = Top of Sample, B* = Bottom of Sample

REMARKS:

A thin coating over the entire sample length was observed. Sample top shows negligible pitting.

Table A-47

Experiment No. 123
Material — Haynes Alloy 25
Flame Environment — $CO\text{-}O_2$
Initial Weight — 2.0864 g
Final Weight — 2.0868 g
Apparent Corrosion Rate — 3.47 $mg/cm^2\text{-}hr$
Calculated Steady State Temperature — 2015°F
Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
30	1696 T*
45	1863 T
60	1696 B*
75	1891 T
120	2057 T
130	1881 B
160	2086 T
180	2086 T
220	1901 B
240	2094 T
280	1910 B
300	2102 T
330	2102 T
360	2110 T

T* = Top of Sample, B* = Bottom of Sample

REMARKS:

Sample shows a very thin oxide coating over entire length. Sample top shows no pitting or corrosion.

Table A-48

Experiment No. 124
Material — Haynes Alloy 25
Flame Environment — CO-O_2
Initial Weight — 2.0503 g
Final Weight — 2.0504 g
Apparent Corrosion Rate — 0.973 mg/cm^2-hr
Calculated Steady State Temperature — 2085°F
Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
30	1789 T*
60	1901 T
70	1711 B*
90	2057 T
100	1808 B
120	2193 T
130	1979 B
150	2143 T
190	1979 B
240	2135 T
250	1979 B
270	2143 T
280	1998 B
300	2143 T
330	2143 T
340	1998 B
360	2152 T

T* = Top of Sample, B* = Bottom of Sample

REMARKS:

See Remarks Experiment No. 122.

Table A-49

Experiment No. 125

Material—Haynes Alloy 25

Flame Environment—$CO-O_2$

Initial Weight—2.0785 g

Final Weight—2.0787 g

Apparent Corrosion Rate—0.0667 mg/cm^2-hr

Calculated Steady State Temperature—2085°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
30	1734 T*
75	1881 B*
120	2160 T
150	1998 B
180	2160 T
225	2037 B
240	2193 T
300	2037 B
360	2193 T
420	2037 B
480	2226 T
660	2037 B
720	2209 T
900	2097 B
960	2217 T
1140	2037 B
1200	2209 T

T* = Top of Sample, B* = Bottom of Sample

REMARKS:

A flakey oxide coating was observed to form on the top of the sample only. A white intermittent coating was observed to form on the remainder of the sample.

Table A-50

Experiment No. 126

Material — Haynes Alloy 25

Flame Environment — CO-O_2

Initial Weight — 2.0800 g

Final Weight — 2.0841 g

Apparent Corrosion Rate — 35.74 mg/cm^2-hr

Calculated Steady State Temperature — 2000°F

Temperature-Time Data:

Optical Pyrometer	
Time (sec)	Temperature (°F)
15	1657 T*
30	1959 T
60	2160 T
70	1979 B*
120	2209 T
150	2077 B
180	2209 T
220	2077 B
240	2209 T
250	2057 B
270	2201 T
310	2057 B
330	2209 T
360	2209 T

T* = Top of Sample, B* =Bottom of Sample

REMARKS:

A flakey oxide coating was observed over entire sample length. The sample top showed negligible erosion.

Table A-51

Experiment No. 127

Material — Haynes Alloy 25

Flame Environment — CO-O_2

Initial Weight — 2.0505 g

Final Weight — 2.0537 g

Apparent Corrosion Rate — 27.87 mg/cm^2-hr

Calculated Steady State Temperature — 2080°F

Temperature - Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
15	1826 T*
30	2094 T
60	2235 T
70	2085 B*
90	2285 T
120	2285 T
130	2143 B
150	2285 T
180	2285 T
190	2127 B
210	2295 T
240	2295 T
270	2135 B
300	2295 T
330	2127 B
360	2295 T

T* = Top of Sample, B* =Bottom of Sample

REMARKS:

Sample shows a flakey oxide coating over entire length. The sample top shows very slight pitting.

Table A-52

Experiment No. 128

Material—Haynes Alloy 25

Flame Environment—CO-O_2

Initial Weight—2.0756 g

Final Weight—2.0839 g

Apparent Corrosion Rate—72.3 mg/cm^2-hr

Calculated Steady State Temperature—2165°F

Temperature-Time Data:

Time (sec)	Optical Pyrometer Temperature (°F)
15	2020 T*
30	2280 T
60	2420 T
75	2260 B*
90	2460 T
120	2470 T
130	2250 B
150	2480 T
180	2480 T
190	2280 B
210	2290 B
240	2280 B
270	2470 T
300	2290 B
330	2480 T
360	2480 T

T* = Top of Sample, B* = Bottom of Sample

REMARKS:

A heavy, flakey oxide coating was observed over the entire sample length. The sample top shows considerable pitting.

Table A-53

Experiment No. 46
Material—Hastelloy C
Flame Environment—H_2-O_2
Initial Weight—2.0459g
Final Weight—2.0458g
Apparent Corrosion Rate— -0.89 mg/cm^2-hr
Calculated Steady State Temperature—1810°F
Temperature-Time Data:

Time (sec)	Optical Pyrometer Temperature (°F)
30	1603 T*
60	1639 T
120	1696 T
180	1734 T
210	1603 B*
240	1752 T
300	1752 T
360	1761 T

T* = Top of Sample; B* = Bottom of Sample.

REMARKS:

No melting or hot spots observed. No sample deterioration. A very thin oxide coating formed.

Table A-54

Experiment No. 47

Material—Hastelloy C

Flame Environment—H_2-O_2

Initial Weight—2.0616g

Final Weight—2.0600g

Apparent Corrosion Rate— -13.96 mg/cm^2-hr

Calculated Steady State Temperature—2380°F

Temperature-Time Data:

Time (sec)	Optical Pyrometer Temperature (°F)
30	2037 T*
60	2305 T
120	2397 T
150	2086 B*
180	2438 T
240	2450 T
300	2450 T
360	2450 T

T* = Top of Sample; B* = Bottom of Sample.

REMARKS:

No melting or hot spots observed. The sample top shows very slight pitting. A visible oxide coating formed.

Table A-55

Experiment No. 48
Material—Hastelloy C
Flame Environment—H_2-O_2
Initial Weight—2.0500g
Final Weight—2.0468g
Apparent Corrosion Rate— -27.9 mg/cm^2-hr
Calculated Steady State Temperature—2540°F
Temperature-Time Data:

	Optical Pyrometer
Time (sec)	Temperature (sec)
30	2346 T*
60	2428 T
75	2086 B*
90	2468 T
120	2478 T
150	2143 B
180	2468 T
195	2127 B
240	2468 T
255	2094 B
300	2450 T
360	2450 T

T* = Top of Sample; B* = Bottom of Sample.

REMARKS:

The sample top shows some melting; top erosion moderate. A visible oxide coating was observed over the entire sample length.

Table A-56

Experiment No. 49

Material—Hastelloy C

Flame Environment—H_2-O_2

Initial Weight—2.0691g

Final Weight—2.0689g

Apparent Corrosion Rate— -1.745 mg/cm^2-hr

Calculated Steady State Temperature—2670°F

Temperature-Time Data:

Time (sec)	Optical Pyrometer Temperature (°F)
30	2525 T*
60	2580 T
90	2160 B*
120	2580 T
165	2160 B
180	2618 T
240	2618 T
270	2143 B
300	2618 T
330	2618 T
360	2618 T

T* = Top of Sample; B* = Bottom of Sample.

REMARKS:

Melting was observed at 30 seconds on the sample top. Considerable top erosion evident. A visible oxide coating formed.

Table A-57

Experiment No. 50
Material — Hastelloy C
Flame Environment — H_2-O_2
Initial Weight — 1.9428g
Final Weight — 1.9422g
Apparent Corrosion Rate — -5.23 mg/cm^2-hr
Calculated Steady State Temperature — 2770°F
Temperature-Time Data:

Time (sec)	Optical Pyrometer Temperature (°F)
30	2562 T*
40	2226 B*
60	2585 T
90	2244 B
120	2637 T
135	2264 B
150	2637 T
180	2637 T
210	2637 T
225	2264 B
240	2637 T
300	2637 T
360	2637 T

T* = Top of Sample; B* = Bottom of Sample.

REMARKS:

The sample top shows a great deal of erosion attributable to melting. A heavy oxide coating formed over the entire sample length.

Table A-58

Experiment No. 51
Material—Hastelloy C
Flame Environment—H_2-O_2
Initial Weight—1.9862g
Final Weight—1.8646g
Apparent Corrosion Rate— -10,620 mg/cm^2-hr
Calculated Steady State Temperature—3000°F
Temperature-Time Data:

Two Color Pyrometer

Time (sec)	Temperature (°F)
6	2600
7.5	2915
9	2885
12	2885
15	2885
15+	2895
18	2830
21	2950
24	2770
27	2830
30	2854
33	2895
36	2922

REMARKS:

Very rapid melting observed. Exposed portion of sample 100 percent eroded. However, no apparent ignition occurred.

Table A-59

Experiment No. 52

Material—Hastelloy C

Flame Environment—H_2-O_2

Initial Weight—2.1128g

Final Weight—2.1128g

Apparent Corrosion Rate—0 mg/cm^2-hr

Calculated Steady State Temperature—2045°F

Temperature-Time Data:

	Optical Pyrometer
Time (sec)	Temperature (°F)
30	1696 T*
60	1920 T
90	1998 T
105	1798 B*
120	1998 T
135	1808 B
150	2037 T
180	2037 T
210	2057 T
225	1863 B
240	2057 T
270	2057 T
285	1863 B
300	2057 T
360	2057 T

T* = Top of Sample; B* = Bottom of Sample.

REMARKS:

No melting, etc. No visible sample erosion. Little, if any, oxide film observed.

Table A-60

Experiment No. 53

Material—Hastelloy C

Flame Environment—H_2-O_2

Initial Weight—2.0295g

Final Weight—2.0298g

Apparent Corrosion Rate— +2.62 mg/cm^2-hr

Calculated Steady State Temperature—2135°F

Temperature-Time Data:

Time (sec)	Optical Pyrometer Temperature (°F)
30	1771 T*
60	2028 T
90	2102 T
105	1911 B
120	2127 T
135	1920 B
150	2160 T
180	2160 T
210	2160 T
240	1979 B
270	2226 T
300	2226 T
330	2226 T
360	2226 T

T* = Top of Sample; B* = Bottom of Sample.

REMARKS:

No observable sample erosion apparent. A very thin oxide film formed.

Table A-61

Experiment No. 54
Material—Hastelloy C
Flame Environment—H_2-O_2
Initial Weight—2.0313g
Final Weight—2.0303g
Apparent Corrosion Rate— -8.93 mg/cm^2-hr
Calculated Steady State Temperature—2340°F
Temperature-Time Data:

	Optical Pyrometer
Time (sec)	Temperature (°F)
30	2077 T*
60	2254 T
90	2305 T
120	1930 B*
150	2305 T
180	2110 B
210	2326 T
225	2127 B
240	2326 T
270	2326 T
300	2326 T
315	2143 B
360	2326 T

T* = Top of Sample; B* = Bottom of Sample.

REMARKS:

Very slight sample top erosion. A thin oxide coating formed on the sample surface.

Table A-62

Experiment No. 55
Material—Hastelloy C
Flame Environment—H_2-O_2
Initial Weight—2.0377g
Final Weight—2.0373g
Apparent Corrosion Rate— -3.49 mg/cm^2-hr
Calculated Steady State Temperature—2495°F
Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
30	2438 T*	283	2600
60	2543 T	294	2610
75	2305 B*	327	2618
120	2543 T	333	2622
150	2580 T	348	2628
180	2305 B	363	2630
210	2599 T	366	2629
240	2599 T		
270	2637 T		
300	2637 T		
360	2637 T		

T* = Top of Sample; B* = Bottom of Sample.

REMARKS:

The sample top shows considerable erosion due to melting. A moderate oxide coating observed on the remainder of the sample.

Table A-63

Experiment No. 56

Material—Hastelloy C

Flame Environment—H_2-O_2

Initial Weight—2.0545 g

Final Weight—1.4736 g

Apparent Corrosion Rate—-28,410 mg/cm^2-hr

Calculated Steady State Temperature—2805°F

Temperature—Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature ($^{\circ}$F)	Time (sec)	Temperature ($^{\circ}$F)
30	2737 T^*	21	2614
		24	2630
		27	2665
		30	2683
		33	2705
		36	2700
		39	2683
		42	2705
		45	2790
		48	2820
		51	2845
		54	2850
		57	2860
		60	2923
		63	2950

T^* = Top of Sample

REMARKS:

Early signs of melting. By 30 seconds 2/3 of the sample had melted. The sample then collapsed into a molten drop. Complete erosion.

Table A-64

Experiment No. 57

Material—Hastelloy C

Flame Environment—H_2-O_2

Initial Weight—2.0093 g

Final Weight—0.9785 g

Apparent Corrosion Rate— -77,200 mg/cm^2-hr

Calculated Steady State Temperature—2920°F

Temperature—Time Data:

Two Color Pyrometer

Time (sec)	Temperature (°F)
1.50	2600
3.00	2695
4.50	2625
7.50	2640
12.75	2682
15.00	2715
18.00	2733
21.00	2810
24.00	2880
27.00	2880
30.00	2810
31.50	2960
33.00	2700
35.25	2737
39.75	2862
41.61	2737

REMARKS:

Very rapid, if not instantaneous, melting and sparking. Sample coagulated into a molten drop. Complete erosion.

Table A-65

Experiment No. 58

Material—Hastelloy C

Flame Environment—H_2-O_2

Initial Weight—2.1041 g

Final Weight—2.1011 g

Apparent Corrosion Rate—-7.86 mg/cm^2-hr

Calculated Steady State Temperature—2540°F

Temperature—Time Data:

	Optical Pyrometer
Time (sec)	Temperature (°F)
60	2305 T*
120	2346 T
180	2143 B*
300	2367 T
360	2176 B
420	2367 T
600	2382 T
660	2193 B
840	2382 T
870	2193 B
1020	2382 T
1050	2193 B
1200	2382 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

See remarks experiment No. 48.

Table A-66

Experiment No. 59
Material—Hastelloy C
Flame Environment—H_2-O_2
Initial Weight—2.0452 g
Final Weight—2.0446 g
Apparent Corrosion Rate— -1.572 mg/cm^2-hr
Calculated Steady State Temperature—2340°F
Temperature—Time Data:

	Optical Pyrometer
Time (sec)	Temperature (°F)
60	2264 T*
120	2367 T
240	2418 T
270	2193 B*
420	2418 T
480	2209 B
600	2418 T
720	2418 T
840	2418 T
870	2217 B
960	2367 T
990	2209 B
1080	2367 T
1200	2382 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

Very slight top melting observed with negligible erosion. A visible oxide coating formed on the sample surface.

Table A-67

Experiment No. 60
Material—Hastelloy X
Flame Environment—H_2-O_2
Initial Weight—1.9007 g
Final Weight—1.9006 g
Apparent Corrosion Rate— -1.047 mg/cm^2-hr
Calculated Steady State Temperature—1810°F
Temperature—Time Data:

	Optical Pyrometer
Time (sec)	Temperature (°F)
30	1530 T*
60	1639 T
120	1752 T
135	1548 B*
150	1771 T
210	1771 T
240	1566 B
270	1771 T
300	1771 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

No melting or any signs of erosion except for sample discoloration.

Table A-68

Experiment No. 61

Material—Hastelloy X

Flame Environment—H_2-O_2

Initial Weight— 1.8726 g

Final Weight— 1.8724 g

Apparent Corrosion Rate— -1.748 mg/cm^2-hr

Calculated Steady State Temperature—2380°F

Temperature— Time Data:

	Optical Pyrometer
Time (Sec)	Temperature (°F)
30	2160 T*
60	2193 T
90	2285 T
120	2110 B*
150	2305 T
180	2326 T
240	2326 T
250	2127 B
270	2326 T
300	2326 T
310	2143 B
330	2326 T
360	2326 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

No melting. Sample top shows negligible erosion. A very thin oxide coating was observed.

Table A-69

Experiment No. 62

Material—Hastelloy X

Flame Environment—H_2-O_2

Initial Weight— 1.8684 g

Final Weight— 1.8691 g

Apparent Corrosion Rate—+6.10 mg/cm^2-hr

Calculated Steady State Temperature—2540°F

Temperature— Time Data:

Time (Sec)	Optical Pyrometer Temperature (°F)
30	2244 T*
60	2346 T
90	2143 B*
150	2438 T
180	2459 T
240	2459 T
250	2285 B
270	2468 T
300	2459 T
315	2285 B
360	2459 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

Sample top shows slight pitting. Extent of erosion is small though. A visible oxide coating formed on the surface.

Table A-70

Experiment No. 63
Material—Hastelloy X
Flame Environment—H_2-O_2
Initial Weight—1.7987 g
Final Weight—1.8016 g
Apparent Corrosion Rate—+25.3 mg/cm^2-hr
Calculated Steady State Temperature—2670°F
Temperature—Time Data:

	Optical Pyrometer
Time (Sec)	Temperature (°F)
30	2346 T*
60	2450 T
90	2209 B*
120	2515 T
150	2543 T
180	2285 B
210	2543 T
240	2543 T
270	2285 B
300	2543 T
330	2553 T
360	2553 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

A rapid reaction zone was observed on the sample top. Partial melting may have occurred. The sample was covered by an oxide film.

Table A-71

Experiment No. 64

Material—Hastelloy X

Flame Environment—H_2-O_2

Initial Weight— 1.8612 g

Final Weight— 1.8636 g

Apparent Corrosion Rate— +20.92 mg/cm^2-hr

Calculated Steady State Temperature— 2770°F

Temperature— Time Data:

Time (Sec)	Optical Pyrometer Temperature (°F)
30	2487 T*
60	2505 T
90	2505 T
120	2209 B*
150	2505 T
180	2505 T
210	2505 T
240	2244 B
300	2505 T
360	2505 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

Top melting observed at 30 seconds. The sample top severely eroded and pitted.

Table A-72

Experiment No. 65

Material—Hastelloy X

Flame Environment—H_2-O_2

Initial Weight—1.8979 g

Final Weight—1.9017 g

Apparent Corrosion Rate—+33.15 mg/cm^2-hr

Calculated Steady State Temperature—3000°F

Temperature—Time Data:

Optical Pyrometer

Time (Sec)	Temperature (°F)
30	2367 T*
60	2346 T
90	2176 B*
120	2450 T
180	2459 T
210	2209 B
240	2505 T
300	2468 T
310	2209 B
330	2468 T
360	2468 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

Very severe sample top erosion observed. Partial top melting apparent. The remainder of the sample shows negligible erosion.

Table A-73

Experiment No. 66

Material—Hastelloy X

Flame Environment—H_2-O_2

Initial Weight—1.8946g

Final Weight—1.8949g

Apparent Corrosion Rate—+2.618 mg/cm^2-hr

Calculated Steady State Temperature—2045°F

Temperature-Time Data:

Time (sec)	Optical Pyrometer Temperature (°F)
30	1808 T*
60	1920 T
90	1734 B*
120	1998 T
150	2090 T
180	1930 B
210	2110 T
240	2110 T
300	2110 T
310	1940 B
330	2110 T
360	2110 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS

No melting and no erosion observed. A very thin oxide film formed.

Table A-74

Experiment No. 67
Material—Hastelloy X
Flame Environment—H_2-O_2
Initial Weight—1.8661g
Final Weight—1.8668g
Apparent Corrosion Rate—+6.11 mg/cm^2-hr
Calculated Steady State Temperature—2135°F
Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
30	1881 T*
60	2077 T
90	2143 T
120	1998 B*
150	2209 T
180	2226 T
210	2037 B
240	2226 T
270	2037 B
300	2226 T
330	2226 T
360	2226 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS

No melting and no erosion apparent. A thin oxide film formed over the entire sample length.

Table A-75

Experiment No. 68

Material—Hastelloy X

Flame Environment—H_2-O_2

Initial Weight—1.8324g

Final Weight—1.8327g

Apparent Corrosion Rate—+2.618 mg/cm^2-hr

Calculated Steady State Temperature—2340°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
30	1920 T*
60	2057 T
90	2143 T
120	1920 B*
150	2264 T
180	2295 T
210	2057 B
240	2305 T
270	2326 T
280	2094 B
300	2315 T
330	2315 T
360	2315 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS

Very slight top erosion observed. A thin oxide coating was observed.

Table A-76

Experiment No. 69

Material—Hastelloy X

Flame Environment—H_2-O_2

Initial Weight—1.8740g

Final Weight—1.8740g

Apparent Corrosion Rate—0

Calculated Steady State Temperature—2495°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
30	1920 T*
60	2057 T
90	2143 T
120	1920 B*
150	2264 T
180	2295 T
210	2057 B
240	2305 T
270	2326 T
280	2094 B
300	2315 T
330	2315 T
360	2315 T

T* = Top of Sample; B* = Bottom of Sample.

REMARKS

Top melting observed with subsequent erosion. A thin oxide film formed on the sample surface.

Table A-77

Experiment No. 70
Material—Hastelloy X
Flame Environment—H_2-O_2
Initial Weight—1.8619g
Final Weight—1.8637g
Apparent Corrosion Rate—+99.3 mg/cm^2-hr
Calculated Steady State Temperature—2805°F
Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
~10	2717 MT*	12	2600
		18	2645
		24	2675
		27	2753
		30	2770
		36	2802
		42	2828
		48	2838
		51	2868
		54	2898
		57	2942

MT* = Molten Temperature

REMARKS:

Very rapid top melting. Sample top completely eroded.

Table A-78

Experiment No. 71
Material—Hastelloy X
Flame Environment—H_2-O_2
Initial Weight—1.8715g
Final Weight—1.8574g
Apparent Corrosion Rate—+537.5 mg/cm^2-hr
Calculated Steady State Temperature—2920°F
Temperature-Time Data:

Two Color Pyrometer	
Time (sec)	Temperature (°F)
1.5	2600
3	2690
6	2630
9	2753
12	2779
18	2746
21	3018
24	2989
27	3177
30	3150
33	3109
34.5	3088

REMARKS:

Instant top melting observed. Sample top and exposed portion completely eroded. An optical melt temperature of 2757°F was recorded (only optical data point).

Table A-79

Experiment No. 72

Material—Hastelloy X

Flame Environment—H_2-O_2

Initial Weight—1.8878g

Final Weight—1.8869g

Apparent Corrosion Rate—-2.356 mg/cm^2-hr

Calculated Steady State Temperature—2380°F

Temperature-Time Data:

Optical Pyrometer	
Time (sec)	Temperature (°F)
60	2305 T*
120	2367 T
180	2367 T
210	2110 B*
270	2346 T
300	2346 T
360	2346 T
420	2127 B
480	2346 T
540	2346 T
600	2346 T
720	2143 B
840	2346 T
960	2367 T
1080	2367 T
1200	2367 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

No melting observed. No sample erosion visible. A thin oxide coating formed.

Table A-80

Experiment No. 73
Material—Hastelloy X
Flame Environment—H_2-O_2
Initial Weight—1.8661g
Final Weight—1.8654g
Apparent Corrosion Rate— -1.832 mg/cm^2-hr
Calculated Steady State Temperature—2340°F
Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
60	2160 T*
120	2244 T
180	2305 T
240	2346 T
300	2346 T
360	2127 B*
420	2346 T
480	2143 B
600	2346 T
660	2143 B
720	2346 T
840	2346 T
960	2152 B
1080	2356 T
1200	2356 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

See Remarks Experiment No. 72.

Table A-81

Experiment No. 74
Material—Uncoated Tungsten
Flame Environment—H_2-O_2
Initial Weight—1.4471g
Final Weight—1.4632g
Apparent Corrosion Rate—-193.3 mg/cm^2-hr
Calculated Steady State Temperature—1970°F

Optical Pyrometer

Time (sec)	Temperature (°F)
30	2080 T*
60	2080 T
90	2080 T
120	2140 T
180	1540 B*
210	2160 T
240	1560 B
270	2180 T
300	2160 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

No signs of rapid reaction. Very little sample deterioration. A powdery green oxide coating formed.

Table A-82

Experiment No. 75

Material— Uncoated Tungsten

Flame Environment—H_2-O_2

Initial Weight— 1.4627g

Final Weight— 0.2462g

Apparent Corrosion Rate— -1.332 x 10^5 mg/cm^2-hr

Calculated Steady State Temperature—2530°F

Temperature-Time Data:

Two Color Pyrometer

Time (sec)	Temperature (°F)
3	2600
4.5	2660
6	3600
9	3620
12	3120
15	3395
18	3160
21	3300
24	2845
27	2925

REMARKS:

A very rapid ignition was observed. A considerable amount of vapor evolved from sample upon ignition. A very heavy oxide coating formed on the sample. Total sample erosion.

Table A-83

Experiment No. 76

Material—Uncoated Tungsten

Flame Environment—H_2-O_2

Initial Weight— 1.4754 g

Final Weight— 1.4254 g

Apparent Corrosion Rate— -600 mg/cm^2-hr

Calculated Steady State Temperature—2110°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
15	2560 T*
30	2560 T
60	2600 T
90	2000 B*
120	2640 T
130	2660 T
150	2660 T
180	2060 B
210	2660 T
240	2660 T
300	2660 T

T* = Top of Sample

B* = Bottom of Sample

REMARKS:

The sample did not appear to ignite. Little sample erosion. A thin oxide coating formed.

Table A-84

Experiment No. 77

Material—Uncoated Tungsten

Flame Environment—H_2-O_2

Initial Weight—1.4711 g

Final Weight—1.3910 g

Apparent Corrosion Rate— -961 mg/cm^2-hr.

Calculated Steady State Temperature—2180°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
30	2700 T*
60	2700 T
90	1980 B*
120	2700 T
150	2700 T
180	2740 T
200	2020 B
240	2700 T
270	2020 B
300	2700 T

T* = Top of Sample

B* = Bottom of Sample

REMARKS:

No signs of rapid reaction. Some sample deterioration due to oxidation.

Table A-85

Experiment No. 78
Material — Uncoated Tungsten
Flame Environment — H_2-O_2
Initial Weight — 1.4414g
Final Weight — 0.9927g
Apparent Corrosion Rate — -8.974×10^3 mg/cm^2-hr
Calculated Steady State Temperature — 2385°F
Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
30	3211 T*	3.75	2675
60	3295 T	4.50	2720
90	2320 B*	6.00	2816
120	3274 T	8.25	2861
150	3274 T	9	2870
180	3274 T	21	2845
		21.75	2940
		22.5	3004
		24	3040
		30	3130
		75	3115
		120	3100
		150	3000
		180	2915

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

A moderate ignition took place with considerable sample erosion. A visible oxide smoke evolved from the sample during testing.

Table A-86

Experiment No. 79

Material — Uncoated Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.4077 g

Final Weight — 0.3329 g

Apparent Corrosion Rate — -1.548×10^6 mg/cm^2-hr

Calculated Steady State Temperature — 2695°F

Temperature-Time Data:

Two Color Pyrometer

Time (sec)	Temperature (°F)
1.5	2600
4.6	3700
6.1	3700
6.85	3480
7.6	3380
8.35	3120
12	3120
13.5	3326
15	3525
16.5	3370
18	3328
19.5	3410
21	3525
22.5	3561
24	3450
24.75	3370

REMARKS:

Sample ignited immediately. Very rapid oxidation and volitization of film with a considerable amount of smoke being evolved. Complete sample erosion.

Table A-87

Experiment No. 80

Material—Uncoated Tungsten

Flame Environment—H_2-O_2

Initial Weight—1.4750 g

Final Weight—0.8095 g

Apparent Corrosion Rate— -3.99×10^4 mg/cm^2-hr

Calculated Steady State Temperature—2555°F

Temperature-Time Data:

Two Color Pyrometer

Time (sec)	Temperature (°F)
12	3028

REMARKS:

A moderate ignition occurred. Considerable sample erosion resulted. Test discontinued at 60 seconds due to two color pyrometer malfunction.

Table A-88

Experiment No. 81

Material—Uncoated Tungsten

Flame Environment—H_2-O_2

Initial Weight—1.4206g

Final Weight—0.9886g

Apparent Corrosion Rate— -2.59×10^4 mg/cm^2-hr

Calculated Steady State Temperature—2555°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
30	3466 T*	24	3450
45	3476 T	40	3410
60	3454 T	60	3370

T* = Top of Sample

REMARKS:

See remarks Experiment No. 80.

Table A-89

Experiment No. 82

Material — Uncoated Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.4467g

Final Weight — Not Obtainable

Apparent Corrosion Rate — Not Obtainable

Calculated Steady State Temperature — 2830°F

Temperature-Time Data:

Two Color Pyrometer

Time (sec)	Temperature (°F)
1.5	3600
2.25	3355
3	3120
4.1	2770

REMARKS:

Sample jumped out of transite board and was lost into the vacuum system.

Table A-90

Experiment No. 83

Material—Uncoated Tungsten

Flame Environment—H_2-O_2

Initial Weight—1.4421g

Final Weight—1.3141g

Apparent Corrosion Rate—-1.152 x 10^5 mg/cm^2-hr

Calculated Steady State Temperature—2920°F

Temperature-Time Data:

Two Color Pyrometer

Time (sec)	Temperature (°F)
1.50	3700
2.25	3315
3.00	3087
3.75	2668

REMARKS:

A very rapid ignition occurred. Test stopped as sample began to fall over.

Table A-91

Experiment No. 84

Material — Uncoated Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.4397 g

Final Weight — 0.6221 g

Apparent Corrosion Rate — -7.0×10^5 mg/cm^2-hr

Calculated Steady State Temperature — 2980°F

Temperature-Time Data:

Two Color Pyrometer Inoperative

Optical Pyrometer

Time (sec)	Temperature (°F)
15	3788
30	3725
42	3725

REMARKS:

Sample appeared to ignite totally.

Table A-92

Experiment No. 86

Material — Uncoated Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.4569 g

Final Weight — 0.4137 g

Apparent Corrosion Rate — -1.728 x 10^6 mg/cm^2-hr

Calculated Steady State Temperature — 2695°F

Temperature-Time Data:

Two Color Pyrometer

Time (sec)	Temperature (°F)
1.5	2600
3	3700
4.5	3380
6	3490
7.5	3275
9	3120
10.5	2900
12	2645
13.5	2790
15	3530
16.5	3530
18	3700
19.5	3700
21	3700
21.75	3530

REMARKS:

See Remarks Experiment No. 79.

Table A-93

Experiment No. 88

Material — Uncoated Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.4482 g

Final Weight — 0.8710 g

Apparent Corrosion Rate — -3.575×10^4 mg/cm^2-hr

Calculated Steady State Temperature — 2695°F

Temperature-Time Data:

Two Color Pyrometer

Time (sec)	Temperature (°F)
0.75	3290
1.5	3555
3	3620
4.5	3640
19.5	3620
46.5	3655
48	3655
49.5	3640
50.5	3555
52	3530
53.5	3555
55	3570
56.5	3570
58	3555

REMARKS:

A moderate oxidation reaction was observed with considerable sample erosion.

Table A-94

Experiment No. 89

Material — Tantalum -10% Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.2670 g

Final Weight — 1.2670 g

Apparent Corrosion Rate — 0

Calculated Steady State Temperature — 1925°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
30	2300 T*
60	2260 T
80	1775 B*
90	2260 T
105	1775 B
120	2260 T
180	2300 T
195	1775 B
210	2320 T
240	2320 T
250	1775 B
270	2320 T
300	2320 T
310	1793 B
330	2320 T
360	2310 T

T* = Top of Sample

B* = Bottom of Sample

REMARKS:

No signs of melting or igniting. A thin flakey, white oxide coating began to form on the sample top.

Table A-95

Experiment No. 90

Material — Tantalum -10% Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.3247 g

Final Weight — 1.4535 g

Apparent Corrosion Rate — $+3.56 \times 10^4$ mg/cm^2-hr

Calculated Steady State Temperature — 2465°F

Temperature-Time Data:

Two Color Pyrometer

Time (sec)	Temperature (°F)
1.5	3410
2.25	>3700
12.75	>3700
13.15	3700

REMARKS:

> Sample appeared to ignite instantly. Complete sample erosion observed. Partial melting may have occurred as a crystalline type coating remained on the surface fused to a white oxide film.

Table A-96

Experiment No. 91

Material — Tantalum -10% Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.3042 g

Final Weight — 1.3762 g

Apparent Corrosion Rate — $+4.06 \times 10^4$ mg/cm^2-hr

Calculated Steady State Temperature — 2630°F

Temperature-Time Data:

Two Color Pyrometer

Time (sec)	Temperature (°F)
1.5	~3980
3	>4500
6	>4500
6.38	~4500

REMARKS:

An instantaneous ignition occurred. Complete sample erosion. A dark crystalline coating was observed on the entire sample surface.

Table A-97

Experiment No. 92
Material — Tantalum -10% Tungsten
Flame Environment — H_2-O_2
Initial Weight — 1.3188 g
Final Weight — 1.3797 g
Apparent Corrosion Rate — $+1.18 \times 10^5$ mg/cm^2-hr
Calculated Steady State Temperature — 2630°F
Temperature-Time Data:

Two Color Pyrometer

Time (sec)	Temperature (°F)
0.75	~4200
1.50	~5930
1.86	~6000

REMARKS:

An instantaneous ignition occurred. Sample erosion severe. A crystalline coating resulted.

Table A-98

Experiment No. 93

Material — Tantalum - 10% Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.3166 g

Final Weight — 1.3411 g

Apparent Corrosion Rate — +245 mg/cm^2-hr

Calculated Steady State Temperature — 2055°F

Temperature-Time Data:

	Optical Pyrometer
Time (sec)	Temperature (°F)
15	2480 T*
30	1941 B*
60	2540 T
75	1960 B
120	2560 T
150	2560 T
165	1960 B
180	2560 T
210	2560 T
220	1970 B
270	2560 T
300	2560 T
330	2560 T
340	1960 B
360	2560 T

T* = Top of Sample

B* = Bottom of Sample

REMARKS:

No ignition or melting observed. Very little visible sample erosion.

Table A-99

Experiment No. 94

Material — Tantalum - 10% Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.2012 g

Final Weight — 1.2347 g

Apparent Corrosion Rate — +335 mg/cm^2-hr

Calculated Steady State Temperature — 2125°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
15	2380 T*	60	2600
30	2600 T	69	2619
60	2700 T	75	2700
90	2060 B*	84	2745
120	2760 T	90	2737
130	2140 B	150	2820
150	2780 T	210	2838
180	2160 B	270	2838
210	2780 T	330	2838
240	2780 T	360	2838
300	2180 B		
330	2780 T		
360	2790 T		

T* = Top of Sample

B* = Bottom of Sample

REMARKS:

See Remarks Experiment No. 93.

Table A-100

Experiment No. 95

Material — Tantalum -10% Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.2420 g

Final Weight — 1.3191 g

Apparent Corrosion Rate — +771 mg/cm^2-hr

Calculated Steady State Temperature — 2335°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
30	3090 T*	1.5	2889
90	2944 T	3	3275
105	2380 B*	9	3130
120	2944 T	18	3086
180	2944 T	30	3068
195	2390 B	45	3086
210	2954 T	90	3037
240	2944 T	120	3037
250	2380 B	180	3009
270	2944 T	240	3000
310	2380 B	300	3000
330	2944 T	360	3000
360	2944 T		

T* = Top of Sample

B* = Bottom of Sample

REMARKS:

No ignition or melting. The sample top shows considerable erosion with apparent splitting of the uppermost top edges.

Table A-101

Experiment No. 96
Material — Tantalum-10% Tungsten
Flame Environment — H_2-O_2
Initial Weight — 1.2973g
Final Weight — 1.4033g
Apparent Corrosion Rate — $+2.48 \times 10^4$ mg/cm^2-hr
Calculated Steady State Temperature — 2200°F
Temperature-Time Data:

Time (sec)	Two Color Pyrometer Temperature (°F)
1.5	2600
3	>3700
12	3700
13.5	3328
15	3078
15.38	3018

REMARKS:

A top ignition occurred. Sample top severly eroded. A crystalline type coating remained on the sample top surfaces.

Table A-102

Experiment No. 97

Material—Tantalum-10% Tungsten

Flame Environment—H_2-O_2

Initial Weight—1.2212g

Final Weight—1.2546g

Apparent Corrosion Rate— +334 mg/cm^2-hr

Calculated Steady State Temperature—2125°F

Temperature-Time Data:

Time (sec)	Optical Pyrometer Temperature (°F)
30	2340 T*
60	2600 T
75	2000 B*
90	2640 T
110	2640 T
150	2640 T
160	2040 B
180	2680 T
210	2680 T
220	2020 B
240	2680 T
260	2000 B
300	2780 T
330	2680 T
360	2040 B

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

No melting or ignition. A heavy white oxide coating formed on the sample. The top shows early stages of splitting. It was quite apparent that the sample was on the verge of igniting.

Table A-103

Experiment No. 98

Material — Tantalum-10% Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.3090g

Final Weight — 1.3974g

Apparent Corrosion Rate — -3.48×10^3 mg/cm^2-hr

Calculated Steady State Temperature — 2051°F

Temperature-Time Data:

Time (sec)	Two Color Pyrometer Temperature (°F)
3	2715
3.75	>3700
12	3700

REMARKS:

The sample ignited with severe top erosion resulting. A crystalline coating remained.

Table A-104

Experiment No. 99

Material — Tantalum-10% Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.2761g

Final Weight — 1.3654g

Apparent Corrosion Rate — +2.655 x 10^4 mg/cm^2-hr

Calculated Steady State Temperature — 2505°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
15	3662 T*	1.5	2600
30	3725 T	3	3700
60	3683 T	18	3465
90	3683 T	30	3410
105	2500 B*	60	3410
120	3683 T	90	3410
150	3683 T	120	3424
160	2480 B	150	3410
180	3683 T	180	3480
		108.38	3480

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

No apparent ignition took place. A clear, white, crystalline coating formed on the extreme top of the sample. A moderate, flakey, white coating formed on the remainder of the sample.

Table A-105

Experiment No. 100

Material — Tantalum-10% Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.2821g

Final Weight — 1.3073g

Apparent Corrosion Rate — $+2.42 \times 10^4$ mg/cm^2-hr

Calculated Steady State Temperature — 2630°F

Temperature-Time Data:

	Two Color Pyrometer
Time (sec)	Temperature (°F)
1.5	2600
2.25	>3700
3	>3700
3.75	3660

REMARKS:

See remarks Experiment No. 92.

Table A-106

Experiment No. 101
Material — Tantalum-10% Tungsten
Flame Environment — H_2-O_2
Initial Weight — 1.2821 g
Final Weight — 1.3690 g
Apparent Corrosion Rate — $+5.025 \times 10^3$ mg/cm^2-hr
Calculated Steady State Temperature — 2810°F
Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
15	3940 T*	0.75	3600
30	3662 T	1.5	>3700
45	3620 T	7.5	3700
55	2780 B*	10.5	3676
60	3476 T	16.5	3588
		22.5	3548
		31.5	3765
		43.5	3410
		55.5	3380
		61.5	3355
		62.25	3328

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

Sample showed no true ignition. Very hot top zone. Sample appeared to melt gradually.

Table A-107

Experiment No. 102

Material — Tantalum-10% Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.3102 g

Final Weight — 1.3237 g

Apparent Corrosion Rate — $+1.128 \times 10^4$ mg/cm^2-hr

Calculated Steady State Temperature — 2925°F

Temperature-Time Data:

	Two Color Pyrometer
Time (sec)	Temperature (°F)
0.38	2600
0.75	2908
1.5	>3700
3.0	3700
3.75	3425
4.25	3355

REMARKS:

> No visible ignition occurred. The sample geometry, however, remained intact. The sample has a thin crystalline coating over the entire sample length.

Table A-108

Experiment No. 103
Material — Tantalum-10% Tungsten
Flame Environment — H_2-O_2
Initial Weight — 1.3333 g
Final Weight — 0.7443 g
Apparent Corrosion Rate — -2.07×10^5 mg/cm^2-hr
Calculated Steady State Temperature — 2630°F
Temperature-Time Data:

Two Color Pyrometer

Time (sec)	Temperature (°F)
1	2600
1.5	3585
2.25	>3700
9	3700
10	3700
11	3700
12	3700

REMARKS:

A very rapid ignition occurred with subsequent total sample erosion.

Table A-109

Experiment No. 104

Material — Tantalum-10% Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.3139 g

Final Weight — 1.4444 g

Apparent Corrosion Rate — $+9.58 \times 10^4$ mg/cm^2-hr

Calculated Steady State Temperature — 2630°F

Temperature-Time Data:

Two Color Pyrometer

Time (sec)	Temperature (°F)
0.75	2600
1.5	3450
3	3420
6	3465
9	3450
12	3420
15	3369
18	3327
21	3327
27	3300
36	3300
49	3300

REMARKS:

A moderate ignition occurred with severe top erosion. A thin white oxide coating covered the remainder of the sample.

Table A-110

Experiment No. 105

Material — Tantalum-10% Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.3115 g

Final Weight — 0.7443 g

Apparent Corrosion Rate — -1.855×10^5 mg/cm^2-hr

Calculated Steady State Temperature — 2630°F

Temperature-Time Data:

Two Color Pyrometer	
Time (sec)	Temperature (°F)
0.75	2600
1.5	>3700
10.5	>3700
11	3700

REMARKS:

See remarks Experiment No. 103.

Table A-111

Experiment No. 129

Material—Tantalum-10% Tungsten

Flame Environment—CO-O_2

Initial Weight—1.3159 g

Final Weight—1.3308 g

Apparent Corrosion Rate— +149 mg/cm^2-hr

Calculated Steady State Temperature—1905°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
30	2500 T*
45	1885 B*
60	2500 T
90	2520 T
105	2000 B
120	2520 T
135	2010 B
180	2540 T
195	2000 B
210	2530 T
240	2530 T
250	2010 B
270	2530 T
310	2020 B
330	2540 T
360	2540 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

No observable corrosion evident.

Table A-112

Experiment No. 130

Material—Tantalum-10% Tungsten

Flame Environment—$CO-O_2$

Initial Weight—1. 3149 g

Final Weight—1. 3312 g

Apparent Corrosion Rate— +195. 6 mg/cm^2-hr

Calculated Steady State Temperature—2022°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
30	2640 T*
50	2640 T
60	2020 B*
90	2640 T
100	2030 B
120	2640 T
130	2050 B
150	2620 T
160	2060 B
180	2620 T
195	2060 B
210	2620 T
240	2600 T
260	2060 B
270	2600 T
300	2600 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

A white oxide film formed on top. Considerable top erosion. Top shows preliminary signs of splitting.

Table A-113

Experiment No. 131

Material — Tantalum-10% Tungsten

Flame Environment — $CO\text{-}O_2$

Initial Weight — 1.2333 g

Final Weight — 1.2856 g

Apparent Corrosion Rate — +523 $mg/cm^2\text{-}hr$

Calculated Steady State Temperature — 2118°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
15	2882 T*
30	2640 T
60	2680 T
70	2280 B*
90	2660 T
100	2300 B
120	2660 T
135	2290 B
150	2660 T
210	2650 T
220	2290 B
250	2290 B
270	2660 T
300	2670 T
330	2660 T
360	2670 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

Sample shows top erosion with white oxide coating. Top shows considerable splitting.

Table A-114

Experiment No. 132

Material — Tantalum-10% Tungsten

Flame Environment — CO-O_2

Initial Weight — 1.2065 g

Final Weight — 1.2464 g

Apparent Corrosion Rate — +399 mg/cm^2-hr

Calculated Steady State Temperature — 2189°F

Temperature-Time Data:

	Optical Pyrometer
Time (sec)	Temperature (°F)
20	3788 T*
55	3132 T
70	2480 B*
90	3040 T
100	3480 B
120	3111 T
150	3111 T
160	2500 B
180	3090 T
195	2510 B
210	3069 T
255	2490 B
270	2500 B
300	3048 T
330	3048 T
360	3038 T

T* = Top of Sample; B* = Body of Sample

REMARKS:

Sample shows complete top erosion with a very thick oxide coating over entire sample. Severe splitting of top and edges apparent.

Table A-115

Experiment No. 133

Material—Tantalum-10% Tungsten

Flame Environment—CO-O_2

Initial Weight—1.2518 g

Final Weight—1.3223 g

Apparent Corrosion Rate— +1410 mg/cm^2-hr

Calculated Steady State Temperature—2114°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
30	2964 T*
45	2954 T
60	2954 T
75	2240 B*
90	2943 T
120	2882 T
135	2228 B
150	2851 T
165	2240 B
180	2862 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

Severe top erosion observed. Splitting on top and edges evident. These split areas appear to be the zones of intense oxidation.

Table A-116

Experiment No. 134
Material — Tantalum-10% Tungsten
Flame Environment — CO-O_2
Initial Weight — 1.3273 g
Final Weight — 1.3884 g
Apparent Corrosion Rate — +1222 mg/cm^2-hr
Calculated Steady State Temperature — 2031°F
Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
10	3400 T*
30	2882 T
60	2903 T
75	2020 B*
90	2882 T
105	2050 B
120	2872 T
135	2040 B
150	2882 T
180	2882 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

Top eroded with a white oxide coating covering entire sample. Sample top shows considerable splitting.

Table A-117

Experiment No. 106

Material—Pfaudler Coated Tungsten

Flame Environment—H_2-O_2

Initial Weight—1.5208 g

Final Weight—1.5190 g

Apparent Corrosion Rate—-18 mg/cm^2-hr

Calculated Steady State Temperature—1970°F

Temperature-Time Data:

	Optical Pyrometer
Time (sec)	Temperature (°F)
15	2180 T*
30	1775 B*
45	2280 T
60	1812 B
90	2280 T
105	1793 B
120	2280 T
150	2280 T
180	2280 T
205	1793 B
240	2280 T
270	1793 B
300	2280 T
345	1812 B
360	2280 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

No visible reaction. Coating intact during test.
No visible sample corrosion.

Table A-118

Experiment No. 107

Material — Pfaudler Coated Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.5365 g

Final Weight — 1.5330 g

Apparent Corrosion Rate — -35 mg/cm^2-hr

Calculated Steady State Temperature — 2530°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
15	2944 T*	2.25	2600
30	2580 B*	3	2705
45	2964 T	6	2830
60	2560 B	9	2730
90	2944 T	12	2722
100	2580 B	24	2715
120	2944 T	30	2715
150	2944 T	60	2715
165	2600 B	90	2705
180	2964 T	120	2700
210	2933 T	150	2691
250	2560 B	180	2683
270	2923 T	240	2683
300	2923 T	300	2683
330	2560 B	330	2705
360	2923 T	360	2691

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

No visible reaction. Coating intact with little erosion.

Table A-119

Experiment No. 108
Material — Pfaudler Coated Tungsten
Flame Environment — H_2-O_2
Initial Weight — 1.5760 g
Final Weight — 1.5707 g
Apparent Corrosion Rate — -63.6 mg/cm^2-hr
Calculated Steady State Temperature — 2695°F
Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
7	3170 T*	1.13	2600
30	3243 T	1.5	2870
45	2740 B*	3	3098
60	3151 T	6	3000
75	2730 B	9	3068
90	3170 T	12	3120
120	3170 T	30	3120
130	2730 B	60	3058
150	3190 T	90	3058
180	3170 T	120	3037
190	2740 B	150	3047
210	3170 T	180	3027
240	3151 T	210	3000
250	2740 B	240	3027
270	3151 T	270	3009
300	3151 T	300	3047

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

No melting or any signs of ignition. Coating remained intact with some slight erosion visible.

Table A-120

Experiment No. 109

Material — Pfaudler Coated Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.5409 g

Final Weight — 1.5387 g

Apparent Corrosion Rate — +528 mg/cm^2-hr

Calculated Steady State Temperature — 2830°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
7	3274 T*	0.75	2600
		1.5	3109
		3	3130
		6	3145
		7.5	3120
		9	2820
		10.5	2960
		12	3000
		13.5	3088
		15	3098

T* = Top of Sample

REMARKS:

See Remarks Experiment No. 108.

(Note: Run discontinued when sample began to fall)

Table A-121

Experiment No. 110

Material — Pfaudler Coated Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.5174 g

Final Weight — 1.4992 g

Apparent Corrosion Rate — -224 mg/cm^2-hr

Calculated Steady State Temperature — 2920°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
8	3488 T*	0.75	2600
30	3358 T	1.5	3236
40	2841 B*	3.0	3249
60	3253 T	5.25	3223
75	3295 T	6.75	3088
90	2841 B	9	3098
120	3253 T	15	3037
130	2800 B	21	3088
150	3253 T	27	3027
180	3274 T	60	3027
210	3232 T	90	2960
240	2841 B	150	2960
260	3253 T	210	2915
		255	2989
		260	2989

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

No melting or ignition. Slight coating breakdown was observed as a small bubbling on one of the sample sides.

Table A-122

Experiment No. 111

Material — Pfaudler Coated Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.5170 g

Final Weight — 1.5094 g

Apparent Corrosion Rate — -285 mg/cm^2-hr

Calculated Steady State Temperature — 3130°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
10	3295 T*	0.1	2600
30	2964 B*	1.5	3262
40	3243 T	3	3370
60	3253 T	6	3223
70	2944 B	12	3196
80	3253 T	15	3110
		18	3110
		24	3249
		27	3130
		60	3160
		96	3088

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

Slight coating breakdown on top edge only.
Remainder of coating intact during test.

Table A-123

Experiment No. 112
Material — Pfaudler Coated Tungsten
Flame Environment — H_2-O_2
Initial Weight — 1.5070 g
Final Weight — 1.5034 g
Apparent Corrosion Rate — -36 mg/cm^2-hr
Calculated Steady State Temperature — 2110°F
Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
15	2500 T*
30	1960 B*
60	2540 T
90	2540 T
120	2540 T
140	2160 B
150	2540 T
180	2560 T
190	2270 B
210	2560 T
240	2560 T
250	2260 B
300	2560 T
330	2060 B
360	2540 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

No melting or visible sample erosion. The sample shows a severe discoloration on the surface. The coating remained intact.

Table A-124

Experiment No. 113

Material — Pfaudler Coated Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.5193 g

Final Weight — 1.5176 g

Apparent Corrosion Rate — -17 mg/cm^2-hr

Calculated Steady State Temperature — 2180°F

Temperature-Time Data:

Optical Pyrometer	
Time (sec)	Temperature (°F)
15	2580 T*
30	2610 T
60	2620 T
70	2140 B*
90	2630 T
120	2620 T
130	2140 B
150	2630 T
190	2120 B
210	2620 T
240	2640 T
270	2640 T
285	2130 B
300	2640 T
330	2640 T
360	2640 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

Sample showed no corrosive characteristics. However, a very fine yellow-white oxide powder was observed on the sample top edges. No apparent coating breakdown. Sample showed considerable discoloration.

Table A-125

Experiment No. 114

Material — Pfaudler Coated Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.4842 g

Final Weight — 1.4774 g

Apparent Corrosion Rate — -129.8 mg/cm^2-hr

Calculated Steady State Temperature — 2385°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
20	2923 T*	2.25	2600
30	2964 T	3.0	2667
50	2280 B*	3.75	2715
60	2985 T	9	2737
70	2340 B	15	2745
90	2995 T	21	2753
120	2985 T	30	2761
150	2320 B	60	2770
180	2995 T	90	2777
210	3000 T	120	2777
220	2340 B	150	2777
240	2995 T	180	2777
250	2320 B	210	2777
300	2995 T	240	2777
~330	3006 T	300	2777
		327	2770

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

No melting or ignition. The sample's coating showed signs of discontinuity on all edges where a white oxide film was observed to form.

Table A-126

Experiment No. 115

Material—Pfaudler Coated Tungsten

Flame Environment—H_2-O_2

Initial Weight—1.5159 g

Final Weight—1.5086 g

Apparent Corrosion Rate— -73.6 mg/cm^2-hr

Calculated Steady State Temperature—2555°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
15	3048 T*	3	2000
40	3253 T	4.5	2701
60	2560 B*	15	2880
90	3274 T	27	2777
120	3274 T	36	3047
135	2660 B	60	3047
150	3295 T	90	3047
180	3284 T	120	3047
195	2640 B	150	3037
240	3284 T	180	3037
270	3274 T	210	3037
285	2650 B	240	3037
300	3295 T	270	3047
330	3295 T	300	3058
360	3295 T	330	3058
		357	3068

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

Little, if any, observable sample corrosion. Sample edges show beginning signs of breakdown. Otherwise the coating remained intact.

Table A-127

Experiment No. 116

Material—Pfaudler Coated Tungsten

Flame Environment—H_2-O_2

Initial Weight—1.5303 g

Final Weight—1.4946 g

Apparent Corrosion Rate— -1753 mg/cm^2-hr

Calculated Steady State Temperature—2865°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
15	3466 T*	1.13	2600
45	3704 T	3	3395
60	3704 T	12	3480
65	Sample fell	18	3540
		24	3620
		33	3570
		43	3660
		51	3660
		57	3620
		60	3585
		63	3502

T* = Top of Sample

REMARKS:

The sample showed top erosion. The protective coating broken down by blistering. The sample retained its geometric shape. Yellow-white smoke evolved in small amounts from top.

Table A-128

Experiment No. 117

Material—Pfaudler Coated Tungsten

Flame Environment—H_2-O_2

Initial Weight—1.5483 g

Final Weight—1.3021 g

Apparent Corrosion Rate— -5515 mg/cm^2-hr

Calculated Steady State Temperature—2980°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
15	3940 T*	0.75	2600
30	3830 T	1.5	3965
45	4061 T	6	3680
65	3190 B*	18	3660
80	4006 T	27	3632
100	4017 T	42	3570
120	3940 T	60	3570
135	3253 B	105	3490
150	3788 T	150	3437
160	3767 T	161	3410

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

Considerable top erosion. The top appeared to melt slowly. Remainder of sample's coating attacked with the severity of erosion decreasing from top to bottom.

Table A-129

Experiment No. 118

Material — Pfaudler Coated Tungsten

Flame Environment — H_2-O_2

Initial Weight — 1.5401 g

Apparent Corrosion Rate — +253 mg/cm^2-hr

Calculated Steady State Temperature — 2695°F

Temperature-Time Data:

Two Color Pyrometer	
Time (sec)	Temperature (°F)
1.5	2600
3	3236
9	3287
15	3287
18	3340
21	3410
24	3410
27	3196

REMARKS:

Very slight sample top erosion. Remainder of sample intact. Very thin white oxide coating visible on upper portion of sample.

Table A-130

Experiment No. 119

Material—Pfaudler Coated Tungsten

Flame Environment—H_2-O_2

Initial Weight—1.5114 g

Final Weight—1.4718 g

Apparent Corrosion Rate— -464 mg/cm^2-hr

Calculated Steady State Temperature—2695°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
10	3263 T*
35	2933 B*
60	3389 T
80	2964 B
120	3263 T
150	3006 B
205	3274 T
240	2933 B
280	3326 T

Two Color Pyrometer

Time (sec)	Temperature (°F)
1.13	2600
1.5	3009
3	3287
9	3355
15	3370
30	3380
60	3355
90	3340
120	3340
150	3340
180	3275
210	3275
240	3262
270	3313
300	3262
300.75	3262

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

See Remarks Experiment No. 118

Table A-131

Experiment No. 120

Material—Pfaudler Coated Tungsten

Flame Environment—H_2-O_2

Initial Weight—1.5306 g

Final Weight—1.4756 g

Apparent Corrosion Rate—-643 mg/cm^2-hr

Calculated Steady State Temperature—2695°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
25	3200 T^*
45	3006 B^*
70	3455 T
100	3048 B
130	3466 T
155	3151 B
180	3368 T
210	3006 B
235	3466 T
255	2923 B
280	3433 T

Two Color Pyrometer

Time (sec)	Temperature (°F)
0.87	2600
1.5	2860
6	3088
15	3130
21	3172
30	3380
60	3424
90	3395
120	3450
150	3437
180	3465
210	3480
240	3480
270	3465
300	3450
300.87	3465

T^* = Top of Sample; B^* = Bottom of Sample

REMARKS:

See Remarks Experiment No. 118

Table A-132

Experiment No. 121

Material—Pfaudler Coated Tungsten

Flame Environment—H_2-O_2

Initial Weight—1.4896g

Final Weight—1.3873g

Apparent Corrosion Rate—-537.5 mg/cm^2-hr

Calculated Steady State Temperature—2695°F

Temperature-Time Data:

Optical Pyrometer		Two Color Pyrometer	
Time (sec)	Temperature (°F)	Time (sec)	Temperature (°F)
25	3368 T*	0.8	2600
60	2974 B*	3	3287
85	3368 T	12	3340
110	3037 B	21	3287
135	3316 T	27	3313
160	3037 B	60	3196
185	3433 T	120	3110
210	3048 B	180	3380
260	3263 T	240	3380
300	3100 B	300	3380
325	3466 T	360	3380
355	3069 B	420	3380
455	3455 T	480	3355
505	3037 B	540	3326
580	3368 T	600	3300
		600.85	3300

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

See remarks, Experiment No. 118.

Table A-133

Experiment No. 135

Material—Pfaudler Coated Tungsten

Flame Environment—CO-O_2

Initial Weight—1.5389g

Final Weight—1.5377g

Apparent Corrosion Rate—-18 mg/cm^2-hr

Calculated Steady State Temperature—2181°F

Temperature-Time Data:

Time (sec)	Optical Pyrometer Temperature (°F)
15	2660 T*
30	2700 T
45	2300 B*
60	2700 T
75	2320 B
90	2700 T
105	2310 B
120	2710 T
150	2700 T
165	2140 B
180	2700 T
210	2710 T
225	2120 B
240	2700 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

Very slight bubbling around top edges observed. No other visible sample corrosive characteristics.

Table A-134

Experiment No. 136

Material—Pfaudler Coated Tungsten

Flame Environment—CO-O_2

Initial Weight—1.5213g

Final Weight—1.5181 g

Apparent Corrosion Rate—-46.5 mg/cm^2-hr

Calculated Steady State Temperature—2087°F

Temperature-Time Data:

Optical Pyrometer

Time (sec)	Temperature (°F)
8	2400 T*
30	2560 T
40	2000 B*
60	2540 T
90	2540 T
105	2020 B
120	2540 T
135	2000 B
150	2550 T
180	2540 T
195	2035 B
210	2540 T
240	2540 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

Sample top shows a visible array of white and white-yellow oxide films. The remainder of the sample surface shows considerable discoloration.

Table A-135

Experiment No. 137

Material — Pfaudler Coated Tungsten

Flame Environment — $CO\text{-}O_2$

Initial Weight — 1.5003g

Final Weight — 1.4992g

Apparent Corrosion Rate — -11 mg/cm^2-hr

Calculated Steady State Temperature — 2250°F

Temperature-Time Data:

	Optical Pyrometer
Time (sec)	Temperature (°F)
10	2700 T*
45	2380 B*
60	2780 T
80	2400 B
90	2780 T
105	2420 B
130	2390 B
150	2780 T
165	2420 B
180	2790 T
195	2400 B
230	2400 B
270	2780 T
300	2780 T
315	2400 B
360	2780 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

Very slight sample top erosion observed.
Remainder of sample intact.

Table A-136

Experiment No. 138

Material — Pfaudler Coated Tungsten

Flame Environment — $CO-O_2$

Initial Weight — 1.5585g

Final Weight — 1.5564g

Apparent Corrosion Rate — -21 mg/cm^2-hr

Calculated Steady State Temperature — 2094°F

Temperature-Time Data:

Optical Pyrometer	
Time (sec)	Temperature (°F)
30	2720 T*
45	1970 B*
60	2720 T
90	2720 T
105	2070 B
120	2720 T
165	2080 B
180	2720 T
195	2140 B
210	2700 T
235	2140 B
240	2700 T
255	2150 B
280	2700 T
330	2140 B
360	2710 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

No visible sample erosion observable.

Table A-137

Experiment No. 139

Material — Pfaudler Coated Tungsten

Flame Environment — $CO\text{-}O_2$

Initial Weight — 1.5273g

Final Weight — 1.5211g

Apparent Corrosion Rate — -18.6 mg/cm^2-hr

Calculated Steady State Temperature — 2181°F

Temperature-Time Data:

	Optical Pyrometer
Time (sec)	Temperature (°F)
30	2480 T*
60	2180 B*
90	2490 T
180	2490 T
210	2280 B
240	2530 T
390	2320 B
480	2600 T
510	2420 B
720	2640 T
780	2640 T
900	2640 T
930	2460 B
1050	2450 B
1080	2640 T
1200	2640 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

Slight top erosion observed. A spotty yellow-white oxide coating formed in the middle of one sample surface

Table A-138

Experiment No. 140

Material—Pfaudler Coated Tungsten

Flame Environment—$CO\text{-}O_2$

Initial Weight—1.5084g

Final Weight—1.4927g

Apparent Corrosion Rate—-47.1 mg/cm^2-hr

Calculated Steady State Temperature—2250°F

Temperature-Time Data:

Time (sec)	Optical Pyrometer Temperature (°F)
30	2740 T*
90	2440 B*
120	2720 T
240	2460 B
300	2750 T
390	2500 B
480	2821 T
510	2590 B
600	2821 T
630	2560 B
660	2841 T
750	2580 B
960	2841 T
990	2580 B
1080	2841 T
1200	2841 T

T* = Top of Sample; B* = Bottom of Sample

REMARKS:

No observable sample corrosion.

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